Disposal of oil-based cuttings

Report RF-98/097

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Scope: To investigate the various possibilities of handling oil-based cuttings piles in connection with field abandonment. To evaluate seven scenarios, including retrieval technology, with respect to handling rates, costs, emissions and discharges, safety, risks and environmental impacts:

- Leave the piles undisturbed
- Cover the pile for protection
- Bioremediation
- Retrieval technology
- Removal and reinjection in a well
- Respreading on the sea floor
- Treatment and disposal - offshore or onshore

To develop a decision tree to aid the identification of suitable and unsuitable handling solutions.

Key-words:

Oily drill cuttings, bioremediation, reinjection, respreading, treatment, disposal, environmental impacts, costs, emissions, energy.

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CONTENTS

SUMMARY

Nineteen operations comprising the seven options for handling existing oily drill cuttings piles were described: leave the piles undisturbed; bioremediation in situ; capping; gravel dumping; spreading; retrieve with suction; retrieve with dredging; retrieve with a sea-floor crawler; sub-sea entombment in a pit; reinjection into a well; bioreactor treatment offshore; super-critical treatment offshore; land-farming; mechanical treatment onshore; distillation onshore; stabilisation onshore; combustion onshore; landfill, either of treated or untreated wastes. Where possible, each operation was described in terms of eighteen parameters including equipment, handling rates, costs, emissions and discharges, risks and environmental impacts.

The data presented in Chapters 2 to 10 of the study, and summarised in Section 11, were then used to assess the performance of the key operations or end-points, in terms of the criteria of environmental impact, energy use, safety, cost and technical feasibility. The "performance" of the key operations and end-points was examined on the basis of these criteria, both when taken individually and when taken in various combinations. It was thus possible, in an intra-generic group comparison, to identify one specific decommissioning option which was judged to be particular suitable for incorporation into a generic option. The relative performances of these selected options were then assessed in an inter-generic group comparison, using the same criteria of environmental impact, energy use, safety, cost and feasibility, both individually and in combination.

Of the specific cutting pile handling techniques evaluated, covering with gravel using a fall-pipe delivery system appeared overall to offer several advantages compared with other covering or capping techniques, a sea-floor crawler was an appropriate retrieval technique, a bioreactor an appropriate offshore treatment technique, and distillation was judged a suitable onshore treatment technique. Using these specific techniques in the evaluation of the different total handling processes, retrieval, slurrification and reinjection appeared a particularly promising commercially available technique. Bioremediation *in situ* appeared to offer much potential, but the method is currently not developed. Leaving in place was also promising, but aspects such as decommissioning damage, hindrance and liability need to be considered. The reinjection option has a moderate level of environmental impact as a result of the requirement to retrieve the cuttings from the sea-floor and has a net energy consumption which appears to be in the middle of the range that was able to be determined for the nine generic options. In all other respects this option performs well or very well: it is safe, commercially available and affordable. It does though require that necessary topsides reinjection and buffer storage facilities are available, and most importantly, the rock formation is able to accept sufficient quantities of the reinjected slurry.

All the handling options had advantages and disadvantages relative to the other options, so a case-by-case assessment of each pile is needed. For this reason, this study has avoided the ranking of operations, or the recommendation of any one specific operation, end-point or generic option. The methods and data presented in this study can be used to assist such assessment studies, as well as to tentatively indicate an overall policy.

PREFACE

The Norwegian Oil Industry Association (OLF) commissioned a study of the various options associated with the handling of existing oil-based cuttings piles in connection with field abandonment. In order to conduct this wide-ranging multi-disciplinary investigation a team comprising a broad range of competence was established. The team included the following researchers from four main institutions:

Amy Annand Candida Heyworth	**Cordah**	Energy and respreading
Craig Marken	**Rogaland Research**	Cuttings reinjection
Daryl Shaw	**Reverse Engineering**	Retrieval & treatment technology
Gordon Picken	**Cordah**	Project manager - Cordah Respreading and assessment
Inge Brun Henriksen	**Rogaland Research**	Treatment technology
Jens Petter Aabel	**Dames & Moore**	Project manager - Dames & Moore/REL Retrieval & treatment technology
John-Eirik Paulsen	**Rogaland Research**	Bioremediation
Monica Jakobsen	**Dames & Moore**	Retrieval & treatment technology
Odd-Ketil Andersen Troels Jacobsen	**Rogaland Research**	Leave in place
Rolv Kristiansen	**Rogaland Research / Nordland Research**	Bioremediation
Simon J. Cripps	**Rogaland Research**	Project co-ordinator Environment, assessment, collation

The project steering committee for the OLF comprised:

Arvid Sande	Committee chairman BP Norge
Bente Jarandsen	OLF
Britt Brun	Phillips PCoN
Eli Dalland	Statoil
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RF ROGALAND RESEARCH	DAMES & MOORE GROUP A DAMES & MOORE GROUP COMPANY	CORDAH

1 INTRODUCTION

1.1 Decommissioning

The following summary of North Sea decommissioning is partly taken from Aabel *et al.* (1997).

The fate of oil and gas platforms in the North Sea that are decommissioned as a result of declining production in some fields, or changes in management strategy, has been the subject of much debate. There is a growing realisation that decommissioning is not just a technical, environmental or navigation issue: there are safety, economic and social implications to consider (Figure 1). These must be balanced, preferably on a case-by-case basis, in order to achieve the best possible decommissioning plan that is acceptable to the operator, authorities and the general public.

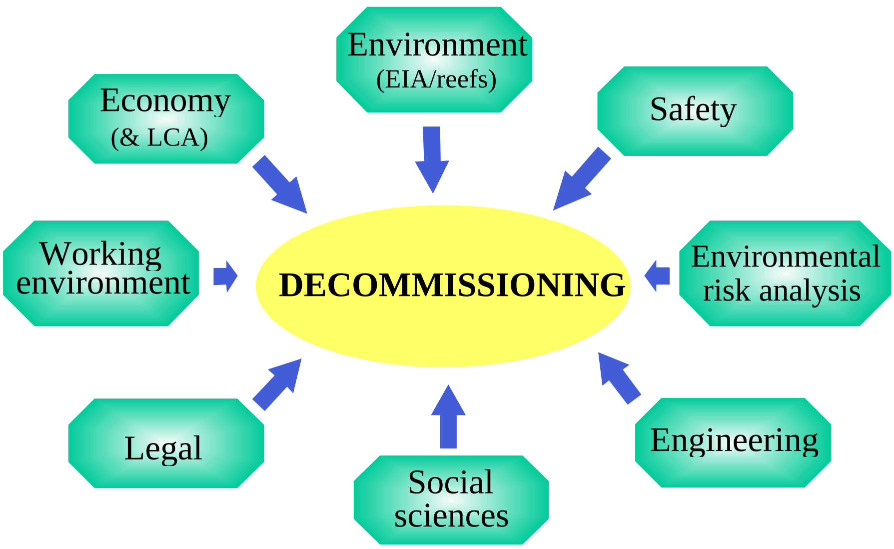


Figure 1*: Parameters associated with the decommissioning process.*

Various options have been proposed for dealing with decommissioned structures:

- alternative use *in-situ;*
- reuse at another field;
- deep-sea disposal;
- dismantling and recycling on/inshore;
- toppling;
- abandonment in place;
- artificial reefs.

There are 420 platforms in the North Sea, of which approximately 210 are in the UK sector. In the Norwegian sector there are approximately 70 working and planned structures, all located in the central and northern North Sea. The structures are fairly large and are placed in water depths ranging from 70 to 300 m. The Troll platform now built will be placed at a depth of 302 m.

Other structures in the North Sea area (about 150) are mainly small and situated in the shallow southern North Sea. They are mostly owned by Dutch and Danish interests (Corcoran, 1995; Laver, 1992; NOU, 1993; Williams, 1995).

The majority of structures in the North Sea are constructed of steel. Only 26 structures are concrete. Of the concrete structures, 15 are in the Norwegian sector, 10 in the UK sector, and there is 1 Dutch structure (Corcoran, 1995; Williams, 1995).

Only a few structures in the North Sea have stopped production, but several fields and structures are to be taken out of service in the near future. The exact cessation dates are frequently being reviewed because of changes in the requirements of the authorities, development of new decommissioning technology and enhanced exploitation of marginal fields. ODIN was shut-down on the 1st August 1994 (Anon, 1994). Production on North East Frigg stopped on the 8th May 1993. A date for a halt in production for many of the larger, or new, fields has yet to be decided upon, but it is expected that several of the structures in the Ekofisk field will be abandoned within the next five years.

It is technically possible to remove most of the structures placed in the British and Norwegian sectors, but in some instances there may be considerable environmental, socio-economic, health and safety consequences to consider. Certain high profile cases such as the unusual case of the Brent Spar have brought the subject to the attention of the public, and increased the interest of regional, national and multi-national authorities.

To achieve the best possible means of evaluating different abandonment strategies and methods, as many as possible of the different aspects must be identified and evaluated. One such aspect is the fate of oil-based drill cuttings, previously deposited on the sea-floor as a result of exploration and production drilling operations.

1.2 Types of cuttings

Three main types of cuttings can be defined, depending on the drilling muds used to facilitate the boring process and to carry the cuttings to the surface:

- water-based, containing for example KCl/polymers or glycol;
- pseudo-oil-based, commonly comprising olefins and esters;
- oil-based comprising either clean mineral oils or in the early stages, diesel.

The latter type are considered to have the most deleterious effect on the local environment (especially diesel) and so their use has been gradually phased out in the North Sea during recent years, as described by Kjeilen *et al.* (1996).

Until 1990, the use of oil-based fluids was dominant, but these were only used in the lowest sections of the well that were also the narrowest and hence produced the lowest quantity of cuttings per metre drilled (Teigen, pers. comm.). Alternative types of drilling fluids have been developed as a consequence of increasingly strong environmental protection legislation. The alternative drilling fluids have been designed to have less negative impact on the environment, i.e. they are more easily degradable and less toxic than oil-based drilling fluids. Until September 1991, the discharge limit to the sea, of oil attached to cuttings, was 100 g oil per kg dry cuttings. After September 1991, the discharge limits was reduced to 10 g per kg dry cuttings. No oil contaminated cuttings may be discharged into the sea from 1st January 1994.

1.3 Characteristics of cuttings piles

Anderson *et al*. (1996) reported that the definition of a cuttings pile was complicated because a there is no strict boundary between the piles and the ambient environment. Hydrographic and design parameters (e.g. discharge outfall height) influence dispersion and accumulation of cuttings material, hence a gradient usually builds up. A thin layer of cuttings often extends far further away from the discharge point than the pile itself.

Cuttings piles include the following constituents Anderson *et al.* (1996):

- solid phase material cut from the well;
- liquid phase mud components;
- hydrocarbons in oil-based muds;
- sand and cement from casing operations;
- sea water;
- heavy metals from mud components and the reservoir;
- H_2S from anaerobic bacteria;
- LSA (low specific activity) scale.

To aid in the assessment of different handling methods, the OLF project steering committee defined the properties of a "reference pile" as shown in Table 1.

***Table 1**: Reference pile constitution as defined by OLF Steering Committee.*

Parameter	Value
Form	Cone
Height (m)	7.5
Radius (m)	25
Volume (m3)	4906
Water (% by weight)	40
Oil (% by wet weight)	2
Barite (% by dry weight)	10
Density of cuttings (kg/L)	2
Density of oil (kg/L)	0.83
Density of water (kg/L)	1.027
Pile bulk density (kg/L)	1.54
Total pile content (tonnes)	
Water	2850
Oil	143
Cuttings	3780
Barite	413
Total	7186

In addition to these constituents, piles may contain a range of debris resulting from years of maintenance, construction and remedial work as described by Brown & Root (1997). This includes scaffolding poles and clips, welding rods, bolts, spanners, gloves, boots, wire rope, rigging and various construction materials. This material can be buried in the piles or may protrude out from the pile surface. Buried or protruding debris must be dealt with by any retrieval technique, whilst protruding material may also form a hindrance to fishing operations if left *in situ*.

Due to the various fluids and material incorporated into a pile, there is a large variation in shear strengths of the piles. On average, the shear strength of the piles is a magnitude higher than typical tidal bed shear stress, it is therefore unlikely that mass movement of cuttings *in situ* will occur apart from local erosion. The cuttings tend to consolidate and become more resistant to erosion, over a period of 24 hours. Some data indicates that piles have reduced in vertical height, but there is no knowledge about whether they have extended in area. The surface layer of the piles can range from near liquid, to hard cement layers. Some layers can have a plasticine-like consistency that hinders retrieval.

The total volume of the piles are greater than the amount discharged. This can partly be correlated to the fact that the average density of the piles is lower than the discharged material and that 20 - 60 % of the pile is composed of water. A more detailed description of typical constituents has been given by Anderson *et al.* (1996). Further information about the composition and the suitability of the piles for bioremediation is given in Section 4.1.

Numerous studies of the environment around oil-based cutting piles (Gray *et al.*, 1990) have indicated significant negative impacts on the benthic fauna and flora. These result primarily from hydrocarbon contamination and the physical effects of an increased sediment load. Raised levels of heavy metals in the sediments have also been documented, though their effect on the local fauna is less certain. Other types of cuttings, derived from water and pseudo oil-based muds are considered to be considerably less harmful to the ambient environment.

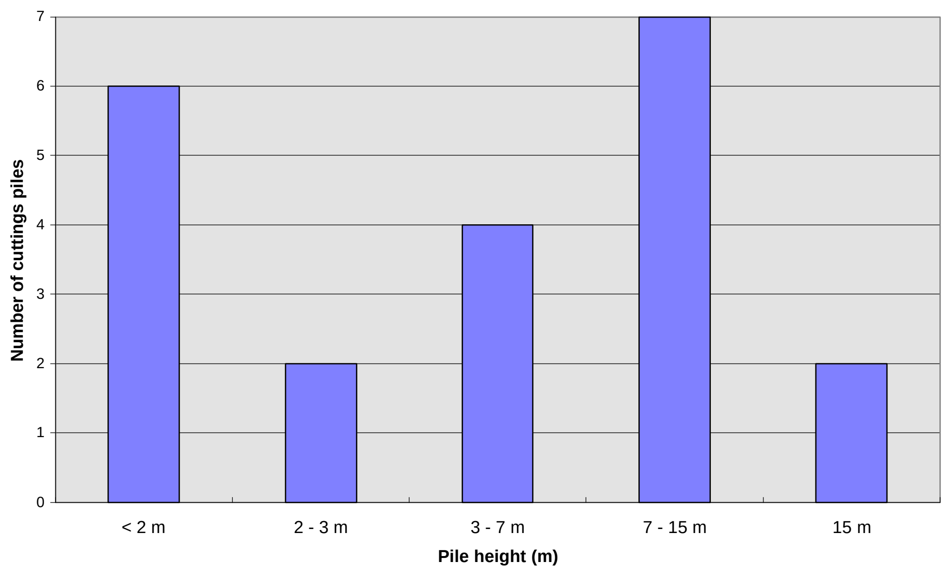


***Figure 2**: Frequency distribution of pile heights (from data in Anderson et al., 1996)*

Figure 2 indicates the maximum pile dimensions from a study of about 50 cuttings piles (Anderson *et al.*, 1996). A significant correlation was found between estimated discharge weight and pile height:

$y = 0.0002x + 1.6002$ ($r^2 = 0.4738$)

where: y = pile height (m); x = total drilling discharges (tonnes)

The angle of repose found in that study varied but was commonly less than 40^o. Volumes were considered difficult to estimate, but ranged between 1000 - 14,000 m^3. The North West Hutton pile was though surveyed as 25,225 m^3 (Hartley and Watson, 1993 in Anderson *et al.*, 1996). A representation of a fairly large cuttings pile in shown in Figure 3.

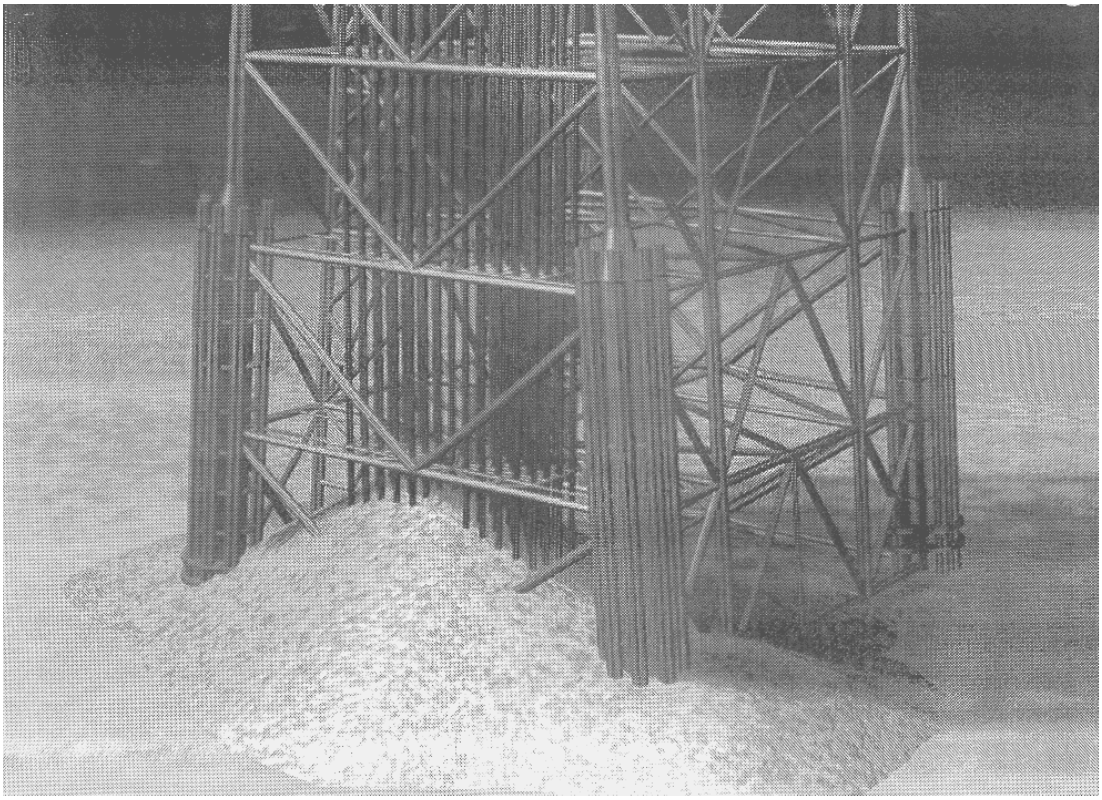


***Figure 3**: Graphical representation of a platform jacket and cuttings pile (Heather Platform) courtesy of AEA Technology*

1.4 Discharge volumes

Several studies have estimated the quantity of cuttings and muds discharged into the North Sea, including Auris (1995), Anderson *et al.* (1996), Kjeilen *et al.* (1996). The following summary is taken from Kjeilen *et al.* (1996).

The exact quantity of oil contaminated cuttings discharged to the sea since drilling operations were initiated at the beginning of the 1970s, is difficult to estimate because of missing and dispersed data. Discharge data have been reported from 1983 onwards (SFT, 1992), as has data concerning the total number of wells drilled (OD, 1995). Discharge data from the period 1983 - 1992 inclusive is presented in Table 2.

***Table 2**: Discharge of oil attached to drill cuttings during the period 1983 - 1992 on the Norwegian continental shelf.*

Year	**83**	**84**	**85**	**86**	**87**	**88**	**89**	**90**	**91**	**92**
# wells drilled	63	80	97	83	84	84	94	96	111	129
Tonnes	1500	3500	3300	2000	1200	1700	1000	600	700	50

Table 2 shows that a total of 15,500 tonnes of oil attached to drill cuttings has been discharged to sea during this period. Compared to the UK sector, where about 142,000 tonnes were discharged during the same period (AURIS, 1995), the discharges within the Norwegian sector were small at about one tenth of the UK discharges. If it is assumed that the quantity of oil amounts to an average of 10 % of the cuttings (by weight), and that 50 % of the cuttings have been drilled using oil-based drilling fluids (AURIS, 1995), then the oil contaminated cuttings will amount to about 300,000 tonnes of cuttings.

It has not, within the limited time schedule of this project, been possible to obtain exact data for discharges prior to 1983. In the period between 1966 to 1982, 595 wells have been drilled, of which 235 were production wells (OD, 1995). It is difficult to calculate the amount of cuttings produced per well. To do this, the drilling history of each well must be analysed. The drilling history of individual wells would also enable the calculation of the amounts of oil-based drill cuttings discharged.

In a Scottish report, the amount of oil discharged was estimated by assuming an average 1,000 tonnes of cuttings per well, 50 % oil-based cuttings, and 10 % of oil-based cuttings as oil (Auris, 1995). If these assumptions are valid for the 600 wells drilled in the Norwegian sector, then the total discharge of oil during the period 1966 - 1982 would have been about 30,000 tonnes of oil attached to drill cuttings.

Discharges in the Norwegian sector between 1966 to 1992 will then be in the order of 45,000 tonnes of oil attached to cuttings, corresponding to about 900,000 tonnes of cuttings material. Again, it must be emphasised that the estimate of discharges prior to 1983 was based on UK assumptions, and as such only roughly indicates Norwegian discharge quantities were are expected to have been considerably lower.

Examining the central and northern parts of the North Sea as a whole, Anderson *et al.* (1996) estimated the total weight of cuttings and mud discharged during an unspecified period to be 695,726 m^3, with a weight at discharge of 1,473,282 tonnes. These discharges were from 1,467 wells at 56 sites. This was calculated to 1,004 tonnes/well and 26,309 tonnes/site, though site values varied considerably.

1.5 Introduction to handling options

Though a proportion of the drilling muds and cuttings will be dispersed into the water column and hence transported varying distances form the well site, the majority of cutting will be deposited in the form of a pile in the vicinity of a drilling rig or platform jacket, as described above. The associated structure can be thought of as guarding the cuttings piles, because it will offer a degree of protection against human and current flow disturbances.

Upon decommissioning, the jacket may be removed. The operations involved with removal of a structure, such as cutting, lifting, or refloating, may cause the cutting piles to be disturbed or resuspended. Additionally, with the loss of the guarding structure, the piles could then be open to disturbance from, for example, current changes and trawling activity. Many of the oil-based cuttings piles will either have an encrusted surface layer that, because of its availability to aerobic bacteria, will have a reduced hydrocarbon content, or will be covered by several layers of non oil-based cuttings and muds. Nevertheless the potential for damage during removal, disturbance in the absence of the guarding structure, and the continued presence of the cuttings in perpetuity, form a significant problem that needs to be addressed.

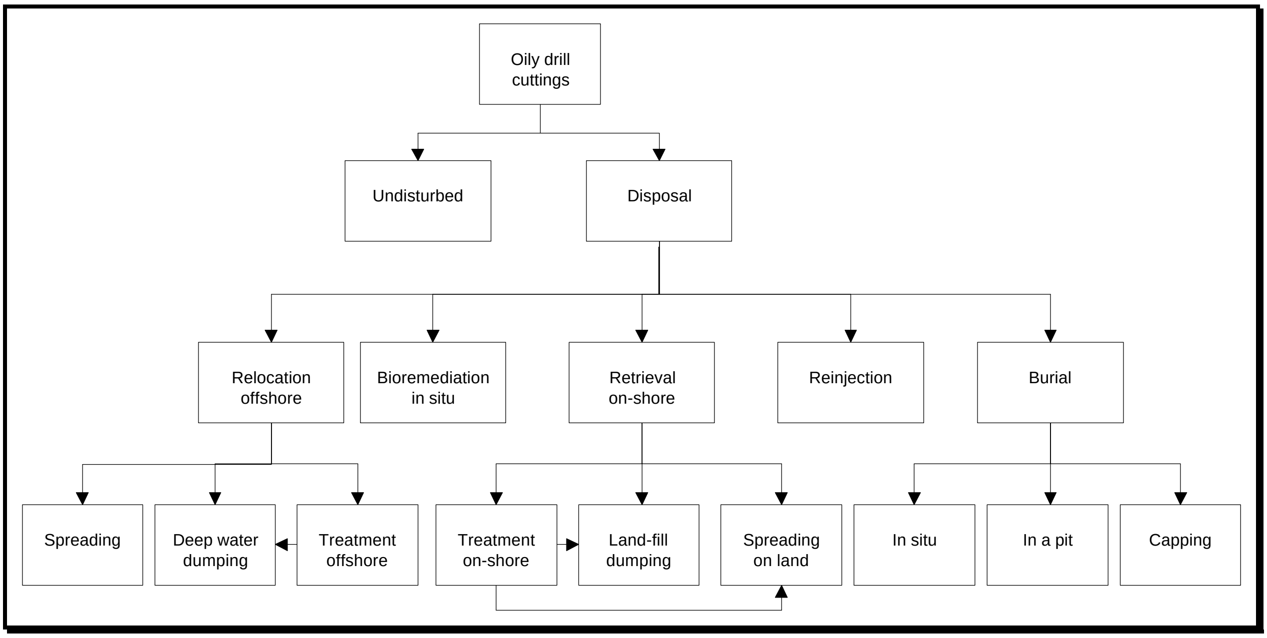


***Figure 4**: Summary of options available for dealing with oil-based drill cuttings piles (From Kjeilen et al., 1996)*

Various methods are available or have been proposed for handling and subsequent treatment and/or disposal, as reviewed by Kjeilen *et al.* (1996) and Brown & Root (1997). These methods are summarised in Figure 4 (Kjeilen *et al.*, 1996).

The current study aimed to evaluate seven of the main handling options, i.e.:

- Leave the piles undisturbed
- Cover the pile for protection
- Bioremediation
- Retrieval technology
- Removal and reinjection in a well
- Respreading on the sea floor
- Treatment and disposal - offshore or onshore

Within these handling options, 19 handling methods or stages were identified and evaluated. Several of the methods, e.g. crawler retrieval refer to only one stage of the total process required to handle the waste. By maintaining the methods separate, a more flexible evaluation can be conducted whereby methods from different stages can be combined in different permutations.

The methods can be divided into those that are: sub-sea, i.e. the cuttings are not brought to the water surface; retrieval technology; treatment technology (offshore or on land); and disposal options:

Sub-sea

- leave in place - either undisturbed or disturbed during structure removal (Chapter 2);

- entombment (Section 3.2);
- capping (Section 3.3);
- gravel dumping (Section 3.4);
- bioremediation in situ (Chapter 4);
- respreading (Chapter 7).

Retrieval

- mechanical dredging (Section 5.2);
- suction pumping (Section 5.3);
- crawler retrieval (Section 5.4).

Treatment

- bio-reactor (Sections 4.4 and 8.7);
- land farming (Section 4.5);
- mechanical separation (Section 8.3);
- distillation (Section 8.4);
- stabilisation (Section 8.5);
- combustion (Section 8.6);
- supercritical extraction (Section 8.8).

Disposal

- landfill (Section 8.9);
- reinjection (Chapter 6).

2 LEAVE UNDISTURBED

2.1 Introduction

From both economic and environmental viewpoints, this would appear to be a strategy with much potential. As the piles age, evidence suggests that they crust over and that aerobic bacteria metabolise a large fraction of the hydrocarbons in the outer layers. Whilst there is a risk of disturbance or alteration in the situation, with time, this has to be weighed against alternative strategies, such as the probability of resuspension of material if the piles are to be retrieved to the surface (Kjeilen *et al*., 1996).

Several reports have reviewed the state of knowledge, or lack of such, with regard to the composition of piles, changes in composition with time, and their fate (Kjeilen *et al*., 1996; Anderson *et al*., 1996; Brown & Root, 1997; Rullkötter, 1997). Their content will not be repeated here and only the main areas that have to be addressed are discussed below.

Environmental studies (Anderson *et al.*, 1996) indicated serious effects during the period when the cuttings were discharged. They also indicated that when this period terminates, the area outside the direct impact of the cuttings is restored to the normal background situation within a few years (Davies & Kingston, 1992; Daan & Mulder, 1995). These findings are based on recolonisation of the benthic fauna to “background levels” of diversity. For most installations “background levels” are regained within 1,000 m. The extend to which the benthos adapts to higher levels of hydrocarbons is not possible to state, but elevated hydrocarbon levels were detected beyond the areas of biological effects (Davies *et al*., 1984). Long term effects from cuttings piles on the benthos are unknown.

The environmental impacts of the initial release of oily drill-cuttings on the benthic communities have been documented (Anderson *et al*., 1996; Rullkötter, 1997), but to date, the ecotoxicological impacts of the piles themselves have not been identified. Leaching of chemicals from the piles and the rates of degradation of the piles are also largely unknown. A study with benthic chambers in the sea addressing the leaching from a thin layer (2 mm) of a mixture of oil and sediment showed that most of the leaching occurred during the first two months after deposition, but some hydrocarbons persisted for more than a year. A long term study performed in the Dutch sector showed that 8 years after the initial release of oil-based muds, macrofauna was still affected to at least a distance of 500 m from the platform. The hydrocarbon levels where also higher than background levels in the same range (Daan & Mulder, 1996).

The method, to leave undisturbed, is basically very simple, but it is necessary to address several issues in connection to possible consequences of such a no-action option. Little is known or documented with regard to the physical and chemical composition, or the long-term fate, of piles of oily drill-cuttings. It is therefore necessary to document the state of the piles on decommissioning. Parameters to be considered include:

- physical properties;
- chemical composition;
- degree of degradation;

- chemical gradients within the pile;
- leakage rate from the pile;
- identification of leachate.

These studies may have to be followed-up on a regular basis until the piles are defined as stable and externally non-toxic. It is possible that the operator will retain responsibility and liability for the piles and any possible negative effects or accident where the piles are involved, for a long time.

Recognising that there is considerable variation in cutting pile characteristics, and that each pile is to some extent unique, it is at present not possible to define even discreet groups of cutting piles (Anderson *et al.*, 1996; Rullkötter, 1997). Until such time that enough experience has been accumulated to define specific types of piles and predict their property and fate, each pile has to be treated individually on a case-by-case basis.

The main areas of conflict will be towards other users of the shared marine resource. Specifically this includes commercial fishing activity, artificial reefs and shipping. The fishermen may experience problems as a result of their nets or trawls being caught in the piles and hence being torn or fouled. They may also haul debris and pile material to the surface, causing further fouling problems. Spreading of the pile by bottom trawling activity is also possible but highly unlikely for the majority of piles with some degree of structural integrity.

If artificial reefs are constructed in the vicinity, the piles may be afforded some shelter against disturbance, but it is important that the possible ecotoxicological issues, by leaving the piles within such and ecological important area, are carefully evaluated.

Other possible shipping conflicts are limited to the chance of anchors being dropped into or dragged through the piles and thereby disrupting them.

It is recognised that if the piles of oily cuttings are to be left in place, they should be disturbed as little as possible to keep the leaching of components low and so as not to impact fishing equipment. It will be a challenge to ensure this, given that the piles are located around the base of existing physical installations (Brown & Root, 1997). It is likely, though not certain, that explosives will be used to sever the jacket legs. It is questionable whether the associated piles in the vicinity to cutting activity will be left in a state that is fit to be left at the sea-floor.

2.2 Methods

The active and important part of this method is the decommissioning operation. The following parameters will determine if the pile is suitable to be left *in situ*:

- physical characteristics of the piles, with regard to size, encrustment and geotechnical stability;
- access to jacket, template and other components, presence of debris and other remnants;
- disturbance by structure decommissioning;
- chemical characteristics of the piles with identification of possible environmental toxins

- rates of release, degradation or neutralisation of these toxins. Oil and metal components in the pile are expected to be the main risk, and their ability to leach to the surrounding when the piles are left in peace or when the piles are disturbed should be identified. The rate of decomposition of the pile should be estimated.
- Possible effects of fishing activity and accidental disturbance of the piles and consequences on its structure and the ambient environment.

An environmental hazard and risk assessment, during environmental monitoring, which identifies most critical ecotoxicological issues, should be conducted following decommissioning.

Inspections and environmental monitoring and effect studies (short and long-term) should be conducted in the vicinity of the cuttings pile.

2.3 Operation and equipment

Most of the above methods are to be performed before, during and on termination of decommissioning and environmental monitoring as follow-up at given intervals.

Before decommissioning, the cutting-piles should be physically characterised by measuring size by side scan sonar, surface inspection and description by ROV. Studies of encrustment and chemical composition, leaching and ecotoxicological studies based on surface and core samples from the cutting-piles would be most useful.

During decommissioning, measurements and estimates of resuspension and fragmentation of the piles during the jacket removal operation should be conducted using sonar and ROVs.

On termination of the removal of the jacket, the state of the cutting-piles will have to be evaluated, with regard to the need for clean-up, reshaping of piles, etc.

Following this, inspections of the cutting-piles will need to be performed on a regular basis (1-5 years) to detect any disturbance of the piles and indicate decomposition rates.

Environmental monitoring of the cutting piles and the surrounding areas are expected to go on until the piles are completely decomposed (every 2-10 years), or it is identified that they do not pose any risk to the environment and other users. The methods used for this environmental monitoring have to be adapted so that they are suited to, and standardised for, these specific pile survey purposes.

2.4 Technical status

Once described, the services can be performed by applied research companies in this market.

2.5 Risks

The main risks with this method concern other users and the environment. The decommissioning phase is critical, and the risks are closely associated with the methods deployed for loosening or cutting of the jacket structures. Since the cutting-piles are associated with the structures, and partly or totally covering the areas around the base of the structures, local removal or disturbance around these structures is inevitable.

The use of explosives for shaking and loosening, or as cutting tools, will probably pulverise parts of the cutting-piles and bring it into suspension, thereby exposing the environment to all the components of the piles again. Depending on the size of the cutting-piles that are brought into suspension, this environmental load can get to a higher level than during drilling operation. Acute toxic conditions can be created by a large load during a short time span.

The use of cutting equipment or torches can be more gentle with regard to environmental effects, but still it may be necessary to dig around the bases of the structures to cut below the sea-bed level. Whether these trenches can be left in place, filled back into the holes or needs to be taken away, depends on the risk assessment with regard to environmental effects from leaching and possible later redistribution, and the risks identified for other users.

There is also an identifiable risk by leaving piles that extend above the sea-floor and pose a hindrance for fishing equipment and anchors. The shape and height of the piles might have to be restructured.

Components leaching from the pile, whether these are modified or not, do pose an environmental risk. The extent and size of this risk will vary much with the history of the piles, and most with the degree of disturbance during decommissioning.

There is a small risk of a slow spreading of the cuttings by currents along the sea-floor. These current can be variable during the different seasons. This spreading action will depend on the geo-technical stability of the piles and the variation in this property with time and decomposition.

In the case of using structures as artificial reefs, either by toppling of structures or cutting, the cutting-piles might have an even higher environmental risk It is uncertain whether toppling can be performed without disturbing the piles. Artificial reefs are also associated with the more complex ecosystem and a larger quantity fish and other marine species around the reef.

The risk towards other users will be related to fishing equipment and anchors catching or disturbing the cuttings piles. Fishing nets or trawls, caught in the piles, may be torn and destroyed. They can also be fouled by oily grease.

Boats or other vessels can drag anchors trough the piles, thereby disrupting them, with the risk of leakage of chemicals. The pile can afterwards pose a grater risk for fishing equipment.

2.6 Marine discharges

Very little by the method itself. Small erosions might occur but would probably be dependent on the shear strength of the surface layer. The main discharges will be associated with the decommissioning phase. The only acute discharges from the cutting-piles would be in connection to serious disturbances of the geotechnical stability of the piles.

The potential erosion effect with subsequent marine discharge of a trawl passing over a pile has yet to be described. There will, however, be slow leaching of components, metals and organic, that also has to be quantified. This process will decrease with time as the piles decompose.

2.7 Operating costs

Monitoring will cost approximately £50.000 per OLF unit and 5 years (Anderson *et al*. 1996). Based on traditional surveys. Novel methods and standards may have to be deployed, but these are not expected to change the estimated costs dramatically.

3 COVERING THE PILES

3.1 Introduction

Several means of covering have been suggested:

- Entombment: with the aim of reducing/eliminating the potential for chronic pollution. This involves dredging seabed silos, removing and relocating the drill cuttings in the silos and covering the top of the piles.
- Capping: this could be achieved by means of an impermeable synthetic membrane.
- Gravel-dumping: with a layer of gravel to protect the cuttings from being disturbed.

The following text will discuss the technical issues associated with these options.

3.2 Entombment

3.2.1 Method

Entombment involves excavating seabed trenches or silos of sufficient dimensions to accommodate the drill cuttings. The dimensions of these silos will be significant, for example it is estimated that four silos each of 25m width x 25m length x 12m depth would be required to hold a 25,000m3 drill cuttings pile.

Seabed conditions would dictate whether this option were feasible. Generally seabed conditions may consist of clay strata covered with sand or silty layers. The silos would be constructed in the lay strata thereby requiring prior removal of the upper sand or silty layers. This can be achieved using existing equipment such as a Jet Prop excavator.

The Jet Prop series of excavators generate large diameter, low velocity water columns which are directed at the material to be removed. Turbulent flow over the material boundary layers entrain the material particles to form a slurry which is dispersed horizontally by the large excess of water flowing over the workface. The excavating water column is generated by a preset variable pitch heavy duty propeller driven by high pressure axial flow water jets mounted on the blade tips.

The velocity of the excavating water column is controlled by varying the jet pressure to suit the characteristics of the soil to be excavated and to achieve the desired excavation profile. The tools are deployed on either an umbilical or drill string from a surface support vessel are capable of removing large quantities of material every hour. For example, the smaller Jetprop 25000 is capable of excavating up to 2000m3/hour of mobile course sand, 100-500m3/hour of drill cuttings and 50-100m3/hour of clay. The larger Jet Prop 250000 is capable of excavating up to 10,000m3/hour of mobile course sand. Although designed primarily for operation in silt, sand and gravel soils, the Jet Prop can be used to excavate drill cuttings and weak clays up to about 25 kPa shear strength. Depending on soil conditions, trenches up to 10 metres in width (at trench top) and depths between 0.1 and 8 metres can be excavated in a single pass.

Each tool is equipped with it's own sonar and TV cameras to monitor the excavation operation. Depth of operation on umbilical is up to 250m and on drill string up to 5,000m.

Following excavation, the drill cuttings will be removed and relocated in the silos using either tracked cutter suction dredgers or diver/ROV operated dredging systems. On filling of the silos, they would be covered by back-filling some of the excavated natural seabed material.

3.2.2 Operation and equipment

Assuming the use of a Jet Prop system to excavate the silos, the operation would be performed from a DSV or other surface support vessel. Silo construction would begin by removing the top sand layer from the seabed to expose the clay strata. The distance of the silos from the cuttings piles will be dictated by the type and power of the pumping systems used to dredge the cuttings from the vicinity of the platform.

However, local soil conditions may prevent excavation of the silos using the Jet Prop tools alone. In areas where high strength clay exists, tools such as UEL's Claycutter and Water Canon may be required. The Clay Cutter is a high pressure water jetting tool used to construct 0.5m deep, 7m wide trenches in strong soils. The Water Canon system is used primarily to move boulders or small areas of high strength soil. These tools are deployed on a drill string and would thus dictate the use of alternate vessels, such as shallow coring vessels, to the use of DSV's.

The sequence of events for this operation would first involve mobilisation to site and excavating the top sand layer at the silo location using a Jet Prop excavator. In the event a Clay Cutter were required, this would be deployed with the Jet Prop to make, for example, a 7m wide 0.5m deep trench the desired length of the silo. The tools would then make continuous passes to form a 0.5m deep trench of the required length and width. The cycle would then be repeated until the required trench depth was attained.

Assuming that a 25m wide, 25m long, 12 m deep trench were required, this will involve 4 passes per 0.5m trench depth or a total of 96 passes. The trenching rate for this scenario would be 50m per hour giving a total of 48 hours per silo. During this operation the Jet Prop would be intermittently used to disperse the excavated spoil over a wide area away from the silo site.

Following completion, a survey of the silo would be undertaken prior to filling. As stated earlier, the cuttings would be removed from their current location by tracked or diver/ROV operated dredging equipment and pumped into the silo. When full, the silo would be covered with natural seabed back-fill using the Jet Prop.

3.2.3 Technical status and limitations

The excavation of trenches/silos of this size has not been undertaken previously. However, UEL have successfully cut 7m wide, 4m deep trenches over 100m long in clay in water depths of 210m using similar procedures. The trenching of silos of the sizes stated above are thought to be possible in clay. However, it is recognised that local sand pockets in the clay may give rise to some local collapse of the silo walls during the operation.

The technology to dredge and relocate material elsewhere on the seabed has previously been employed.

3.2.4 Costs

Economics may be an important factor in the viability of this option. Each silo, of the size stated above, would take about three days in total to construct (allowing for set-up, survey etc.). Although accurate cost breakdowns for this are not available, confidential information indicates the cost for excavating these four silos to be in the order of £1 million. To this would have to be added to the cost of dredging, filling and covering the silos.

Previous decommissioning work has identified the following costs for the Jet Prop 25000. Note: these should be taken as indicative prices only:

Jet Prop 25000	£10,000/day
Personnel	£6,000/day
Mob/Demob.	£50,000

Similarly, day rates for a 4 inch hand held dredge system, including all equipment and engineers, would be in the order of £1000/day.

The costs of moving the drill cuttings to the silos can easily be greater than expected. Assuming the platform is still in place or even operating during the procedure, it will more difficult to gain access to and removal of cuttings piles. It is likely that diver intervention will be high and thereby costs will be significantly greater. It is though not possible to reliably estimate how much higher costs will be as a result of the presence of the platform.

3.2.5 Environmental Impacts

This option involves excavating/dredging a somewhat larger amount of material than that of the drill cuttings. Although most of the material excavated during silo construction will be natural seabed, from an environmental perspective it can be seen that significant local disturbance of the seabed will occur.

The most serious contamination problem will probably occur when the cuttings pile is to be moved. Any disturbance of a pile containing oily drill cuttings may cause resuspension of hydrocarbons and heavy metals. The degree of resuspension and contamination depends on the nature of the pile. A part of the resuspended hydrocarbons will probably dissolve into the water column, and may be seen as a sheen on the surface. Heavy metals, such as mercury, are often absorbed by particulate material and are likely to contaminate sediments. Should the platform be present as a shielding structure, resuspension may be increased because of the difficulty of accessing and moving the pile material.

It is also possible that some type of barrier membrane or filter over the top of the silos may be required to prevent re-suspension of the drill cuttings material in the water column. The material pumped into the silo will be fluidised to some extent. Due to the large volumes being pumped, disturbance of the material already in the silo will occur. A membrane or filter may then be required to retain the drill cutting material in the silo while allowing the water to exit.

As the drill cuttings will be contained under the seabed and with several metres of sand covering on top of the silos this option poses minimal future risk to fishing in areas of stable seabed.

3.3 Capping

3.3.1 Method

Capping of a drill cuttings pile can involve the placing of concrete mats with an impermeable synthetic membrane over the drill cuttings. If the drill cuttings pile is obstructed by the platform jacket, this operation will firstly require removal of the jacket down to at least the level of the drill cuttings pile.

The mats would be designed to be joined together, for example by lacing, and would be placed over the drill cuttings pile and joined together by divers. The mats would be anchored where they contacted the seabed (see Figure 5).

It has also been suggested that gravel-dumping could be undertaken on the covered pile to ensure the membrane remained *in situ*. Fronded mats could also be installed around the perimeter of the pile to encourage the development of a natural ecology.

The method is likely to be fairly expensive and will probably only be used in sensitive zones (for instance in fish spawning areas), or if the pile is unstable (leaching). If the intention of the covering is to protect the pile from physical damage, other options will probably be more suitable. Section 2 indicates that the leaching rate from the piles may not be great if they are not disturbed too greatly during platform removal. Capping should then have as its main aim the prevention of physical damage to the pile from trawling activity rather than as a seal to prevent leaching. In such a case, capping by gravel-dumping (section 3.4) using gravel, may be more suitable.

3.3.2 Operation

This option is diver intensive and would commence by mobilising a DSV with full dive team in saturation. Each mat would be lifted by the DSV crane and placed individually on the pile under the guidance of the divers who would then fasten the mats together. There would also be an opportunity here for the mats to be designed so that ROVs could be used instead of divers. The mats would be secured to the seabed around the perimeter of the pile using hydraulically driven anchors. Fronded mats could also be installed if required. Following placement of the mats, an ROV site survey would be performed prior to demobilising the DSV.

If gravel-dumping were required, the gravel-dumping vessel would be mobilised to site to perform operations. A final ROV survey would then be undertaken on the covered pile.

Depending on the nature of the pile and the reason for covering it, it might not be necessary to add a covering membrane. Some piles tend to develop a crust over time thereby preventing leakage of hydrocarbons.

3.3.3 Technical status and limitations

Although diver intensive, this operation is technically feasible using available equipment. The scope exists for engineering the operation to employ ROVs instead of divers. Conventional concrete mats could be fitted with impermeable membranes during manufacture. Their placement sub-sea is a fairly routine procedure, although the effect of placing them on the cuttings pile will need to be analysed.

3.3.4 Costs

It is not possible to accurately predict the size of the mats that will be required but a size of 5 m by 4 m has been suggested by one contractor, who examined this option for capping the North West Hutton drill cuttings pile. Unfortunately no information is available on the cost of the mats.

For this scenario a total of 742 mats were required (Figure 5). The contractor assumes a time of 1 hour per mat and gives a total project DSV time of 43 days including mob./demob. Assuming a cost for a DSV with divers in saturation of £70,000 per day, this gives a total DSV cost of just over £3 million. Added to this cost would be costs for manufacture and supply of the mats and for gravel-dumping if required.

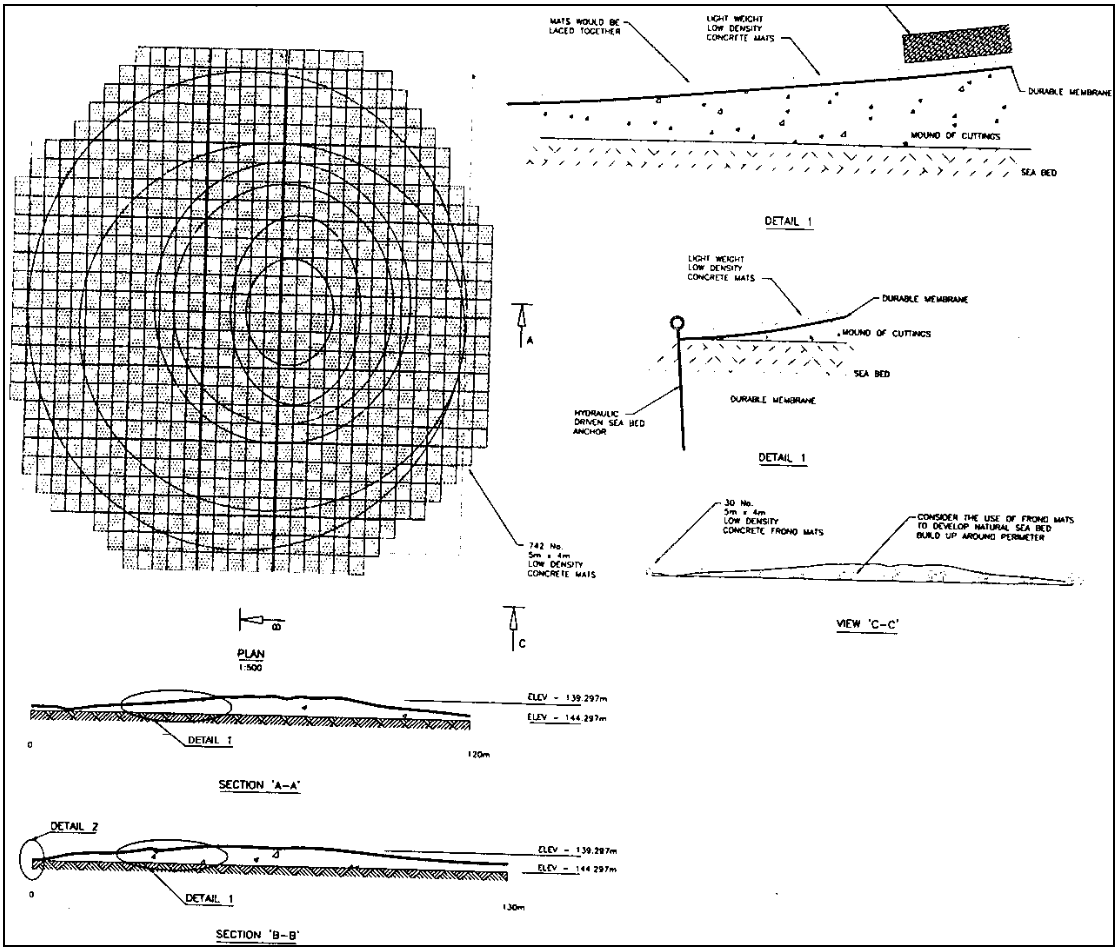


***Figure 5**: Capping of drill cuttings pile*

3.3.5 Environmental Issues

The main purpose of this method will be to protect the environment. The impermeable membrane will prevent leaching of the contaminants into the water column, and may encourage the development of natural ecology in the proximity of the pile.

Only minimal disturbance of the cuttings pile should occur during placing of the mats. The drill cuttings will be encapsulated and will therefore not pose a major future pollution risk.

The profile of the capped drill cuttings pile could be designed to deflect fishing gear, thereby reducing the hazard to commercial bottom trawling fishing activity. Gravel-dumping could be used to improve the profile design for this purpose.

It may be considered that prevention of physical damage is the main likely use of capping, rather than as a seal to prevent leaching. If this is the case then gravel dumping may be a more suitable option. If leaching is known to occur, as a result of an unstable pile or because of damage to the pile, then capping, as described above using impermeable membranes, may be most suitable.

3.4 Gravel-Dumping

3.4.1 Method

Gravel-dumping is an established technique in the offshore industry used for applications such as adding protective covering to exposed or free-spanning pipelines, or other structures. The method involves dumping material ranging from gravel to small boulders from surface vessels. The material is deposited on the seabed either in bulk through opening hatches in the vessel, or can be more accurately placed by depositing through a fall-pipe. Gravel is thought to be preferable to boulders because of the reduced risk of damage to the pile and associated re-suspension, and because of the reduced hindrance to commercial trawling.

3.4.2 Operation

If gravel-dumping is to be used to cover the drill cuttings pile it is likely that the jacket will have been removed down to the level of the pile. Following mobilisation of the vessel to site, the pile will be covered in a pre-determined sequence of gravel-dumps to ensure adequate spread and depth of cover. When gravel-dumping operations have finished, an underwater survey of the mound will be undertaken to ensure complete coverage.

Side dump vessels often have compartmentalised bunkers to allow one or more of these bunkers to be dumped at any one time. Fall-pipe vessels often have several hoppers which deposit material onto a conveyor belt which feeds the fall pipe. Both types of vessels are dynamically positioned and can control the dumping operation in order to achieve the required bottom profile.

3.4.3 Technical status and limitations

Gravel-dumping is an established technique used in the offshore industry. In order to cover the larger drill cuttings piles a large quantity of gravel material will have to be deposited on the seabed. The method of dumping will need to be considered carefully. Some of the piles are located in over 100 m of water, so the efficiency of coverage from a surface dump procedure will need to be addressed. It will probably be necessary to use a fall-pipe system to achieve the required coverage. There are several fall-pipe vessels available with fall-pipes up to 300 m in length that can deliver sand and gravel.

Typically gravel dump vessels (Figure 6) have maximum loads between 1000 - 2000 tonnes for side-dump vessels and up to 18,000 tonnes for fall-pipe dump vessels. Discharge rates for fall pipe vessels vary between 600-1,000 tonnes/hour.

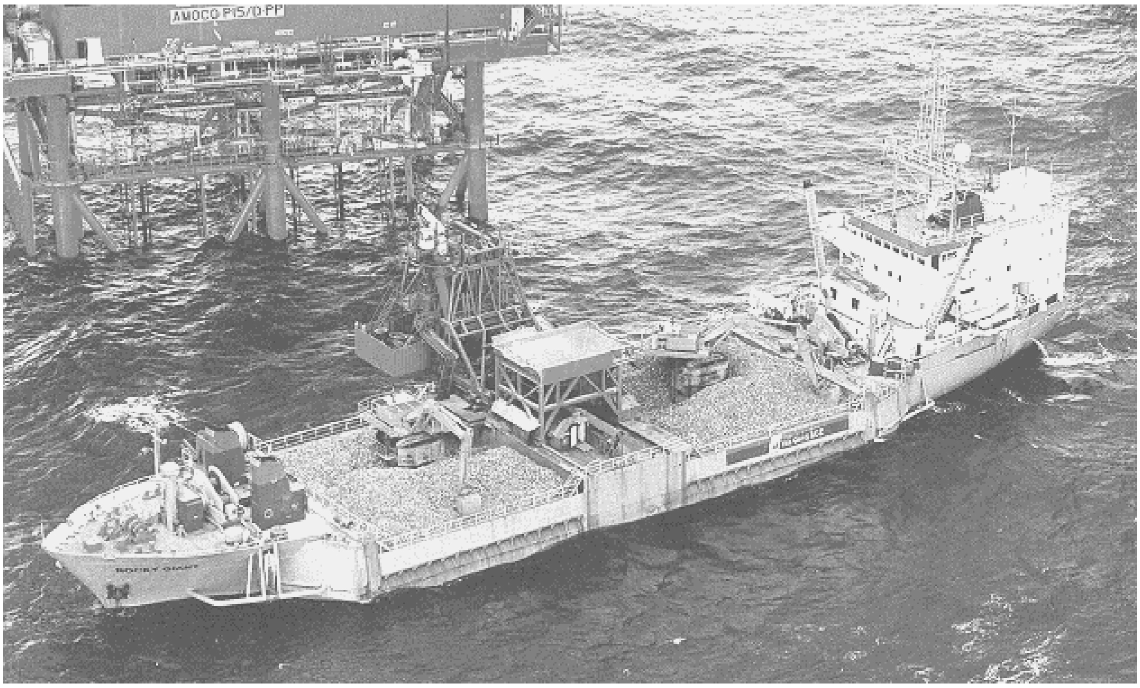


***Figure 6**: Fall-pipe dump vessel (Halsvik Cementstøperi as).*

The effects of dumping material as regards the disruption to the drill cuttings pile will also need to be investigated. It would be expected that a fall-pipe procedure would damage the piles less than a surface dump method.

3.4.4 Costs

Day rates for these vessels vary but a figure in the region of £10,000 -15,000 /day for side dumping vessels is indicative, excluding materials.

3.4.5 Environmental Issues

The gravel-dumping method has previously been used to cover pipelines on the seabed. The method is well established as well as inexpensive compared to other options. From an environmental point of view the method is known to locally smother the benthos living in and on the sediments. The seabed close to a cuttings pile is however unlikely to have a diverse benthic community as a result of the physical presence as well as the contamination of the sediments in the proximity of the pile. Gravel-dumping of cuttings piles are therefore considered to have a geographically limited impact on marine organisms.

The greatest concern of gravel-dumping will probably be the extent to which the pile will be physically disturbed and oily cuttings re-suspended into the water column. In such an event, the marine organisms nearby may suffer from the impacts of heavy metals and hydrocarbons. This should be avoided. Most vessels that are used for gravel-dumping are equipped with a fall-pipe system that reduces the physical impact of the dumped material on the piles (Figure 7). Re-suspension of the piles should then be possible to avoid. The grain size of the gravel that will be used for this purpose will probably be from 0 up to 16 mm which is comparable to that of the seabed. If necessary, the grain size can be reduced to 2 mm. In areas with strong currents, some of the gravel may erode.

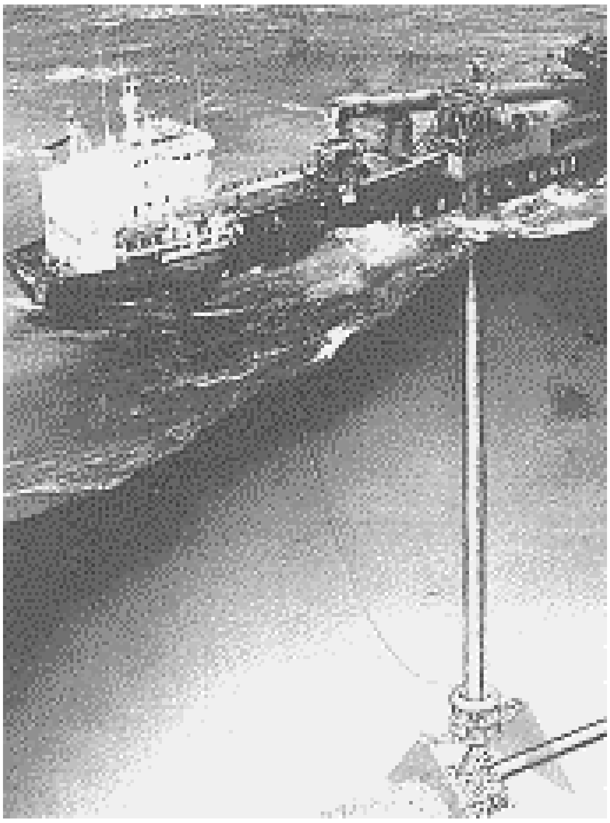


***Figure 7**: Fall-pipe gravel dump system (Halsvik Cementstøperi as).*

Monitoring of the cutting piles show that the leaching rates are decreasing over time, some of the piles have even developed a crust on the surface that prevents leaching. A successful gravel-dumping operation would enhance this effect and encapsulate the pile, thereby preventing any future spreading of contamination in the area.

Another aspect of the gravel-dumping method is the impact it might have on the trawling activity in the area. Gravel-dumping of pipelines has for a long time been assumed to have minor effects for the fishermen. Recent studies have however shown that this is not the case. The trawls tend to catch large amounts of rocks/gravel (diameters of 5 to 15 cm) in their nets, causing destruction and even loss of equipment (Soldal, 1997). This is especially a problem where one pipeline meets another, because the piles of rock/gravel can get large in these areas (Stavanger Aftenblad, 17.11.97). The combined size of a gravel-dumped cuttings pile will also be expected to be large, as a size of 20 000 $m^3$is not unusual for a cuttings pile (before gravel-dumping). The grain size of the gravel that will be dumped on the piles is likely to be small, but further research is necessary to determine any possible impact on the trawling activity. It is also possible, or even likely that the gravel piles will act as artificial fish attracting reefs, with the associated benefits that these can confer on an area (Aabel *et al.*, 1997).

4 BIOREMEDIATION

4.1 Bioremediation technology

4.1.1 Methods

Bioremediation technology encompasses the controlled, practical use of micro-organisms for the breakdown of chemical pollutants. These various technologies rely on the biodegradation activities of micro-organisms. The goal of bioremediation is to degrade pollutants so that remaining concentrations are either undetectable or, if detectable, below the limits established as safe by regulatory agencies.

A large number of reports exists where it is confirmed beyond doubt, that indigenous micro-organisms have the capacity to detoxify a variety of compounds including petroleum products. No single microbial species has the enzymatic ability to metabolise more than two or three classes of petroleum compounds. Thus, a composite of many different bacterial species is needed to complete the breakdown of mixed material.

The largest field demonstration of bioremediation ever undertaken was carried out after the grounding of the oil tanker Exxon Valdez in Prince William Sound, Alaska, 1989. This provided the field data needed to convincingly show that bioremediation based on indigenous micro-organisms is a viable concept. Bioremediation is currently used on a regular basis as a method for cleaning of soil, sediments, industrial sludge and a variety of other substances worldwide. From this perspective bioremediation technology appears a promising method for the treatment of oil-based cuttings.

4.1.2 Operation and technical status

Table 3 shows the common parameters that are subject for the operation and optimisation of a given process.

***Table 3**: Input parameters for the bioremediation of oily cutting piles*

INPUT PARAMETER	PRODUCT	COMMENTS
<u>Oxidants</u> Air or oxygen Nitrate	 Compressed air or oxygen, H_2O_2. Commercial fertilisers	Liquid oxygen prod. off-site commercially, - other on-site. Nitrate in excess may cause nutrification
Carbon sources	Fish meal /meat extract	Commercial available
Nutrients (N and P)	Commercial biorem. products/ fertilisers	Slowly soluble to avoid nutrification
Micro-organisms	Commercial available: special enrichments/ biosorbents	Introduced organisms not recommended
Emulsifiers	Commercial available	Biosurfactants recommended

Several basic conditions, as described by Alexander (1994), must be satisfied for bio-degradation to take place in an environment. Most important are:

- organisms with the necessary enzymes to bring about the biodegradation must exist;
- the organisms must be present in the environment containing the chemical(s) to be treated;
- the chemicals must be accessible to the organisms having the requisite enzymes;
- conditions in the environment must be conducive to allow the proliferation of the potentially active micro-organisms.

Most of the oil-based cutting piles have been lying for years on the sea bed, undisturbed. Bacteria specially adapted to the prevailing condition and capable of oil decomposition, have evolved inside these piles and at the interface between the pile surface and the water. This is nature's own process, natural selection of the most fit organisms to survive under the given conditions.

It should be noted that the use of gene manipulated organisms (GMOs) is often discussed in the context of bioremediation. Such organisms have been manipulated to become adept at degrading specific components. This is a highly controversial topic. The general opinion today is that addition of GMOs has had no detectable, or only short-term, effects on enhancing bioremediation of petroleum products. GMOs may only have a practical importance in bioreactors where competition from indigenous bacteria is low (Alexander, 1994). GMOs may also be regarded as pollutants; a threat to the environment. It is most probable that in the future there will be very strict regulations connected to the use of GMOs. It is believed that GMOs are therefore not suitable for use in bioremediation of oil drill cuttings. Bioremediation should be based on a controlled augmentation and enhancement of the natural processes already in progress, rather than speculative and controversial biotechnological methods.

In order to fulfil two of the five basic prerequisites listed in Table 3 advanced design technology is required. The chemicals in the piles may need to be agitated or dispersed /emulsified by the use of surface active agents to increase the contact area between water and micro-organisms. Some inputs need to be added, such as water as a medium to feed micro-nutrients, bioremediation enhancers (catalysts, e.g. alternative electron acceptors and hydrogen peroxide). Breakdown products or metabolic waste that may inhibit the breakdown rate will also need to be removed. An increased supply of oxidants may be achieved by injecting air or oxygen into a pile. Before treatment is started, the process should be isolated to prevent leakage into the surrounding environment. Several options are possible including special liners or membranes, or concrete constructions.

4.1.3 Suitability of oil based cuttings for biological decomposition

This study includes diesel oil-based muds, which were the main mud type used at the time of cuttings pile formation relevant for this study. These may be divided into two main categories; one almost free of water and the other type with usually 10- 20% water emulsified in oil. During drilling operations in the 80s various types of cuttings cleaning processes were used, and this is comprehensively reviewed by the IOE (1984a). They mostly comprised simple screening and washing procedures prior to discharge. It appears that no matter how the drill cuttings were treated, residues of oil continued to adhere to cutting particles. In another study (IOE, 1984b), extraction from diesel oil-based, relatively "fresh" cuttings, resulted in about 5% oil (wet w/w). In a recent study, the oil content in the material discharged was claimed to exceed 10 % (Brown & Root, 1997). There was though no data from analyses to confirm this and no comments were made as to the fate of the oil content after discharge. No published data on oil contents in cuttings of various ages and with different histories have been identified. Variations in hydrocarbon concentrations in the piles, ranging from about zero up to significant high levels of oily material, are expected, depending on the pile history. Clearly, there may not be a single technology that is applicable for all cases, as was also shown by Rullkötter (1997) and Anderson *et al*. (1996). A standardised assessment of different parameters should be employed, and the data generated should provide the basis for working out combined treatment solutions.

"Diesel oil" is not a chemically defined substance but a complex mixture of different hydrocarbons having carbon numbers in the range of C_{10}-C_{21}. Among those, typical poly-aromatic hydrocarbons (PAHs) may occur (Troy *et al*.,1994). Manufacturer's list of formulations of oil-based muds are confidential for proprietary reasons. The exact chemical compositions are therefore not disclosed. Basically a typical mud contains diesel oil, air-blown asphalt and minor amounts of "additives" (IOE, 1984b).

Numerous studies of petroleum degradation in marine environments and soil, demonstrate that organic ingredients in oily cuttings are biodegradable under aerobic conditions (Prince, 1993; Swanell *et al.,* 1996; Kjeilen, 1997; Paulsen *et al.*, 1997). This therefore suggests that biodegradation of oily drill cuttings will occur if proper conditions are established. Degradation of a large number of aromatics, but not aliphatics, are also described, where other oxidants than oxygen were used (Reinhard, 1994). Weathering processes, the combined influence of physical, chemical and various biological processes, have continuously been affecting the characteristic of the piles since the time of disposal. Intuitively, the oil content must have decreased and the relative amounts of different compounds changed compared to the original formulation.

In an oil drill cutting pile the petroleum residues are expected to either be adhered as a thin film to the pile mineral particles, or trapped in pores by capillary forces. The particle size distribution of the cuttings, has a direct influence on the porosity of the medium and the number of capillaries per volume unit. The number of pores vary according to the type of formation drilled, type of drill bit used and its rotational speed and weight, mud type and weight and mud flow rate (IOE, 1984a). The mineralogy of the cuttings is a composite of the formations drilled into, and will influence the availability of inorganic nutrients needed for microbial oil degradation in the cutting piles. This picture is further complicated by the assumption that aggregates have developed, with various sizes thereby limiting gaseous and nutrient diffusion processes critical to degradation rates. Tar is probably the dominant gluing material.

The redox potential may reach low values in anaerobic pockets and zones, and generally the degradation rate is lower under these circumstances. In some cases however, recalcitrant molecules (chloro-organics) are more effectively degraded by anaerobic microbes. A more homogenous medium may be obtained by breaking the aggregates mechanically and thus allowing a more even distribution of oxygen. The large volumes of a typical cutting pile requires a process technology with a high capacity.

If a slow degradation rate is acceptable, attenuated, intrinsic biodegradation of aggregates will occur due to a slow diffusion of oxidant and nutrients into the otherwise anaerobic interior of aggregates. Eventually this helps break the chemicals down to its possible limit.

4.1.4 Forecasting bioremediation potential of oil cutting piles

Published data on biodegradation with regards to "old," or weathered oil cutting material has not been located. It is not expected that such material will be a united group of compounds. Undoubtedly the characteristics of the piles will vary from case to case. Hydrocarbon analysis from core samples taken from five cutting piles in the periods 1988 and 1991-93 (Anderson *et al*., 1996) strongly suggested that partial biodegradation of base oils present within the piles had occurred. In one case, up to 75% of the original oil was degraded. This was interpreted as oxidative degradation that had occurred during the period when the piles were growing and the surface of the cuttings material was exposed to surrounding water. These periods may have varied in length before the respective surface layers became buried by continued cuttings deposition. Nevertheless, these findings help demystify the cutting material as seen from a biological point of view. Sea bed disposed oily cutting material may be perceived as a regular pile of contaminated soil material found onshore. Hydrocarbon polluted soil is routinely bioremediated both in Europe and the U.S., and this is recognised as the most prominent soil reclamation technology.

Rulkötter (1997) reviewed the UKKOA report (Anderson *et al*., 1996). His comments regarding the approach of *in situ* bioremediation is quite unmistakable "overall, this option appears to have received too little attention. It is suggested that it is reviewed again, eventually supported by additional research including field experiments, in the most creative way possible." This statement can be endorsed in the current report, as it seems that too much attention has been given to the engineering approach and the practical and technical challenges. The chapter covering bioremediation in this report, is mainly addressing the *in situ* bioremediation approach and aims to answer some of the questions that are raised by Rullkötter (1997).

There are basically two distinct handling options for the bioremediation of cutting piles; offshore or onshore treatment. In both cases treatment may be intensive or extensive. For intensive biotreatment methods (requiring bioreactors), the technology options may be both on-shore and offshore. For onshore treatment, an overview of Scandinavian environmental remediation contractors treating polluted soil and similar material, is given by the Norwegian State Pollution Control Authority (SFT, 1995). For offshore treatment options there exist no similar overview.

4.2 Increased bioavailability by respreading

4.2.1 Methods and operation

Respreading of the pile material breaking down crusts and aggregates will increase the exposed area of oil to both oxygen and nutrients available in the surrounding seawater. It is likely that he material soon will resettle and return to the situation where biological processes are limited by the lack of components necessary to drive the processes. The gain, in terms of enhanced biodegradation will then only be limited. The rate of degradation will depend on the spread-area/ amount of material spread. The thinner the cuttings layer, the more material is likely to be subjected to biological breakdown by mass transfer processes allowed at the seawater interface.

This treatment option may be considered to be a hazardous task, mainly because it is difficult to control: large amounts of material are exposed to the sea-water, thereby causing uncontrolled leakage and dispersion of toxic material to the environment. The effects on degradation are unlikely to be more than temporarily. Rullkötter (1997) comments that confining released hydrocarbons and other mobile materials insoluble in water, but that are unlikely to resettle would reduce the environmental risk. It is difficult to conceive how to confine hydrophobic released material, given the large spread-area. The chance of an increased dispersion of possible toxic material to the surrounding water is likely to be greater than the option of leaving it undisturbed. This view is entirely based on risk evaluation as seen from an environmental perspective. As a bioremediation option, respreading is not further discussed in this report, though it is discussed from a more engineering based perspective in section 7.

4.3 Augmented and enhanced *in situ* bioremediation

4.3.1 Methods and operation

As previously discussed, optimised biological processes are dependant on the continuous supply of limiting nutrients and removal of waste and other products that may have inhibitory effects. Given the complexity of the substances found in the cutting piles, it appears that a combination of chemical flooding and bioremediation is a viable approach. Such a process may be maintained by drilling holes in the piles to allow the injection of chemicals and air/oxygen through horizontally and/or vertically diffusers. Surface active chemicals and bioremediation enhancers are probably needed to establish appropriate conditions for the process and thus allowing a high degradation rate and effective displacement of the oily material. A semi-controlled miscible flooding and oxidation of the oily contents is thus obtained. The process may be designed to avoid exposing significant amounts of interior pile material to the sea water. A process designed on this idea generates an effluent that has to be collected and handled properly. Technology for handling such a waste stream is commercial available and is currently applied in oil production offshore, in which water injection is used to displace oil in the reservoirs.

Surprisingly, such an approach has not been suggested in any earlier reports dealing with these problems (Anderson *et al*., 1996, Rullkötter, 1997). Though the latter report points to the apparent lack of innovative bioremediation approaches as alternatives to more complicated and costly technical methods based on retrieval. A reasonable explanation may be that there are no practical experience, or laboratory studies pertinent to describing such a technology.

Feasibility studies need to be conducted to learn more about the potential efficiency of such a process. The technical requirements related to operation and maintenance supporting equipment also need to be studied.

Considering the required treatment time until acceptable residual concentration is obtained; optimised treatments conditions may give results comparable to what is reported for bed reactors or soil mounds. These are engineered land farming systems used for bioremediation of oil contaminated soil (Alexander, 1994). On a sea bed, with temperatures of 5-6 °C, the viscosity of the oil will be important, as it may be critical for the spread of the oil and thereby reducing the area available for contact with micro-organisms. Slow metabolic rates combined with reduced contact area result in drastically decreased biodegradation rates, despite the higher dissolved oxygen concentrations found in colder waters. Bacteria capable of bioremediation at these low temperatures have, however, been identified (Whyte *et al*., 1995).

4.3.2 Technical status and limitations

In the literature reviewed there is no information concerning *in situ* bioremediation of cuttings piles. Innovative solutions seems possible to develop, where an *in situ* treatment technology comprises the integrated use of chemicals to optimise the recovery and biological breakdown processes. Given the low ambient temperatures at a seabed, biological activity is likely to proceed at a rather low rate. Use of surface active agents and other growth limiting substances will render the hydrophobic components conducive for enhanced biological breakdown, and desorb the oily components from the drill cuttings. The anticipated effect is chemical cleaning (washing) and augmented biological decomposition of the pollutant. The treatment has to be carried out in a confined space to avoid any exchange of material with the surroundings. Thus confinement is a challenge to be resolved. This approach requires that diffusers are inserted in the piles, allowing surface active agents, followed by oxidants and biological nutrients to be injected into the piles. The effluent will contain the recovered components. The process is analogous to *soil washing*, which is a process that is currently commercially available.

With treatment the drill cuttings will become depleted of environmentally polluting material. They will remain on the sea bed. Alternatively they may be respread on the seafloor or recovered for onshore purposes, with minimal exposure risk, though the need for these strategies has been largely negated by treatment.

A considerable amount of field-work is needed, both in the laboratory and pilot scale before this approach can be implemented in the field. Experience pertinent to improved oil recovery, soil washing and bioremediation of petroleum hydrocarbons may be transferred to become an integrated part of the proposed process.

Table 4: *Summary of proposed in situ bioremediation option*

Method	A combination of chemical flooding and bioremediation is suggested. Such a process may be maintained by drilling and installation of diffuser pipes in the piles allowing injection of chemicals and air/oxygen. In addition, surface active chemicals and bioremediation enhancers are required.
Operation	Drilling and installation of diffusers, confinement of piles and installation of waste collection system is dependant of diver/ROV support. Injection of chemicals and air/oxygen. Separation and collection of waste material and spreading of reclaimed material on the sea floor.
Tech. status	Both chemical flooding and bio-technological aided breakdown of oily wastes are field-proven processes. A combined process such as this, has not been applied to this purpose and under these conditions. The combined method is not been found in the literature, but appears as technically feasible.
Equipment	No previous experience. Platform or vessel with drilling equipment, blowers/oxygen-supply and pumps. Storage tanks for separated oil, collected during the pre-treatment flooding.
Capacity & rates	No previous experience. Innovative method. Case specific, depending on oil content of a pile and treatability which requires pre-investigation before engineering. Preliminary suggested design may consist of a few weeks of chemical flooding followed by one summer enhanced biodegradation. Simulation program for forecast analysis appear a useful tool to acquire relevant data.
Limitations	No previous experiences. Need R&D work in lab. and field before implementation.
Man-hours	No previous experiences. Mostly during drilling and pipe installation, thereafter operation and maintenance of pumps and aerators.
Health & safety	No previous experiences. Since the cuttings material is not brought to the surface there is no human contact. Flooding has to be operated in a closed system. Risk caused by use of divers during construction is dependent on drilling method used. Risk of spreading to the environment is believed to be minimal.
Consuma-bles	As with other platform/vessel based options plus bioremediation agents (chemicals for flooding, nutrients). Air /oxygen is made on site.
Marine discharges	No previous experiences. Proper insulation during operation will minimise the risk of discharge/leak to the surrounding water body.
Transport	No transport of cuttings is expected from the site. Need for transportation of consumables is as for other off-shore operated options.
CO_2 , NO_x	CO_2 from the process is assimilated and dispersed in the sea water. No_x is not expected from the process. There may be some discharges from fuel and electrical generation.
Other wastes	Site dependent. Some piles contain other material intentionally/unintentionally buried in the cutting piles. Heavy metals will not be removed, but will be partially unavailable for marine organisms after treatment (oxides).
Cost	No previous experiences. Site dependent. Less than recovery based methods. Most cost effective if platform space is available, alternatively hiring vessel for drilling and diffuser installation, thereafter barge for aerators and nutrient addition.

4.4 Bio-reactor treatment

4.4.1 Methods and operation

Bioremediation treatment offshore, on vessels or platforms, has to be short-term and demand a small area. These criteria exclude most methods used onshore. Various bioreactors have been developed for treatment of hazardous biodegradable wastes. Several commercially available bioreactor treatment systems have been used for petroleum wastes. The main advantage of *ex situ* treatment is that it generally requires shorter time periods than *in situ* treatment, and there is more certainty about the uniformity of the treatment because of the ability to homogenise, screen, and continuously mix the material. However, *ex situ* treatment requires recovery and transportation, leading to increased costs and engineering for equipment, possible permiting, and material handling/worker exposure considerations.

No offshore installations are known to use bioreactors for cuttings piles treatment, and so there is therefore no experience of this in the literature. There are some data originating from onshore systems, (SFT, 1995).

Only one "low area bioreactor system" is described by SFT (1995). This has a capacity of 100 tonnes/y and treatment costs are somewhat above NOK 500/ tonnes. Since there is a continuous development of new technologies and companies treating oily wastes these figures may not be interpreted as fixed for bioreactors. But even with a massive increase in capacity; beyond 100 tonnes/y, bioreactors will not be able to cope with polluted cutting masses of 5-10,000 tonnes per pile within a reasonable time and cost. For this reason, bioreactors as a direct treatment method for oily cutting piles material are not recommended. The only realistic bioreactor approach would be to treat concentrated wash out from the piles, and this may be conducted either offshore or onshore. Process experience from handling that type of waste material is not reported, but the technique employed would be totally dependent on the pre-treatment methods used.

Table 5: *Summary of proposed bioreactor-based bioremediation option*

Method	Bioreactors with controlled aeration and addition of other bioremediation agents have been developed for the treatment of hazardous biodegradable wastes, including petroleum wastes. Bioreactors allow a high degree of certainty about the uniformity of the treatment because of the ability to homogenise, screen, and continuously mix the material..
Operation	*Ex situ* treatment requires recovery and transportation to platform or vessel/barge operated bioreactor, or to on-shore reactor. Redisposal of oil-free cuttings on sea floor or land or landfill.
Tech. status	Bioreactors designed for oily wastes are not commercially in stock. The technology is well known and reactors specially made for the purpose may be designed and built.
Equipment	Generally steel or plastic tanks with aerators and mixing equipment.
Capacity & rates	Limited capacity. Experience described by SFT (1995) in the order of a few hundred tonnes/year.
Limitations	Capacity constraints. Practical application limited by the volume of a typical small cutting pile.
Man-hours	Material dependent. Dependent on on-shore or offshore handling.
Health & safety	As for other retrieval technologies plus risk of exposure during reactor loading. No human contact to chemicals or oily cutting material.
Consum-ables	Similar to other platform/vessel based options when carried out offshore. Bioremediation stimulants. Air/oxygen is generated on site.
Marine discharges	Depends on offshore or on-shore operation. If offshore, reclaimed cuttings may be distributed on the sea floor.
Transport	Depends on offshore or on-shore operation. If on-shore, cutting material requires transport to land.
CO_2 , NO_x	CO_2 emission from the process. No_x is not generated in the process. Fuel combustion, electrical generation or aerators.
Other wastes	Site dependent. Heavy metals will not be removed, but is partly unavailable for organisms after treatment (oxides).
Cost	Dependent on on-shore or offshore treatment, and availability of treatment platform. Generally *ex situ* treatment requires recovery and transportation, leading to increased costs and engineering of equipment. Reactor treatment cost estimate: NOK 500/tonnes.

4.5 Onshore bioremediation systems

4.5.1 Methods

Onshore bioremediation methods (Bourquin and Pedersen, 1995) have been developed primarily for treating polluted soil, sediments and ground water:

- solid-phase bioremediation (landfarming);
- biofilters;
- bio-oxidation piles/biopiles/soil piles;
- bioreactors;
- slurry phase bioremediation;
- *in situ* bioremediation;
- bioventing.

In situ bioremediation and bioreactors are treated elsewhere in this study. Biofilters are used for gaseous volatile organic compounds extracted from the polluted material, and are therefore not suited to oily cutting waste treatment. Slurry phase bioremediation is a reactor treatment method used for aqueous slurry. It has the same limitations as bioreactors. It is not considered useful for cutting piles material, but may be suitable if the pollutants are extracted and the slurry waste needs further treatment.

There are only slight differences between land-farming and bio-oxidation piles. Both methods are based on intrinsic biodegradation activity by indigenous microbial populations. Of those two alternatives land-farming is the most extensive treatment since the optimisation of the process is performed by regular tilling, nutrient addition and watering, while air or oxygen is introduced by an internal piping system in the piles. During operation of these two systems pH, temperature, oxygen and moisture content are maintained within ranges conducive to microbial activity. Mixing the polluted waste with other types of organic material may raise temperatures in the biopiles up to 40-60°C (composting).

Land-farming and biopiles have been successfully used for years in the managed disposal of oily sludge and petroleum refinery wastes, and are undoubtedly applicable for oily cutting piles material. Biotreatability and phytotoxicity studies on material from the specific piles are needed to provide design criteria. In a recent study by Chîneau *et al*., (1996), in which oil-based drill cuttings were used in an agricultural soil, it was found that 90% of the hydrocarbons were removed during a two year period. During the period, phytotoxicity resulting in significant reductions of crop yield was observed.

It is not possible to give a complete documentation of capacities and cost of treatment by these two methods since the quality of the contaminated material has to be determined prior to an inquiry. Estimates may be given from the Scandinavian plants described by SFT (1995). Capacities for the companies described are from 10.000 tonnes to 100.000 tonnes/year mostly at the lower end. All of them were Danish, and described their processes as "composting." The possibility of constructing such treatment plants on the west coast of Norway is not considered.

Restrictions on available land areas for this purpose may be an obstacle. Costs are about NOK 500/ tonne. To these estimates, the cost of final disposal has to be added.

Brown & Root(1997) mention the Soil Recycling Centre at Antwerp which they stated as having a capacity for bioremediation treatment of 35,000 tonnes/year. They refer to a comment from Swaco that they consider "bioremediation, i.e. land spread as having limited capacity."

According to a report by Solgaard *et al*. (1993) land-filling is an appropriate method for oil depleted cuttings disposal on land and cost is significantly size dependent varying from about NOK 400 (1993 prices) for a size of landfill of 10,000 tonnes/year to NOK 150 for a 50,000 tonne/year landfill. Parts of the material may also be recovered. Costs are totally dependent on recovery methods and were not considered in more depth by the consultant.

Direct landfilling without biological pre-treatment as is the case at some sites in the UK (Brown & Root, 1997) is not considered in this study since it is not expected to keep up with future environmental standards.

With regard to land farming, information concerning recovery of the seabed material is found in chapter 5 in this report. Both from a technical and biological point of view land farming seems suitable as a treatment method before final disposal in landfills. Generally the method is expected to be accepted both by public and authorities, but may be anticipated to be met by a "not in my backyard" opinion. Also, the availability of large areas suitable for land farming is expected to be limiting along the Norwegian coastline.

Costs of this option may be about NOK 500/tonnes plus NOK 100-200/tonnes for final land-filling of treated cuttings.

***Table 6**: Summary of land-farming o/ biopiles/composting as bioremediation options*

Method	The method relies on the degradation of oil in cuttings by the intrinsic microflora in a mixture of contaminated material and soil. *Land-farming* is an extensive treatment since the optimisation of the process is performed by regular tilling, nutrient addition and watering, while air or oxygen is introduced by an internal piping system in the *biopiles*. During operation of these two systems pH, temperature, oxygen and moisture content are maintained within ranges conducive to microbial activity. Mixing the polluted waste with other types of organic material may raise temperatures in biopiles up to 40-60ºC (*composting*).
Operations	The treatment method is *ex situ* and requires the recovery and transportation of cuttings to land. The most effective method (composting) requires the balanced addition of organic material (oily cuttings and e.g. sawdust), nutrients (specially formulated N and P), (bio)surfactants and oxygen/air. Temperature, pH and moisture content are kept at optimum levels. Bio-piles, without elevated temperature, and land-farming require less process control equipment than composting. Redisposal of oil-free cuttings can be to the sea floor, on land, or as landfill.
Tech. status	Both land-farming in its most non-technical form, and the more advanced bio-piles and composting-piles, are well known as petroleum waste reclamation systems. Treatment plants specially made for the purpose can be designed and built.
Equipment	Farming equipment, with tractors for simple land-farming. The more advanced methods need a special site with a concrete floor, diffuser pipes, mixers, irrigators, aerators/oxygen generators, temperature controllers etc.
Capacity & rates	Simple land-farming has a constrained capacity. Composting has been described with capacities up to 100,000 tonnes/year.
Limitations	The capacity, availability of land and permit for use, may be restricted by local opinion.
Man-hours	Dependent on technical level.
Health & safety	As for other retrieval technologies, but additionally with a risk of exposure during loading, tilling and mixing. No direct human contact to chemicals or oily cutting material is expected. Special precautions for uncontrolled leakage from the site must be taken.
Consumables	As with other retrieval based options. Bioremediation stimulants, and air/oxygen.
Marine discharges	Depends on retrieval technology and leakage control from the respective land site. Should be minimal if modern design and controlled operation are conducted.
Transport	Cutting transport to land, transport from quay to site and from site to final disposal.
CO_2 , NO_x	CO_2 emission from the process. No_x is not generated in the process itself. Fuel combustion, electrical generation or aerators.
Other wastes	Heavy metals will not be removed, but are partially unavailable for organisms after treatment(oxides). Risk of biohazard if not properly final disposed.
Cost	Mainly dependent on degree of technical design, capacity, limitations for the site chosen and amount of oil in material. Land-based treatment cost may be about NOK 500/tonnes, in addition to land-filling at a cost of about NOK 100-200/tonne.

4.6 Limitations and recommendations for further work

A review of the literature with regard to sea floor deposited oily cuttings, has identified a number of unsolved questions, most of which have been addressed in this report. A number of input data are needed for bioremediation design but there are no published data on oil contents in cuttings at various ages and with different histories that may help to resolve some of the uncertainties. The present characteristics of oil drill cuttings are expected to vary considerably from pile to pile and can only be assessed by analysis of cuttings pile core samples on a case by case basis.

To our knowledge, no published data exists for treatability of oil drill cuttings at the temperatures that are relevant for this case.

The most important unknown parameters which must be recognised as case dependent, are :

- amount and degradability of hydrocarbons at ambient temperatures;
- oxygen demand for the process;
- porosity and flow behaviour of liquids in cutting piles;
- suitability of piles for drilling and diffuser insertion;
- type and need of operation and maintenance of treatment supporting equipment;
- need for nutrients, biosurfactants or other bioremediation enhancers;
- identification of potential inhibitory agents like biocides and heavy metals in the piles.

4.7 Conclusions

In this review bioremediation methods have been identified that seem to be particularly suitable for the treatment of oily cuttings. Two treatment approaches stand out as being particularly promising, despite a number of apparent uncertainties of a technical and economical nature. One method is performed on-site (offshore), while the other requires the retrieval of the material and transport to land. The two approaches are:

- *in situ* treatment by combined chemical and biological remediation;
- advanced land farming, i.e. composting of recovered material.

The *in situ* treatment approach is uncertain because it encompasses a new application of known technology. Since it neither involves retrieval of cuttings from the sea floor, nor final disposal of reclaimed material, it may be conceived as being potentially cost effective and with few environmentally negative consequences. Research and development inputs are required for the final process description and a cost estimate.

Advanced biodegradation of petroleum material on land is a well recognised technology. This approach is potentially a high cost alternative with demands for available land areas for treatment and for final disposal of reclaimed cuttings.

5 RETRIEVAL TECHNOLOGY

5.1 Introduction

Special attention has been paid to this aspect, as this part of the treatment / disposal process will have widespread economic, safety and environmental ramifications. An extreme example of this would be a retrieval-treatment technique that was highly efficient at the treatment stage but was unable to collect and immobilise a large proportion of the cuttings. In this case, though treatment could be judged as efficient, the overall technique would be ineffective and could produce substantial negative environmental impacts.

Isolating this stage of the handling operation should allow a greater flexibility in evaluating the costs and benefits of any vertically integrated technique: a mix-and-match approach in combining different collection, treatment and disposal strategies.

There are several techniques developed for the removal of cutting piles from the sea-bed, as summarised by Kjeilen *et al*., (1996). These include jetting, air lifting, vacuum suction, bucket or grab dredging, or a combination of these. However, although many contractors advertise drill cuttings removal services using these retrieval techniques, the service usually consists of relocating the drill cuttings away from the structure rather than recovery to surface.

In addition, the majority of such retrieval systems are, in practice, only prototypes or are limited to shallow water operation. No equipment capable of retrieving compacted cuttings from deeper than 100 m at commercially viable rates has yet been demonstrated (Auris, 1995).

Due to the nature of this study, the work contained in this chapter has been drawn from a number of sources including information from industry. It should be noted that much of the information is proprietary and as such cannot be regarded as independent. Claims relating to efficiency, feasibility and costs should be assessed with a degree of criticism. Much information has been obtained from a recent study for the Offshore Decommissioning Communications Project of the E&P Forum (Brown & Root, 1997). It was there stated that retrieval options can either be platform based or vessel based. There are essentially four options:

- Tracked vehicle with pump (either platform or vessel based).
- Diver/ROV feeding transfer pump (either platform or vessel based).
- ROV pump feeding fall pipe from gravel dump / dredging vessel (vessel based).
- High suction atmospheric pump (either platform or vessel based).

The first three options necessitate the use of cutting heads to break up crusts and bonded sediments whereas the fourth option relies entirely on high suction pressure to break up and fluidise the cuttings. These options have been termed and grouped together under mechanical dredging. The final option relies entirely on suction pressure to fluidise and entrain the material. This option has been termed suction dredging.

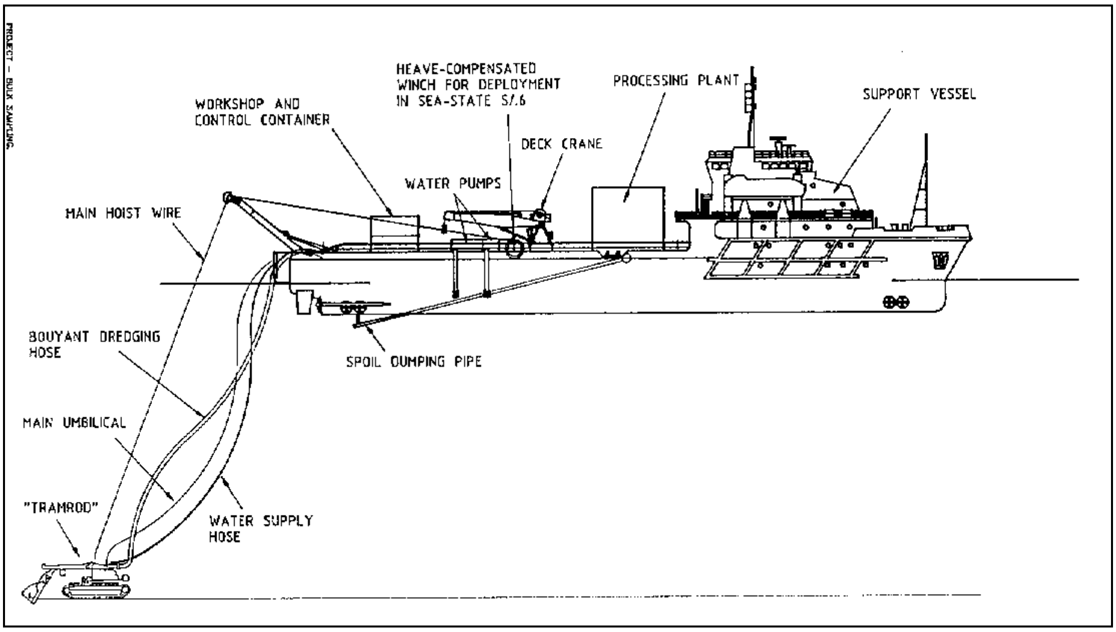
This section will firstly describe the methods, technical status and limitations, principles of operation, equipment, costs, capacities and rates associated with the options. Finally discussion regarding aspects such as health and safety and risk, to which there is more commonality, is addressed.

5.2 Mechanical Dredging

5.2.1 Methods

Mechanical dredging methods for removing drill cuttings employ a variety of equipment for cutting/removing the drill cuttings and pumping the debris either to the surface or, as has more often occurred, for relocation at a site remote from the platform. Although diver held cutting and suction equipment is available (e.g. Kofter Plant Unit), dredging operations are more commonly undertaken by remotely controlled subsea tracked vehicles fitted with a cutter suction arm.

These machines are used by several contractors including Royal Boskalis (Tramrod and Namrod) and Coflexip Stena Offshore (Mobivac). Typically, the tracked vehicle is deployed on site along with a centrifugal or positive displacement pump to recover the removed cuttings to surface via a recovery pipe. The equipment can be operated from a platform or a vessel. Figure 8 shows a typical system deployed from a surface vessel.



Source: Royal Boskalis

***Figure 8**: Surface Vessel Deployed Dredging Unit*

An alternative to the remote deployment of a remote controlled dredging vehicle would be to use a cutter suction dredging vessel. Information suggests however that cutter suction dredging vessels are limited to water depths of 70 m or less. In theory suction pumping units could be attached to the end of the fall pipe on a gravel dumping vessel. However more development on pumping systems would be required.

The advantage of using vessels of this sort is that they already have on-board hoppers for storing retrieved drill cuttings in the event of onshore disposal.

5.2.2 Operation

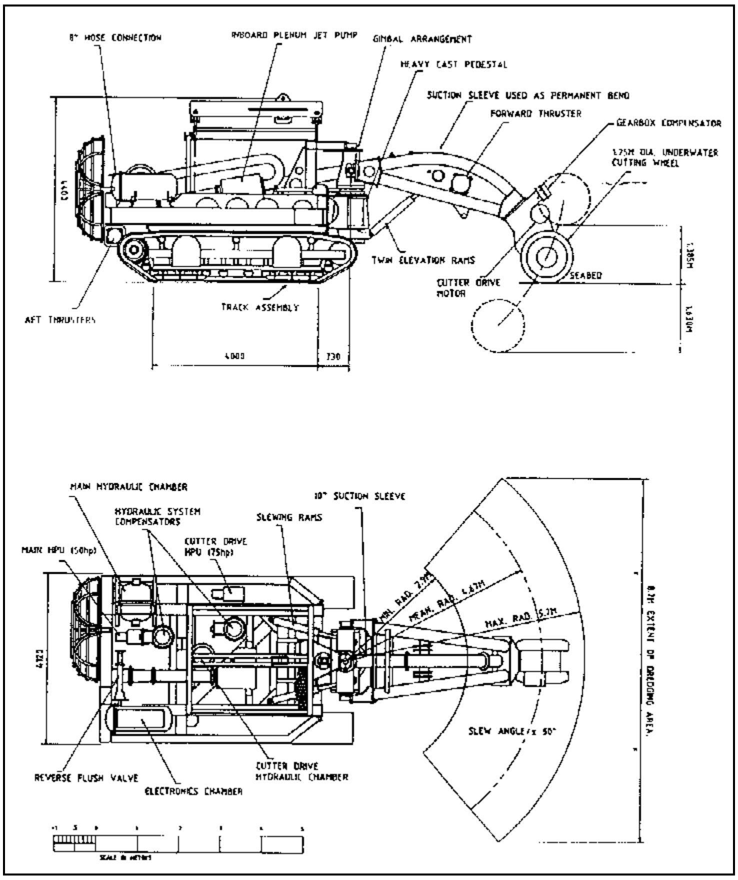
Whichever equipment is ultimately selected for use, the operation will follow a similar pattern. The equipment will first either be mobilised to be deployed from the platform or a surface vessel. Once deployed the drill cuttings will be recovered to surface and transferred to a suitable vessel for transport to shore. Once all cuttings have been removed, a seabed survey will be undertaken prior to demobilisation.

The remotely operated vehicles in the Tramrod / Namrod class consist of a tracked undercarriage onto which is mounted an hydraulically controlled dredging arm, see Figure 9. Dredging power is achieved using a jet pump assembly mounted on the vehicle. A multicord control and signal cable provides the power for the electro-hydraulic submersible power packs as well as the monitoring systems which include SITV, video cameras, scanning sonar, hydro compass/auto heading and bathymetric suite. Motive power is supplied via a flexible hose from the surface centrifugal water pump sets.

Depending on the properties of the drill cuttings, a variety of cutting teeth can be fitted to the drum cutter head. A pressurised jet wash system is utilised to clean cuttings/soil from between the teeth and the standard suction mouth is located behind the teeth to take away the cut material.

Alternatively, fluidising jets can be used to breakdown compacted drill cuttings which is the method employed on the Mobivac systems.

In addition to the tracked unit, dynamically positioned grab units can also be used which can either be mobilised on the vehicle or deployed as a separate unit. Typically a grab may have a capacity of 2.5 m^3 and is sealed to prevent spillage or dilution in the water column. Positioning is achieved by a composite thruster unit above the grab and operated within a transponder grid. Provision of a grab unit will assist in removing any extraneous debris within the cuttings pile.



Source: Royal Boskalis

Figure 9*: Tramrod 250 Dredger Excavator*

There are several diver or ROV operated dredging systems available. All rely to one extent or another on the same principle of operation and many utilise Tritech's ZipJet or ZipPump systems. The diver/ROV held excavating head first fluidises the drill cuttings before sucking the material into a transfer hose connected to a dredging pump skid (ROV systems can operate without the pump skid). Usually the pump discharges the material at another location on the seabed up to 200 m away.

5.2.3 Technical Status and Limitations

The use of tracked cutter suction dredging equipment is well established and proven in removal and relocation of material. Operations of this nature have been undertaken in over 300 m water depth. However, the recovery of material to surface has not been performed in such depths and, like other options, requires further development of the pumping system. Further, it is expected that it would be considerably more difficult to apply this technology to piles with the platform structure in place and with much of the pile in amongst the jacket. In such circumstances access to the piles would be greatly hindered and, should the equipment breakdown under the jacket, then down-time could be substantial and diver intervention required.

5.2.4 Capacities and Rates

Typically values are shown in Table 7:

***Table 7**: Typical capacities and rates for different dredging units*

Kofter Plant Unit	
Pumping Capacity	75 m^3/hour sand (estimated 10 m^3/hour drill cuttings)
Dredge Hog	
4 inch suction hose	80 m^3/hour (free flowing material)
6 inch suction hose	125 m^3/hour (free flowing material)
Namrod	
Operating Depths	up to 120m
Pumping Capacity	400 m^3/hour
Solid Production Levels	25-50 m^3/hour
Pumpable Solids Size	120 mm diameter
Tramrod 250	
Operating Depths	proven in 310m designed for up to 800m
Pumping Capacity (average solids)	150 m^3/hour (assumed same as Tramrod 200)
Pumpable Solids Size	250 mm in size
Mobivac 250	
Solids	200 mm in size

5.3 Suction Pumping

5.3.1 Methods

Suction pumping methods use the principle of pressure differentials caused by hydrostatic head to create suction pressures which can be used to remove either loose material such as sand or gravel, or compacted material such as sediment and drill cuttings. Following removal from the seabed the cuttings are recovered to the surface under air pressure. Once recovered they can be routed either for re-injection, disposal at a site remote from the platform location, or transported to shore for treatment and disposal.

5.3.2 Operation

Hydrostatic pumps can essentially be considered as positive displacement pumps with compressed air taking the place of a mechanical piston. One of the advantages of such a design is that no moving parts, apart from the control valves, come into contact with the material being pumped.

In basic form, the pumping system consists of a suction hose connected to a pressure cylinder, which is in turn connected to a discharge hose and an air supply/exhaust hose. The cylinders have an inlet and outlet valve made from anti-abrasive rubber. The operation of a hydrostatic pump relies on a three stage process, see Figure 10. The stages are as follows:

- *Stage 1:* filling of cylinder with dredge material.

  The differential pressure, equal to the hydrostatic head, between the pump chamber and the end of the suction pipe causes the inlet valve to open and allow the ingress of dredge material.

- *Stage 2:* application of pneumatic pressure.

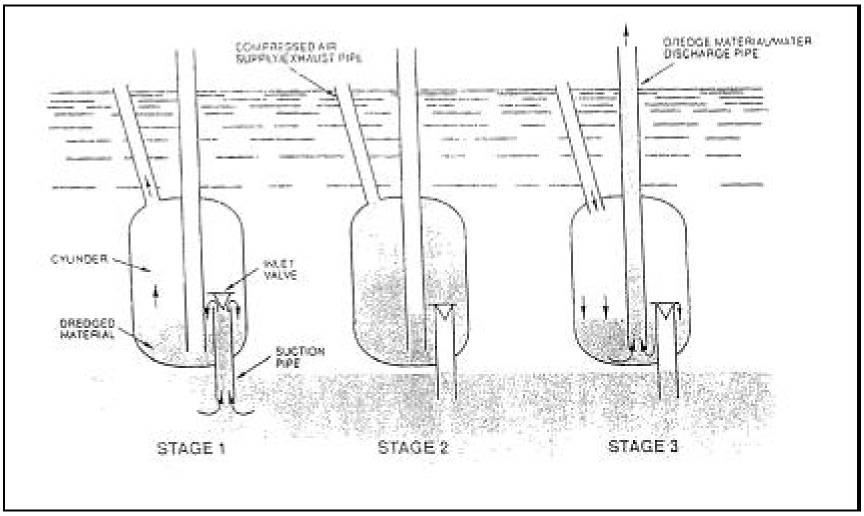
  Once full the exhaust line to atmosphere is closed and compressed air is applied to the cylinder.

- *Stage 3:* Discharge material.

  Under pneumatic pressure the inlet valve closes and the material is forced through the outlet valve. Once the cylinder is empty, the compressed air supply is closed and the exhaust line is vented to atmosphere to re-initiate the cycle.

Generally, a pumping system is made up of more than one cylinder, usually three, the operation of which is regulated by a distributor which controls the inflow and discharge of the compressed air into each cylinder.

The pumping system is designed to be deployed either from the platform or a support vessel. The suction hose can be fitted to a hydraulically powered ROV to enable precise remote control of the suction operations. Secondary pollution is minimised by the high suction rates which entrain the majority of disturbed material thus preventing their re-suspension in the surrounding area.



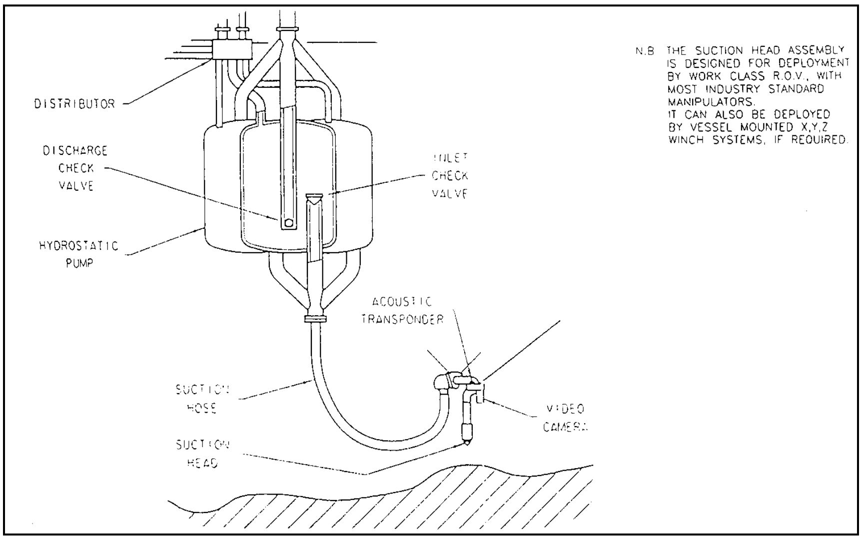
Source: Ian Murray Engineering

***Figure 10**: Operation of Hydrostatic Pump*

The above text has already outlined the principle of operation for a hydrostatic pump. However, the complete dredging system consists of additional components to the pump, distributor and suction head, i.e.:

- surface control equipment;
- compressed air supply system;
- hydraulic power pack.

The new IME design consists of three cylindrical steel pressure chambers arranged in a circle. A three-way suction manifold connects to the inlet at the base of each cylinder. Inside each cylinder, at the inlet connection, there is a rubber poppet type check valve; this prevents dredge material from flowing back into the suction hose during discharge. The system is shown in Figure 11. The deployment of the system is illustrated in Figure 12.

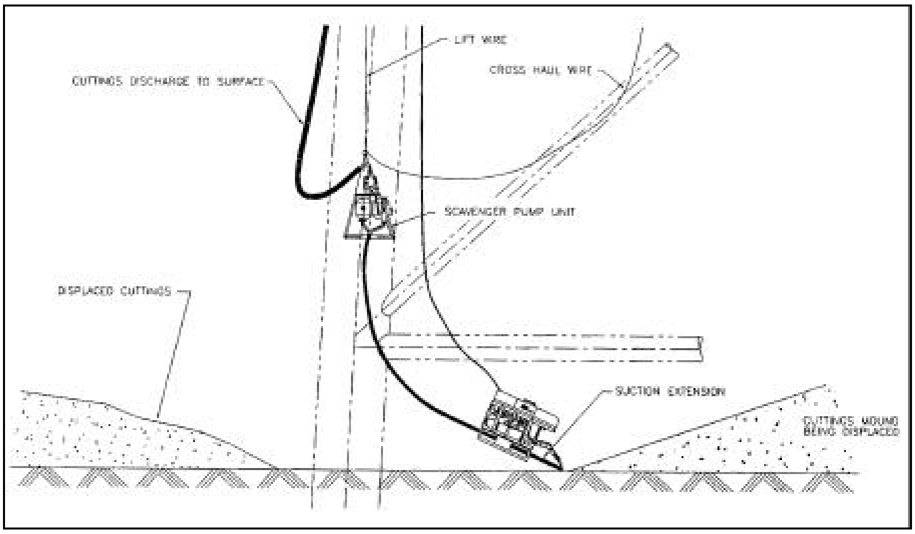


Source: Ian Murray Engineering

***Figure 11**: IME Scavenger Pump System*

The suction head is situated at the end of a flexible hose. The other end of the hose is attached to the manifold on the base of the pump. In the prototype system, positioning of the head, relative to the drill cuttings mound on the seabed, was by means of a series of winches and cross-haul techniques. The length of this hose was dictated by the pump position relative to the drill cuttings material to be dredged.

On top of the cylinders, a three way manifold connects to the discharge outlet of each cylinder. The discharge connection is extended down to the base of each cylinder to ensure that the material is discharged from near the bottom of each chamber. A rubber ball type check valve is fitted in each cylinder's discharge line, to prevent dredge material flowing back into the cylinder.



Source: Ian Murray Engineering

Figure 12: *Deployment of IME Scavenger Pump System*

Connection of the discharge hose is made to the manifold located on top of the pump cylinders. This hose is of the same size and construction as the suction hose; this gives greater flexibility in operation of the system. The length of the discharge hose must be equal to the pump depth plus any additional above water length necessary to enable discharge of the material into a barge, for example.

Also installed on top of the pump is a specially designed, submerged distributor assembly. This consists of a series of depth compensated chambers, fitted with hydraulically operated flow valves. These values alternately connect the cylinders to the exhaust line and to the compressed air supply. An electronic sequencer, which is part of the surface control system, generates signals to operate the valves at the correct point in the working circle. The electronic control signals are carried down the instrumentation/video umbilical to the distributor, where they operate electro-hydraulic solenoid valves. Hydraulic power is provided by an electrically driven open circuit power pack located on the deployment A-frame skid. Two hydraulic lines (supply and return) connect between the power pack isolating controls and the submerged distributor.

Compressed air is fed to the distributor valves by a single hose from the surface. The delivery rate and pressure of the compressed air supply depends upon the operational depth of the pump, and the density of the material to be removed. In most operational configurations, a standard proprietary diesel driven compressor can be used for this function. Flow of the compressed air is via an isolating valve to the pump supply hose. The isolating valve provides the primary means of interrupting the air supply to the pump. Since the air hose could be subjected to an external pressure equal to the head of water at the pump operating depth, it must be collapse resistant. On arrival at the pump, the compressed air flow into the cylinders is controlled by the distributor valves, which sequentially connect each cylinder to the line at the discharge point of its work cycle. The location of the distributor valve, on top of the pump, minimises the loss of compresses air at each exhaust cycle.

Primarily, the control cabin provides the operational centre for the dredge system and its peripheral equipment. The operator's desk is fitted with all the essential control panels, video monitors, subsea positional data display and cutting pile survey system display.

Central to the satisfactory operation of the pump is the management of the submerged distributor assembly, the action of which is described above. An electronic pump sequencer unit is installed at the operator's desk. This allows direct control of the rate at which each cylinder is sequentially connected to the exhaust and compressed air lines. Controls on the electronic sequencer therefore permit variation of the flow rate of dredge material, through the pump. A status display on the control panel gives a direct readout of pump operation, and an indication of the stage reached in its operating cycle.

In order to accurately locate the suction head at the point from which material is to be removed, the operator needs information as to both the head's three dimensional attitude and its position relative to the structure. The attitude information is obtained through use of a video camera, inclinometer, depth gauge and compass mounted on the head. An acoustic transponder is also installed on the head and this, together with a reference beacon, allows positional information to be obtained. All of the controls and displays associated with this equipment are located on or around the operator's desk.

A scanning sonar and 3D mapping system are used to perform site surveys of the cutting mounds to be removed, prior to the commencement of dredging operations. Further surveys can also be carried out during the course of the work, to ascertain progress of the dredging operation. The system consists of a sonar control console, computer systems and displays installed in the control cabin, and an underwater transducer and sensor head. The equipment operates completely independently of the dredge system.

5.3.3 Technical Status and Limitations

Sub-sea pumping methods have been used for harbour dredging and other applications, but in only limited water depths (proven to about 50 m). Further, it is acknowledged that no pumping system currently available on the market is capable of recovering drill cuttings to the surface in water depths of over 100 m. Ian Murray Engineering (IME) in Aberdeen have however designed a pumping system (the Scavenger System) under the CEC's Thermie Programme, to remove drill cuttings in water depths of up to 200 m. This design was adapted from their Pneuma pump system which has successfully operated in the shallower water depths quoted above.

Following the completion of the design, IME unsuccessfully approached the oil industry to support the commercial development of the system. A Scavenger System is currently being built for Racal Underwater Contractors and is due for delivery during the first quarter of 1998. Trials for the deep-water removal of drill cuttings using the Scavenger system are provisionally scheduled for the second quarter of 1998.

Most of the methods for retrieving drill cuttings have not yet been tested where platforms are still in place. The physical presence of the platform may cause a considerable additional hindrance to the retrieval equipment, and it may be necessary to increase the diver assistance, and thereby the cost, as described in section 5.2.3.

5.3.4 Capacities and Rates

The design dredging rate for the IME system is 85m^3/hour to 185m^3/hour depending on pump selection.

5.4 A specific method developed by AEA Technology

AEA Technology have studied and designed a method for the retrieval of drill cuttings from the seabed. The method is described in the report "Seabed Cuttings Reclamation" (AEA Technology, 1997). Most of the information for this section is taken from that report and as such should be regarded as company information.

5.4.1 Methods

AEA Technology have developed a method which includes both retrieval and re-injection of existing drill cuttings piles. The operation involves a remotely controlled Seabed Dredger Vehicle which is lowered onto the seabed to recover the pile to the surface. Recovered solids are separated using existing solids control equipment. The solids and the oily wastes will be ground and mixed with appropriate quantities of sea water to form a slurry suitable for re-injection into subsurface formations. The re-injection process is further described in Chapter 6 of this report. Additional solids control equipment will further clean the recovered seawater used to transport the solids to surface prior to discharge overboard. Waste materials removed at this stage are also recovered for re-injection.

5.4.2 Operation

The Seabed Dredger Vehicle is remotely controlled from the platform using its own launching and recovery system. The Remote Operated Dredger (R.O.D.) would be launched to the seabed in unison with the surface discharge hose, control and monitoring umbilical and the centrifugal pump electric power cable. The R.O.D. has onboard cameras, gyro and scanning sonar. These, in conjunction with a monitoring R.O.V., will allow accurate control from the surface to enable complete recovery of the pile whilst minimising any risk of blockage or equipment or structure damage.

The centrifugal pump mounted on the rear of the crawler will be the prime mover, transferring the cuttings to the surface.

The pile crust breaker and mechanical auger will be rotated to break-up and convey the cuttings to the suction point within the head. The centrifugal pump is then started, ensuring that the maximum amount of solids possible is transferred to the surface with the fluid.

The suction head incorporates a canopy cover design which reduces the disturbance of the pile and minimises the possibility of secondary contamination. The weight of the suction head canopy and the action of the rotating equipment will drive the head down and into the natural seabed. The pile will be removed to approximately 50 cm below the seabed. At this point the R.O.D. will be driven forward and the suction head slowly raised to the top of the next section of pile to be removed. As the head reaches the top of the pile, the R.O.D. will be stopped and the weight and the rotating action of the head will once again drive the head down to the natural seabed. This method of removal ensures that solids in the discharge hose are kept in suspension whilst maximising the recovered solids concentration.

The R.O.D. is fitted with onboard cameras, which, in conjunction with the monitoring R.O.V., will detect any potential hazards, foreign objects and general debris while the operation is proceeding. Any objects requiring removal from the area will be lifted by an onboard hydraulic grab/manipulator. Removed items will be transferred to an area away from the operational site.

This recovery process continues until all cuttings external to the installation structure have been recovered to the surface. The R.O.D. is retrieved to the surface to have the basic suction head replaced with a long reach telescopic slim-line head. The R.O.D. is then re-launched to the seabed and operations begin to recover the cuttings from within the structure and from between the conductors. This operation is carried out entirely from the outside of the structure, the R.O.D. is positioned so that the telescopic arm can be traversed between the conductors allowing the pile to be recovered from top to bottom. The telescopic arm would have sufficient length to reach into the centre of the structure ensuring that all internal cuttings would be recovered.

5.4.3 Technical status and limitations

The results of actual offshore trials will have to be published in order to establish at least the practical recovery rate which would be achievable.

According to AEA (1997) the overall weight of the R.O.D. is being redesigned, concentrating on the superstructure, centrifugal pump and telescopic suction head. Different types of materials and methods of propulsion are also being examined.

There also appears to be different launching and recovery systems under consideration, which may need some further development.

As described in section 5.2.3 and 5.3.3, it is expected that it would be considerably more difficult to apply this technology to piles with the platform structure in place and with much of the pile in amongst the jacket. In such circumstances access to the piles would be greatly hindered and, should the equipment breakdown under the jacket, then down-time could be substantial and diver intervention required. To combat this, an extendible suction head has been developed, that the manufacturers claim will allow the crawler to remain outside the jacket, whilst digging between the members. It remains to be seen how successfully this system will collect the pile material amongst some of the larger and more complicated jackets.

5.4.4 Capacities and rates

With the centrifugal pump selected for this operation, the recovery rate is expected to be at 150 m^3/hour. The pump can handle abrasive solids of up to 175 mm diameter and is said to be capable of lifting the solids/water 200 m to the surface.

Estimated recovery rate for a 20,000 m^3 pile is based on a recovery rate of 150 m^3/h with a minimum solids content of 15 %. For an estimated 18 hours day, 405 m^3 of the pile will thus be recovered. An estimate of the mobilisation and demobilisation of 8-12 days gives a total number of 62 days to complete the operation (including re-injection).

5.5 Limitations

The recovery rate should be compatible with the reinjection rate of slurry, which is normally 0.6 to 1.75 m^3/min. Downtime must though be taken into account.

Debris from years of construction, maintenance and remedial works can collect on the sea floor around and under platforms and this material may be buried in the drill cuttings. Such debris may consist of items such as scaffolding poles and clips, welding rods, bolts, spanners, gloves, boots, wire rope and rigging and various construction materials lost overboard during the life of the platform. Some of this material has been seen during surveys on, or protruding from, the cutting mounds, however much of the material is buried and will only be located during dredging operations. Cuttings removal techniques must cope with such debris and a clear definition is required of what is reasonably for the operator. Downtime will result as a consequence of this debris and the amount of debris will affect the estimation of this downtime.

A target for recovery would be to keep up with injection at approximately 225 m^3 (of the cutting pile) per day (assuming 50 % downtime in the injection process). The tool, should, if operated continuously, return well over 1000 m^3/day, therefore about 6 hours per day of productive dredging will provide sufficient material for injection. This gives some scope for improvement if injection rates can be increased and allows 18 h/day for non-productive operations such as for launch/recovery, breakdowns, positioning, maintenance and debris handling. Total recovery in any one day will be limited to that quantity injected in addition to a 450m^3 buffer storage.

If for example a dead vehicle recovery and repair is required a 48 hour buffer is available for remedial work before injection is held up.

A further problem that has been described in sections 5.2.3, 5.3.3 and 5.4.3 is the difficulty of accessing piles with the platform structure in place and with much of the pile in amongst the jacket. In addition to the hindering of the retrieval equipment by the jacket members and risers, there is also a risk of equipment breakdown under the jacket, that would require time and diver intervention to rectify. Some of the larger and more complicated multi-well jackets would be expected to pose the greatest difficulty in this respect.

The majority of the retrieval equipment has not been tested to retrieve cuttings *to the surface* at depths in excess of 100 m. Whilst many of the fields on which oily cuttings piles are present are in water depths shallower than 100 m, some are not, and so the applicability of the technology must then be questioned at these deep sites.

5.6 Man-hours

The number of man-hours per tonne needed varies slightly, depending on the volume of the pile, situation of the pile and other parameters. For all operations, a manager is needed offshore to supervise the operation. The number of operators/ technicians and pilots are estimated as two and four respectively. In addition there will be a need for a store keeper, assisting personnel and logistics. Onshore backup will consist of a complete replacement team for back-to-back two-week offshore trips.

The recovery rate varies widely from one method to the other, it is therefore difficult to estimate the total number of man-hours. However, the time of retrieval for most methods are somewhere between 62 and 150 days (18 h days).

5.7 Health, safety & risk

While the dredging and recovery of drill cuttings has similarities with other sub-sea activities, the following issues were raised as special concerns by Brown & Root (1997). These issues will require mitigating actions which will be reflected in operational procedures.

- Over-side working. The launching and recovery of the ROVs and the crawler vehicles involves a certain amount of work adjacent to safety barriers and may require temporary removal of barriers. The dangers are similar whether the system is platform or vessel based. Normal over-side or exposed area working practices should be followed.
- High voltage electricity (for sub-sea tools). Sub-sea tools often require high voltage supplies through umbilicals that are subject to damage. Therefore adequate earth leakage and insulation breakdown precautions should be taken.
- Damage to sub-sea cables and pipelines. Adequate precautions should be taken to avoid damage to sub-sea systems. A heavy vehicle could overload unsupported cables or pipelines sufficiently to cause a loss of communications with the satellite, or even a release hydrocarbons.
- High pressure hydraulics and fluids. Normal safety procedures will apply when working with pressure systems, although special care needs to be taken with tripping and slipping hazards and hoses passing over edges.
- Dynamically positioned vessels. If a vessel based solution is used, a major hazard is the continuos operation of the vessel in close proximity to the platform (e.g. within 50 m for about a 60 days period).
- Zones for equipment in hazardous areas. It is likely that lay-down areas used on platforms for ROV launch and recovery will be adjacent to the process plant. The normal zoned equipment standards need to be applied. These include adequate communications, safe egress and interconnected shutdown systems.
- Complacency. Owing to the duration and monotonous nature of the work, special effort is required to stop unsafe working practices developing.
- Debris recovery. During recovery of skips full of debris from ROV operations, precautions should be taken so that unsafe lifts are avoided. Lifts off the platform to supply boats should be covered and properly secured. The potential exists for contamination of debris, so allowance should therefore be made for micro-biological sampling and LSA checks.

Due to the likely anaerobic activity within the cuttings pile, disturbing the pile may release some hydrogen sulphide and free methane. This may be a potential health hazard at sea level, but as the operation is being controlled on the installation and as the sulphide/ methane will not be in any great quantity the health hazard, is deemed likely to be negligible, but must be constantly monitored.

Carbon dioxide, which may also be a by-product of microbial action within the cuttings pile, can be released into the sea water. The concentration is believed to be low and, as a result of this, will dissolve in the sea water and diffuse away. (AEA Technology, 1996).

Most of the existing retrieval techniques available today are prototypes. Some of the methods have been successfully used to move cuttings along the seabed, but not to lift the cuttings to the surface. Also there are very few retrieval methods that can be used at depths greater than 100m. The retrieval methods are also sensitive to the presence of debris. If debris is caught in the equipment, the risk of delays and destruction of machinery appears high. Both for this reason and because of the possibility of breakdown under the jacket structure, if it is still in-place, it may well be that retrieval using various forms of ROV may nevertheless become dive intensive. Divers may also be required if the jacket structure is too complicated for the retrieval equipment to gain access to all the pile.

5.8 Emissions to air and discharges to sea

When planning the retrieval of a cuttings pile, it is important to conduct a comprehensive survey of the area surrounding the sub-sea structure of the installation where the greatest collection of discharged cuttings are expected to be found. It is possible that the pile will be anaerobically active (see section 4.1.1). When the pile is disturbed, some of the products from this anaerobic activity may be released, such as hydrogen sulphide, free methane and CO_2. It is expected that some of these gases will rise to the water surface. This is however considered unlikely to be a safety problem (see section 5.7), because of the predicted small quantities that may be released. The carbon dioxide will probably dissolve in the water mass and diffuse away.

Disturbing oil-contaminated cuttings may release free hydrocarbons, the lighter fractions of which will find their way to the surface and form a sheen or discolouring of the seawater. The effects of this activity will probably be minimal and short lived as the hydrocarbons will essentially oxidise rapidly in the water. Some of the hydrocarbons may also find their way to the sediments and thereby result in some contamination the local area around the pile. The disturbance of the pile may also release heavy metals which may be adsorbed by particulate matter. The particulate matter will settle and thereby contaminating the sediment.

CO_2 and NO_x emissions from the operation will mainly come from the surface vessels and equipment like turbines, pumps etc. The larger amounts of CO_2 will probably come from the treatment or transportation phases, and will be discussed in Section 8.

Primary sources of emissions to air will be:

- operation vessel;
- pumps (centrifugal, hydraulic etc.);
- turbines;
- resuspension from the pile (small amounts of methane and hydrogen sulphide).

Primary sources of discharges to sea will be:

- spill from the surface vessel (sewage, drainage water, accidental spills of oil and hydraulic fluids etc.);
- resuspension from the pile (CO_2, hydrocarbons, heavy metals etc.);
- possible leaks of hydraulic fluids;
- debris which is recovered from the pile;
- debris from the vessel.

It is important to establish routines to control and minimise the discharges. An environmental monitoring of the piles and water column for free hydrocarbons, free hydrogen sulphide and free methane is therefore advisable.

It should also be noted that an environmental management system must be established to ensure a minimal negative environmental impact.

5.9 Capital and Operating Costs

Only indicative prices can be included at this time. These have been taken from Brown & Root (1997) and from information provided by several contractors. Costs contained in Brown & Root (1997) are listed in Tables 8 and 9. These figures may be increased two to three times because of unforeseen events and higher diver intensity. The fact that most of these methods have not been tested at sites where the platform is still in place, indicates that the following figures are probably on the conservative side. They have though been used as they are considered more reliable than speculative assessments of a worst case scenario.

Other, confidential sources indicate that a diver dredging system would cost in the region of £70,000 per day assuming that by utilising a 3-man bell, 2 dredging units could be used, requiring a total of twelve divers in saturation. Likewise, a sub-sea, deep-water dredging unit deployed from a DSV and monitored using a work-class ROV would cost approximately £65,000 per day inclusive of all equipment and personnel.

***Table 8**: Cost breakdown for platform based drill cuttings recovery(k£)*

Platform Based	Tracked Vehicle Onboard Pump	ROV Feeding Transfer Pump
Service provided by the Contractor		
ROV and/or crawler	15k	5k
Pump System	N/A	2k
Personnel 7 man team @ £350/day	2.45k	2.45k
Logistics (spread over 100 days)	0.8k	0.5k
Project Management @ £500/day	0.5k	0.5k
Total Contractors Daily Costs	**18.75**	**10.45**
Services Provided by the Operator		
Accommodation @ £100/man/day	1.1k	1.1k
Water (Treatment)	1k	1k
Power (600kw approx) @£1/kw hr	1.44k	1.44k
Fuel (only for compressor-ATM Pump)	N/A	0.5k
Logistics (helicopter + supply boat)	0.8k	0.5k
Project Management @ £1000/day	1k	1k
Total Operators Daily Cost	**5.34k**	**5.54k**
Total Recovery Option Day-rate	**£24.09k**	**£15.99k**

Source: Brown & Root (1997)

***Table 9**: Cost breakdown for vessel-based drill cuttings recovery*

Vessel Based	Tracked Vehicle	ROV Feed Transfer Pump	Full Pipe ROV Pump
Services Provided by the Contractor			
ROV and/or Crawler	20k	5k	4k
Pump System	N/A	2k	4k
Personnel 7 extras @ 350/day	2.45k	2.45k	2.45k
Vessel	30k	30k	40k
Logistics (Helicopter +Supply)	0.8k	0.5k	0.8k
Project Management	0.5k	0.5k	0.5k
Total Contractors Daily Costs	**53.75k**	**40.45k**	**51.75k**
Services Provided by the Operator			
Project Management	1k	1k	1k
Total Operators Daily Costs	**1k**	**1k**	**1k**
Recovery Option Day-rate	**£54.75k**	**£41.45k**	**£51.75k**

Source: Brown & Root (1997)

6 CUTTINGS PILE DISPOSAL BY REINJECTION TECHNIQUES

6.1 Method

The use of current cuttings reinjection techniques is being considered for the disposal of oil-based drill cuttings piles. The successful implementation of this technology can be divided into four operations. The first operation covers the recovery of the pile from the seabed. This is the subject of a separate part (Section 5) of this report. The second operation may require the separation of the cuttings solids from excess sea water that was recovered during the removal from the seabed. This operation could necessitate the treatment and disposal of the sea water in addition to the recovered drill cuttings. The third operation would involve the slurrification of the cuttings solids to a consistency suitable for pumping. This operation could easily utilise some, if not all, of the recovered seawater. The final operation would entail the injection of the cuttings slurry into the annulus between the casing of an existing well and the formation. The latter two of these operations are the primary concern of this evaluation.

For this method to operate most efficiently, the operating platform should be in place. Infrastructure for the short-term storage of retrieved and possibly slurrified cuttings and for reinjection would therefore be available in the close vicinity of the pile. Whilst retrieval of the piles would be more difficult with the platform in place, pre-treatment, storage and reinjection would be made substantially easier to conduct. For this reason it is envisaged that this method will be started some time prior to cessation of operations at the platform. Should the platform have been removed prior to pile retrieval, some form of interim storage of the cuttings, probably on a barge, would be required. This material would then need to be transported to a suitable reinjection well, thus adding to the logistic problems and cost.

6.2 Operations

As a basis for this current evaluation a typical cuttings pile has been assumed to have a volume of 4906 m^3 with a bulk density of 1.54 kg/l. Of a total cuttings mass of 7,570 tonnes around 1683 tonnes would be water while the remaining material would be oil (81 tonnes), cuttings (5225 tonnes) and barite (581 tonnes). The removal of this pile from the sea bed by a suction technique could incorporate anywhere from 30,000 to 70,000 tonnes of additional seawater. With the likelihood of the removal of seabed surface along with the cuttings pile, the mass of material would be even greater.

A typical reinjection slurry of drill cuttings during a drilling operation would contain 70-80% water, 15-25% solids and 5-15% oil. With a range of 70-80 % water, the slurry from the cuttings pile would contain from 20,000 to 30,000 tonnes of sea water for optimum performance. This volume of water would be derived from the sea water recovered with the cuttings pile. Any water in excess of these quantities would require disposal or injection into the disposal well along with cuttings slurry.

During the recovery of oil from a reservoir, the fraction of water produced with the oil can increase with time. This water, which contains a small fraction of oil after separation, can be reinjected into the reservoir. The quantity of produced water has been as much at 160,000 tonnes of water a day that can be reinjected.

The main difference between water reinjection and cuttings injection is that the produced water is reinjected into the reservoir, while the cuttings are injected into fractured formation above the reservoir. Even though the cuttings pile removal and platform decommissioning implies the end of production, an assessment should be made as to the appropriate formation for the injection of the cuttings slurry and any excess water.

The most appropriate location for injection of the cuttings pile would be in a well at a platform site being abandoned. This would eliminate the possibility of transporting the cuttings pile over large distances. However, an abandoned platform that has been in operation long before drill cuttings reinjection has been available would not have the facilities or may not have a well suitable for pumping the slurry into the casing annulus. In such a case the hardware for the slurrification and injection would need to be available at the platform site. This could require a ship or barge mounted unit on-site. The injection well may also need to be modified (if possible) to accept the cuttings slurry. Additionally, the geological formation will need to be thoroughly evaluated for its acceptability to the injection of the quantity of cuttings pile slurry. In any case the removal of the cuttings pile and reinjection may best be done before the removal of the platform for best access to the wells. If the cuttings pile covers part of the platform legs, the removal of this pile may be necessary before removal of the platform. The use of a movable drilling rig that is already fitted with cutting injection equipment may be an alternative that may make platform removal prior to injection an attractive alternative.

Alternatively, the cuttings could be transported to an existing cuttings injection and drilling operation. Such a site would have to handle both the cuttings pile slurry and its own drill cuttings injection operation. The transportation operation would need to handle at least 36,000 tonnes and possible over 76,000 tonnes of cuttings, seabed and sea water (slurry density 1.15 kg/l). As the transfer of this material to an existing platform could best be done by pumping the injectable slurry, the boat or barge would need to be fitted with slurry preparation equipment and storage tanks. Any remaining slurrification operations could be done during the transportation time.

The potentially large volume of cuttings pile slurry may need to be stored, most likely, on the shipping boat or barge. The quantity of this slurry should preclude storage on the platform prior to injection. The transfer of this slurry to the injection facilities would need to be at a rate that would not overload the injection hardware or interfere with ongoing drilling operations. During current drilling operation an injection rate of 1 m^3/min is considered to be easily achievable (McHattie, pers. com.). With around 66,000 m^3 the injection of the cuttings pile slurry at this rate could take 1,100 hours of uninterrupted injection. This is 46 days of continuous injection with no time for equipment failure.

6.3 Technical status

Current technology for slurrification and injection drill cuttings should be useable with little modification for the injection of recovered cuttings piles. Additionally, the technology for recovering the piles from the seabed would also need to be adapted. The slurrification and injection technology used for drilling operations has been reported in the literature as early as

1991 (Malachosky et al., 1991). The hardware and services for this technology is commercially available from several service companies such as; Apollo Services, MSD (Mechanical Slurry Disposal), Procom, and Swaco. The main adaptations of this existing technology would be required for the improvement in the logistics of handling the recovered piles. The approach used for this technology may also need to be adapted to the quantity of materials needing injection and the time-frame required for these operations.

If the slurrification process is required at a site remote from the injection point, i.e. on a shipping boat or barge, this should be achievable with a little engineering. The resultant slurry should not be too different than drilling fluids, so the technology for storage of the fluids on the barge would not be unusual. The pumping of this slurry to the injection hardware onto the platform would also not be unusual.

Currently, MSD has a co-operation with AEA Technology in the UK for the development of cuttings pile removal and injection equipment. This technology is based on a subsurface "caterpillar" which would suck up the cuttings pile and take it to the surface. This system is capable of removing the pile from around platform legs. Once at the surface, the cuttings would be treated with shakers, grinders and injection equipment. These developments are in the prototype stage. This technology is briefly described in an internal AEA Technology brochure (AEA Technology, 1997).

6.4 Process and equipment

The hardware for drill cuttings slurrification and injection is commercially available. Using this equipment in conjunction with other facilities, to handle the cuttings pile once it is at the surface, would be a matter of engineering and construction. This type of slurrification and injection systems have been previously described (Malachosky *et al.*, 1991; Moschovidis *et al.*, 1994; Minton and Secoy, 1993).

In summary, the process and equipment can be described as follows. The recovered cuttings pile and seawater may need to be passed through solids or water separation equipment. This would remove any excess water. This excess water would require additional processing to ensure sufficient purity to enable returning it to the sea. The remaining water and cutting would then be initially stored in a holding tank which contains an agitator to maintain a suspension. This tank, and a second similar tank, make up part of the slurrification unit. The cuttings and seawater would then be passed through the slurrification pump. The slurrification process is accomplished by specially modified centrifugal pumps, or mills, which contain an impeller with a course tungsten carbide grinding surface. This mixing can grind shale cuttings into particles with a size less than 40 mesh (420 μm) (Moschovidis *et al.*, 1994). In either of the tanks the slurry could be treated with additional water or chemicals during the grinding process. From this unit the slurry would be transferred to a storage tank until sufficient material is present to start the injection process. The injection is facilitated through the use of a triplex injection pump at a pressure of up to 250 bars.

The transport of the injection slurry from the surface to the well head will required a high pressure hose. This hose would need to meet the pressure, operational and lifetime requirements. In a deep water environment, this hose becomes a significant part of the technology.

The well itself should have some specific requirements. The well head should have a design that prevents the slurry from being pumped directly against the casing. This is particularly important if the well is not being abandoned immediately after the injection process. In an active well, the slurry is injected through the casing spool wing-valve into the annulus between two casing strings, for example between the 13 3/8 inch and 9 5/8 inch casing. Since the slurry is pumped down the annulus, the smaller casing is not cemented up to the shoe of the larger casing. The slurry fractures and enters the between the larger casing shoe and the top of the cement column.

6.5 Capacity & rates

The limiting factor in the injection of cuttings seems to be the capability of the formation to take in the slurry. The volume, that a particular formation can take, could easily vary with its composition. The actual capacity of a formation to take in slurry would need detailed analysis for each job. Factors to consider would include formation type and the possibility of contaminating the formation for possible future operations.

The 7,570 tonnes cuttings pile evaluated in this case would contain 4,336 tonnes of non-water components. In addition there would be some solids from the sea bed. With the addition of the seabed materials there could easily be 8,000 tonnes of solids and oil to be injected. With the final slurry containing 80 % water, this would result in a minimum of 40,000 tonnes of material to be injected for each cuttings pile. However, with the additional sea water that could be collected with the initial removal of the cuttings from the seabed, the total volume needing injection could reach 66,000 m^3. Over 54,000 m^3 of drill cuttings, liquids and oil have been reported as being injected into a single well over a two year period (Moschovidis *et al.*, 1994).

Rates for drill cuttings injection have been reported to range from 0.6 to 1.75 m^3/min at pressures ranging from 62 to 100 bars (Wilson, *et al.*, 1993). With around 66,000 m^3 the injection of the cuttings pile slurry at these rates could take from 1,830 to 630 h of continuous injection. This is from 76 to 26 days of continuous injection, with no time for hardware failure. This estimate would be for injection into a dedicated well where no other material are being injected and is considerably shorter than the two year period described from practical experience above. It is expected that it is the reinjection operation rather than the retrieval stage that is rate limited. Substantial surface storage facilities may then be required in order to receive the output from the retrieval equipment, so that sub-sea operations can be conducted in the minimum time possible. This is discussed further in the following limitations section.

When injecting the slurry into a well at which ongoing drilling operation are taking place, further complications can occur that affect the injection time and capacity. Under these circumstances, attention needs to be given to the effects that the injection has on future drilling and recovery operations. It could be possible that the formation would not take the entire amount of slurry without hindering these future operations. For injection into a well where drilling is taking place, the injection of the cuttings pile slurry should not interfere with those drilling operations. Normal drilling operation that is using cuttings injection, may not be injecting continuously. The drill cuttings slurry can be stored until there is sufficient quantity to make the injection both economically and technically feasible. A technical problem may be that the slurring needs to be injected at a sufficiently high rate that the solids do not settle in the well annulus. At a slow drilling rate in a small hole, there would not be enough cuttings produced to continuously inject. At such times, injection of the cuttings pile slurry could be conducted in combination with the drill cuttings slurry. With an ongoing drilling operation where drill cuttings are produced, drill cuttings that needed injection could be produced for 20 to 40 % of the time. Under these conditions, the time to inject this cuttings pile slurry could range from as little as 32 days, to as much as 100 days, depending on the volume.

A critical step in the reinjection of cuttings is to conduct a thorough fracture analysis of the formation receiving the slurry. For safety and environmental reasons, the operator must have confidence that the formation will accept the volume of cutting slurry. It is critical that the formation has a cap formation that will prevent the fractures and the slurry from reaching the seabed.

6.6 Limitations

An initial limitation to implementing cuttings injection of the sub-sea cuttings pile would be the unsuccessful recovery of the pile from the seabed to the surface. This process would need to be accomplished with minimal disturbance to the physical environment and spread of drilling fluid chemicals and oils.

As far as the slurrification and injection of the cuttings pile, a limitation that needs to be considered is the capability of the formation to accept the quantity of cuttings and at a rate that makes the process economical. As each formation is unique, an estimate is difficult to make without the specification of a particular defined location. Each formation should be evaluated on an individual basis. As mentioned above, there has a report of just over 54,000 m^3 of material injected into a single well over a two year period (Moschovidis *et al.*, 1994). In addition, computer simulations have been used to evaluate, in one case, the fracture height above the injection point as a function of injection volume (Wilson, *et al*., 1993). This simulation indicated that a volume of 14,300 m^3 of injection volume was needed to fracture a formation without barriers to a height of 762 m above the injection point (the seabed in this case). In the same type of formation with a shallow sand barrier, a volume of 8,270 m^3 was needed to reach the sand barrier 550 m above the injection point. Additional injection up to at total of 14,300 m^3 did not increase the height of the fracture. With the injection of 8,270 m^3 the horizontal fracture distance was 305 m from the injection point. In the absence of a limiting barrier, a deep well may be needed to handle the anticipated volumes without communication to the seabed.

An additional limitation could possibly be the availability of a suitable well location for the injection. If the location is too far from the cuttings pile this technique may be less competitive to other alternatives.

In section 6.5 it was indicated that differences between the reinjection and retrieval rates may limit the overall speed of the operation. Retrieval rates are expected to be considerably greater than injection rates, and so it likely that either some form of surface buffer capacity storage will be required, or the sub-sea retrieval equipment will need to be working on site, either intermittently or more slowly than the fastest rate they are capable of. Expected reinjection down-time would further increase the size of buffer storage required. Operating platforms are highly unlikely to possess sufficient available storage space, so a barge may be required. An alternative to large surface storage facilities is to match the retrieval rate to the reinjection rate. This would though necessitate the presence of the ROV on the pile for a far longer period that it could potentially use to finish the retrieval operation. Costs would increase concomitantly with the increase in the need for sub-sea operations, but only small, possibly platform based, slurry storage facilities would be required. The rate of the retrieval, slurrification and reinjection operation as a whole will then necessarily by limited by the rate of the slowest sub-operation, which in this case is likely to be the reinjection.

6.7 Man-hours

As the slurrification and injection system would be operated in an offshore environment, the manpower required for its operation would be best described in terms of man-days. This equipment would require the presence of a skilled solids control engineer. This engineer would be rotated on a fourteen day on and fourteen day off basis with a second engineer. An engineer would be required during the duration of the operation to fully optimise and maintain the equipment. With the time estimates made above, the engineer would be required for 32 to 100 days depending on the concomitant drilling operations.

6.8 Health & safety

A consideration for personnel health and safety originates from the age of the cuttings piles. As the original oil-based muds were based on diesel for the oil phase, the older piles may contain more aromatic components than the more recent piles made from mineral oil-based fluids. The presence of these aromatic components could affect the environment and the personnel. This would be more important in the initial phase of the recovery of the cutting pile to the surface where localised high levels of cuttings could be present. The dilution of the oil component in the resulting slurry will however decrease the concentration significantly compared with that of the cuttings pile and the original drilling operation. During original drilling operations the oil component could be 60 % of the drilling fluid. In the cuttings pile this can be 2 % while in the slurry it could be as low as 0.2 %

These piles may also contain other chemicals that were later eliminated from drilling fluid compositions. The records from the original drilling operations need to be evaluated so that the composition of the fluid phase of the cuttings piles can be established. Again the slurrying process will dilute these materials.

If chemicals or flocculants are used in processing the cuttings into the slurry, their health and safety properties need to be known. With the handling of these materials in a relatively concentrated form before their addition to the slurry, these could represent a greater potential hazard for individual personnel than the residuals in the cuttings.

6.9 Risks

As the injection of drill cuttings is an already established technology, most of the risks of adapting it to the injection of a cuttings pile are known. The large unknown in the total operation remains the effective recovery of the cuttings pile from the seabed.

The largest risk relating to the slurrification and injection operations is the bridging and blocking of the injection annulus. This blocking occurs when the solids in the slurry do not remain suspended once injection has started. These solids could settle to the bottom of the annulus. When this occurs, the flowing of the slurry and the fracturing of the formation would stop. If the pressure required to regain flow of the slurry exceeds the pump specifications, the well would be lost to further injection.

The settling of the slurry solids can be a result of interrupted pumping once the injection has started. Therefore, it may be important to continue the pumping process once it has commenced. To prevent this settling it would be necessary to slurrify sufficient cuttings to maintain an uninterrupted pumping process. When injecting the large volumes of slurry from the cuttings pile, this requires particular attention and planning. A second cause of solids settling is the preparation of a slurry with insufficient suspension properties. Therefore, it remains important to control the slurring properties.

No matter what the problem during the cuttings injection, even if it is a blocked annulus, the source of the problem can most often be traced to operator error. As the risk of operator error is always present, the best way to reduce this risk is the use of skilled and experienced engineers.

6.10 Consumables

The largest consumable for the slurrification and injection of the cuttings pile should be fuel for energy generation. It is anticipated that other consumables would be chemicals that may be needed to maintain the slurry properties. The desired viscosity properties of the slurry can be optimised through the addition of seawater, dispersant, caustic, polymers and bentonite (Malachosky *et al*., 1993). As this slurry may already have sufficient, and maybe excess, seawater from the cuttings pile recovery process, it may need treating to maintain sufficient viscosity to keep the solids suspended. This may need to be evaluated in the laboratory.

6.11 Marine discharges

The largest source of contamination of the marine environment is probably from the recovery of the cuttings pile from the seabed. This could result from mixing of the pile materials with sea water that is not recovered.

This should be possible to keep to a minimum by the proper design of the surface facilities used for the slurrification and injection and by good operational practices with respect to marine discharges. Spillage on the surface of the facilities can easily be recovered and added to the slurry injected into the well. With this technique even machinery oils and rain water could be recovered and added to the injection slurry. The main discharges to the sea would then be through mechanical failure, or operator error.

6.12 Transport

Where the cuttings pile is to be injected into a well at the platform abandonment site, there would be essentially no transportation of the cuttings. If the injection well is in a location remote from the recovered cuttings pile, the pile materials will need to be transported to the injection site.

In either case, the transportation of fuel and consumables from the onshore base would be required. Additional transportation would involve the rotation of operational engineers every two weeks. Where the injection is done at an active drilling site, the transportation of consumables and personnel would become part of the drilling operations.

6.13 CO_2 NOX

Without conducting a complete energy consumption analysis, it is difficult to give a valid estimate of the emissions of CO_2 and NO_X. In the cuttings piles injection operations these gases would originate from electrical generation and transportation. The electrical generation would be responsible for the operation of the pumps needed in the slurrification, the operation of the pumps for moving the slurry from tank to tank, and the operation of the triplex pump needed to inject the slurry down the well annulus. The transportation would include both the movement of any cuttings from one location to another and for the transport of supplies and personnel from shore to the offshore location. This would include the transport of the fuel to generate the electricity.

With an estimated diesel consumption of 50 L/h for this operation, it is estimated that the slurrification and injection process could require nearly 1.0 tonne of fuel per day. Just for this part of the operation, for a period of 32 - 100 days, would require 32 - 100 tonnes of fuel. It has been reported that consumption of one tonne of diesel at oil and gas installations produces 3.18 tonnes of CO_2 and 0.063 tonnes of NO_X (OLF, 1993). At this rate this operation would produce 102 - 318 tonnes of CO_2 for the removal of one cuttings pile. The production of NO_X would range from 2.0 to 6.3 tonnes.

The total process, including transportation, could consume more oil than would be removed from the cuttings pile (81 tonnes).

6.14 Other wastes

As current cuttings techniques are already used to inject other surface wastes from drilling operation, the other wastes associated with the cuttings pile slurrification and injection process should also be easily injected along with the cuttings pile solids. With the adequate design of surface facilities, even the run-off from rain water and oil waste from the machinery could be handled. When slurry treatment chemicals are used, there may be some packaging wastes if recycling has not been considered.

6.15 Operating cost

The main operating costs of the slurrification and injection equipment would be manpower. At the current time (1997), this manpower costs for one skilled engineer would be at a rate of 4720 NOK per day. The engineer would be rotated every fourteen days throughout the duration of the injection operations. At an anticipated 32 - 100 days for a cuttings pile, the manpower costs would range from NOK 151,000 to NOK 472,000. As the longer estimate is based on concomitant drilling operations at the injection site, some of this cost would be shared by the drilling operations.

Another source of operating costs is directly related to equipment maintenance. With the assumption that these costs could be up to 15 % per year of the capital costs over the long run, the replacement of parts could be as much as NOK 3,000/day. Over the course of the removal of a cuttings pile, the maintenance costs could be from kNOK 96 to 300.

Other operating costs concern normal offshore related expenses. If the injection operations are done in conjunction with ongoing drilling and cuttings injection operations these costs would be shared with those operations.

Exclusive of possible shared operational and transportation costs, the operation of the cuttings slurrification and injections hardware for a cuttings pile removal could range from kNOK 247 to 772.

6.16 Investment cost

The total investment costs for a system for the slurrification and injection of a recovered cuttings pile would ultimately depend on the method selected for having the facilities at the required site. These costs could include the a boat or barge, if needed, on which the equipment and storage tanks are mounted. Alternatively, if this operation could be conducted on the deck of the existing platform before decommissioning, the investment costs would be reduced to merely the modification of existing facilities with the addition of the slurrification and injection pump (an existing mud pump could be used). The costs for the system for recovering the cuttings pile from the seabed would be additional. For a movable unit on a boat or barge, there would also be the cost of the high pressure hose between the injection pump and well head. The operational specifications for such a hose would make this rather expensive. In addition, more than one hose may be needed to meet the requirements for different water depths.

As for the slurrification and injection facilities itself, typical investment costs are shown in Table 10 (Still, pers. com.).

***Table 10**: Typical investment costs for the slurrification and injection facilities*

1.	One unitised cuttings slurrification system consisting of the following equipment			kNOK
	a.	Two	8 m^3 cylindrical process tanks with agitators	
	b.	Four	Centrifugal grinding pumps	
	c.	One	Central control panel	
	d	All	Valves, pipes, cable, etc. integral to the system skid	
			System total	3,068
2.	Additional equipment			
	a.	One	High pressure re-injection pump	4,130
	b.	One	Mixing hopper	48
	c.	One	Cuttings conveyor (20 m)	590
			TOTAL (exclusive of VAT)	7,836

The installation and shipping of this equipment would be additional costs. A system to remove water from the solids (a solids shaker system) would be an option that may be considered. There could be some costs to survey the installation to establish the exact requirements for accomplishing the injection.

7 RESPREADING BY *IN SITU* REDISTRIBUTION OF CUTTINGS PILES

7.1 Method

Oil-based cuttings piles on the seabed can be a source of contamination, releasing oil and other contaminants into the water column. Cuttings in the aerobic surface layer of the pile degrade more quickly than those beneath, and form a weathered crust over the surface of the pile. The presence or absence of oxygen is one of the principal factors influencing the rate at which base oil within cuttings piles biodegrades. The rate of oil loss by biodegradation is difficult to quantify since oil content in the surface layer of a cuttings pile is also affected by oil leaching into the water column, while at the same time being replenished from deeper cuttings.

A report on the degradation of cuttings at Heather alpha (IOE, 1985) found that in the top 2 cm of the pile, oil content decreased on average by 22 % after 2 years. In the underlying anaerobic portion of the cuttings, the rate of degradation may be 1 to 2 orders of magnitude slower. Furthermore, the "crust" which forms over the surface of the cuttings effectively seals the pile and prevents the influx of the metabolites required for anaerobic degradation to proceed. Consequently, anaerobic degradation within the pile soon ceases and the amount of oil loss that can be attributed to this process is probably less than that lost by upward migration to the surface. *In situ* spreading of drill cuttings to disperse material across the seabed and to increase the oxygenated surface area of the cuttings pile has therefore been proposed as a means of increasing the rate of biodegradation.

The supposed advantages of this method should, however, be viewed with caution. Recent studies on the degradation rates of synthetic mud base fluids mixed with marine sediments, have shown that, under conditions similar to those encountered in the marine environment, test sediments (6 cm in depth), except those treated with biocides, became anaerobic within 7 days (Munro *et al*., 1997). This suggests that if the object of spreading cuttings piles is to maintain aerobic conditions, spreading operations would have to be repeated every few days in order to maintain the advantages of aerobic degradation (Johnstone, pers. com.). At each spreading operation, contamination of the water column and seabed would result from the material released from the disturbed cuttings.

Where spreading is considered an option, various suggestions have been offered as to the best way to proceed. Operations could either be carried out following the removal of an offshore structure, or, depending on the type of equipment used during spreading operations, could be conducted during the lifetime of the oil platform, to allow the material to degrade prior to decommissioning. The drill cuttings may simply be spread in a thin layer over the sea bed to increase the oxygenated surface layer, or may be blended into the seabed sediment by ploughing or harrowing which has the added advantage of "diluting" the cuttings. A SOAEFD study (Munro, *et al*., 1997) showed that the rate of degradation is closely linked to the initial concentration of the mud fluids. It has also been suggested that spreading the cuttings in patches might enhance biodegradation by introducing an "edge effect."

A variety of methods could be used to spread the cuttings over the seabed. Some of these methods require an initial step of retrieval of the pile (using various types of pumps or dredges) prior to the redistribution of cuttings over the seabed. Recovery methods are covered in Chapter 5, although a proposal from AEA which includes details of the subsequent means of dispersing the retrieved cuttings over the seabed will be given here (see also Section 5.4 in the context of retrieval and Section 6.3 in the context of reinjection). Methods which do not require an initial cuttings retrieval stage, but act directly on the pile, include various "harrowing" and "jet propulsion techniques." The first method rakes over the cuttings pile to flatten it, and the second employs a propeller suspended from a platform or vessel to disperse the cuttings by means of hydrodynamic excavation.

The only method which has been used with the specific intention of spreading cuttings in an attempt to increase biodegradation is the trawling method used by the Hamilton Oil Company Limited (now BHP) at the Crawford field. Other methods, however, have been used to clean cuttings from the seabed in order to allow access to drilling templates or other structures, and these techniques can also result in a thin, relatively even layer of cuttings spread over the seabed. Conoco recently reviewed the options available for clearing cuttings from the seabed prior to performing this task at the Heidrun Field in the Norwegian sector. The results of this study are mentioned in this report.

7.2 Operations

The operations which might be involved in spreading cuttings depend on the method chosen to perform the task. This section first describes harrowing operations (similar to those used at the Crawford field), and then the technique identified as the most appropriate method for clearing the seabed in the Conoco report: the use of a water propulsion technique. It also includes a description of the methods involved in redistributing cuttings retrieved by pumping or dredging methods.

- Harrowing operations: Following the removal of any oil platform over the cuttings pile, heavy trawl gear would be used to trawl repeatedly across the cuttings pile until no further drag was detected.

- Jet propulsion technique: UEL have suggested the following operations for spreading a cone shaped cuttings pile of radius 25 m, height 7.5 m, volume 4906 m^3: A JetProp 25 with attached sonar graphics equipment would be operated from a DP vessel. The vessel would travel above the cuttings pile in a "square spiral," with adjacent tracks spaced by the diameter of the effective operating footprint of the JetProp (5 m has been found satisfactory in previous cuttings work). Material would be gradually moved outwards from the centre and would eventually be deposited beyond the square defined by the outermost ship's track. It is estimated that approximately five to six passes at gradually lowering altitude would be required to spread the pile fairly evenly over the seabed over an area of 6,400m^2, with an average depth of 0.76 m. This part of the operation would take in the region of three days, including reasonable down-time.

  The square could then be gradually expanded to reduce the depth of cuttings and extend the area of spread. To reach a cuttings depth of 10 cm, the area of spread would need to be increased to 49,060 m^2, i.e. a 221.5 m x 221.5 m square. This would probably require 1 or 2 further passes over the flattened pile, extending the track length to approximately 9,800 m.

This would increase the time required to complete the job by about 7 to 14 days (depending on how many passes were required). In order to save costs, a trawl could be used to perform this final part of the flattening operations.

By using a larger JetProp (e.g. 75 series), the time required to complete operations could be reduced. Above this size, it is not recommended that the equipment is deployed from a vessel. This would restrict its use to cuttings piles covered by a platform. In such cases, however, it is unlikely that the pile could be spread far enough over the seabed to reach the desired depth of material, since the influence of the JetProp would be limited due to its static nature. The cuttings would be deposited in an annular zone around the platform.

- Dredge and spread of drill cuttings. AEA Technology have suggested deploying an electro-hydraulically powered remote controlled seabed crawler dredge to the outer edge of the cuttings pile, either from the production platform, or from a vessel equipped with a crane. The dredging operation would commence from the outer edge of the pile and involve systematic excavation employing a grid type removal programme. The system incorporates a 3 m wide self-feeding suction skimmer fitted with tungsten carbide tipped cutters to disintegrate hardened and grout laden cuttings to an acceptable size for pumping to a distance of over 1 km.

  To ensure that an even dispersal of the drill cuttings is achieved over a designated area, the discharge pipe would be suspended at a height sufficient to provide an elevated discharge, this would guarantee optimum spread to establish a biodegradable status for drill cuttings.

  Control of dispersal would be via a surface support vessel to which would be connected a drag line, in turn attached to the discharge pipe. The pipe would be dragged in an arc amounting to about 220 degrees during dredging operations. The discharge pipe would gradually be shortened to provide an even dispersal of drill cuttings from the maximum determined discharge length to the shortest required length. Tidal flow and currents would assist greatly to disperse drill cuttings particularly if disposal from the discharge pipe is set at a high level.

7.3 Technical status

The current technology for spreading cuttings piles is commercially available and includes both low and high tech alternatives. However, only one of these techniques (trawling) has been tested for the specific purposes proposed here and minor modifications may be necessary in some cases. Low technology alternatives include those options which involve a harrowing technique (tested at the Crawford field), where equipment is towed across the cuttings pile by a surface vessel. High technology alternatives include methods which have routinely been used to remove sediment and cuttings around structural components of offshore oil platforms on the seabed. They could also be employed to spread cuttings more thinly over the seabed.

7.4 Equipment

There is a range of equipment which could be employed for this technique. This includes:

- Harrowing equipment, e.g. anchor plough, drag chain, trawl or rake deployed from a fishing vessel.

- Jet propulsion equipment, e.g. the Jetprop or Hydrodigger.

  This type of equipment consists of a large "propeller" designed to be suspended from a crane or drill string mounted on a surface vessel or platform, and operated either from a stationary position or moved across the seabed close above the sediment. The action of seawater being forced through the propeller blasts away material lying directly beneath, and this is released into the water column before resettling. The equipment has an unlimited operational depth (the Jetprop has been employed at a depth of 1,560 m at a location in the gulf of Mexico). There would be no requirement for an ROV or divers to perform surveys either during or following operations, since the Jetprop is mounted with sonar and a camera.

- Electrical or pneumatic pumps (these will be described elsewhere in the report).

7.5 Capacity & rates

The type of equipment used to spread the pile will determine the rate at which material is dispersed.

- Trawling gear. It is not possible to provide accurate estimates of capacities and rates for trawling methods since the number of passes which would be required to level the pile is unknown. At the Crawford field, operations to level 6 "pancake" shaped piles over an area measuring 500 m x 1000 m took 4 days. Assuming 4 days to spread the reference cuttings pile evenly over a similar area (giving a final depth of less than 1 cm), and no down-time, the rate of spread would be approximately 50 m^3/h.

- Jet propulsion. The most powerful jet propellers (e.g. UEL's Jetprop 250,000) are capable of excavation rates of approximately 5,000 m^3/h for drill cuttings, although the actual rate is dependent on sediment characteristics. The smaller Jetprop 25,000 unit (25,000 m^3/h water pumped through the unit) is capable of moving 500m^3/h and affects an area of seabed between 2 - 20 m diameter depending on the height of the unit above the seabed.

- Dredge and spread. Average dredging rates are estimated at 40 - 45m^3/h. The equipment is capable of much greater rates, but down-time for blockages etc. has been included in this estimate.

7.6 Limitations

Difficulties in controlling the spread of cuttings may mean that it is not always possible to achieve a thin, even layer over the seabed. The final profile of the spread cuttings would depend not only on the equipment used, but also on prevailing currents and the nature of the material in the cuttings pile.

It has been suggested that drill cuttings could be spread prior to the decommissioning of any platform above it, allowing the process of aerobic degradation to begin as soon as possible. This would limit the type of equipment that could be used to perform the spreading operations. No type of trawling or harrowing could be used since the structure would represent an obstacle to the trawl vessel. On the other hand, use of the largest type of Jetprop would require the platform to be in place since the equipment is too heavy to be suspended from a vessel. In such cases, the extent of spread of the cuttings would be restricted since, as the circumference of spread increased, it would eventually fall outside the zone of influence of the propeller.

Operations resuspend cuttings material causing contaminants contained within the "fresh" cuttings at the centre of the pile to be released into the surrounding water column.

Additionally, it is predicted that debris in the piles such as scaffolding poles etc. (see section 1.3), would either foul the trawl gear or may damage other equipment and reduce the efficiency and evenness of the spread layer.

7.7 Man-hours

It is not possible to predict with confidence the number of man-hours necessary to spread the cuttings pile. No end-point in terms of thickness of the pile has been given in the specification, but the assumption is that the greater the spread, the more effective the degradation process.

Harrowing. Where spreading operations have been performed in the past (Crawford Field), trawling operations used to disperse the "pancakes" of drill cuttings continued for 4 days until no further drag was felt.

Jet propulsion.

Dredge and spread: Six pilots/technicians would be engaged throughout the entire 20 to 23 day dredging programme. This period would include onboard assembly, dredging operations, and dismantling.

7.8 Health & safety

Health and safety issues may arise during operations to carry out the spreading of cuttings piles, and also remain an issue once these operations have been completed and the "end point" has been reached. In terms of end point considerations, levelling of the cuttings piles would remove them as a potential hazard to fishing and navigation.

In terms of operational risks, all options which involve bringing the cuttings to the surface introduce the possibility of human contact with contaminated cuttings. In this respect, the spreading option represents the lowest risk of all options other than the leave undisturbed alternative (Chapter 2). Operational risks will be greater if it is necessary to employ divers during any part of the operations (for example to perform pre and post levelling surveys), although this unlikely since an ROV could be used for these purposes. In the event of divers being deployed, any risks should be no greater than for routine production operations.

The use of the JetProp would remove any risk of damage to subsea cables and pipelines since there would be no contact with the seabed.

Trawling is an inherently risky operation as snagging the drag on bottom debris can cause catastrophic instability in the towing vessel which may capsize.

7.9 Risks

At present, there is no evidence that spreading cuttings piles over the seabed leads to a faster recovery in the surrounding environment. The results of the SOAEFD study (Munro, *et al*., 1997), which found that freshly mixed drilling fluids and marine sediments became anaerobic within days, casts some doubt on the likelihood of sustained aerobic degradation in the spread piles. The lack of previous experience in applying this technique contributes to the lack of certainty in the efficiency of this operation and the associated high risk factor. This has been highlighted in both the UKOOA/DTI report (Anderson *et al*., 1997) and a subsequent review of that document (Rullkotter, 1997).

On a world-wide basis, it has only been possible to find only one example where this approach has been adopted (the Crawford field). Operations here were not altogether successful as the trawl tended to ride up over the cuttings pile. Large cuttings piles with a cemented crust may not be amenable to trawling and the uncertainty factor makes it difficult to predict dispersal times. Other techniques that have been suggested have also yet to prove that a thin, even layer of cuttings can be achieved if very tight level tolerances are specified (although the Jetprop spread material at Heidrun to seabed level tolerances of < 0.2 m). As yet, however, no acceptable final thickness of spread has been suggested.

The greatest risk in terms of this option, and the main reason why this approach may not be favoured by the authorities, is associated with the release of contaminants from the cuttings pile to the water column/seabed during spreading operations. These risks are considered further in the section on environmental impacts.

7.10 Consumables

The consumables that have been identified include fuel, electric power, water, communications, medical facilities, food, accommodation, and transport to and from the site.

7.11 Marine discharges

None of the techniques which could be employed to spread the cuttings pile would result in routine marine discharges from equipment. Spreading the cuttings pile *in situ* would, however, involve the resuspension of the material in the pile and as such would reintroduce this source of contamination to the marine environment both in terms of particulates, suspended droplets of oil, and dissolved components leached from the freshly exposed material.

7.12 Transport

There would be no transportation of the cuttings involved in this option other than to spread the material over the seabed using one of the techniques previously mentioned.

Transport of personnel and consumables would be required from an onshore base. This may tie in to normal drilling operations where the pile is dispersed prior to removal of the platform.

7.13 CO_2 NOX

CO_2 and NO_X emissions would originate from the transportation of fuel and consumables to the offshore location, and from the equipment used during operations.

7.14 Other wastes

There may be a necessity to clean oil from the equipment used to spread the pile. No other wastes associated with any of the techniques which could be used for spreading cuttings piles have been identified.

7.15 Operating cost

Operating costs for spreading cuttings across the seabed depend on the method selected, and the thickness and evenness of spread required. Cost estimates for the various techniques suggested are given below, but it has been pointed out (Follum, pers. com.) that where contractors are willing to give an overall estimate for operating costs, they are likely to include contractual clauses to cover themselves in the event of down-time resulting from blocked apparatus, etc. Because of the considerable amount of debris that is often associated with cuttings piles, down-time is likely to be much more significant where pumping equipment is employed to retrieve the cuttings prior to redistribution. In addition, if the thickness of spread is to be specified, it may be necessary to perform a number of surveys during operations before this end-point is reached. The UKOOA/DTI report (Anderson *et al*., 1996) highlighted the difficulty in accurately predicting costs for this option. There may also be requirements for environmental monitoring during operations.

- <u>Trawling operations</u>**:** The number of days required to spread the pile is unknown, although costs would be in the region of NOK 22,000 per day. Assuming 2 days to reduce the pile to a depth of 10 cm, the cost per cubic metre of cuttings would be approximately NOK 8.8.
- <u>Jetprop operations</u>: UEL have provided a cost estimate for using the Jetprop 25 to disperse 4,906 m^3 of cuttings over a seabed area of 6,400 m^2. The total cost of the exercise would amount to approximately NOK 2.2 M or NOK 448.50 per cubic metre of cuttings. To further reduce the depth of the cuttings to approximately 10 cm might entail a further 6 to 8 days work increasing the cost to over NOK1100 per cubic metre of cuttings. This gives a cost estimate which is orders of magnitude greater than the trawling alternative. Depending on the depth of spread required, it might be more cost effective to employ a larger Jetprop unit. Alternatively, a Jetprop could be used during the first part of the spreading operations, after which a trawl of the area could be undertaken to flatten the cuttings still further.
- <u>Dredge and spread</u>: AEA have provided a cost estimate for using a seabed crawler dredge to recover the reference pile and redistribute it over an area approaching 2.5 km^2. The total costs would be in the region of NOK 4.34 - 4.83 M, or NOK 880 - 979 per cubic metre of cuttings.

7.16 Investment cost

In view of the potential risks to the environment, a comprehensive environmental test case might be required at significant cost. There may also be a requirement for R&D costs to develop, test, or refute current assumptions regarding the effectiveness of the operations.

7.17 Environmental impacts

The environmental impacts for this option can be divided into those resulting from the desired end-point, and those which occur during operations. The ultimate purpose of spreading cuttings on the seabed is to increase the surface area:volume ratio of the pile, and hence improve the rate of recovery (in comparison to the leave undisturbed option) by increasing the aerobic biodegradation of hydrocarbons. In this way, the desired endpoint of weathered cuttings is achieved more quickly. In the few cases where this approach has been adopted, data on recovery of sediments and benthic organisms are inconclusive. Seabed surveys carried out immediately after dredging operations at the Crawford field indicated the disturbed nature of the starting conditions, rather than providing information on recovery time scales.

In contrast to the perceived environmental benefits of spreading cuttings piles, during operations to attain this end-point, contaminants would be re-released into the water column to drift in an uncontrolled manner with the current. This resuspension of oily cuttings would effect the water column and the seabed in a similar manner as that during the original discharge of the cuttings. This could result in significant negative impacts on the biological community in the vicinity of the disturbance, with the possibility of toxic effects, organic enrichment, bioaccumulation of heavy metals and hydrocarbons, fish taint, and smothering of benthic organisms as the suspended material resettles. Quantitative data on the release of contaminants during spreading are not available, although calculations based on the amount of "free oil" in a pile suggest that the amount of oil released would be low (Anon, 1996).

Nonetheless, the long term environmental effects of releasing a flush of pollutants into the water column and widening the area of contamination are not yet fully understood and Greenpeace criticised operations to spread the cuttings at the Crawford field on these grounds. Spreading the pile may only be an acceptable solution where the quantity of cutting material is limited and does not present a significant environmental hazard, for example, where water-based muds have been used and the concentration of other contaminants is acceptable. Spreading of such, low risk, piles would though be less likely to be necessary in the first instance.

8 TREATMENT - ONSHORE OR OFFSHORE

8.1 Methods

Several methods are available for the onshore treatment of retrieved oil-based cutting, as summarised in OLF's Scope of Work and in Kjeilen, *et al.* (1996). Each of these techniques will be reviewed, and those with the most potential will be analysed in greater detail.

There are only a few disposal and treatment facilities in Norway today, and the treatment is based on thermal and combustion methods. One of the largest problems faced by these operators is the limited capacity. A new treatment plant for drill cuttings is too expensive, and because of the situation today, when most cuttings are reinjected, it is also an uncertain and variable market.

8.2 Transportation to Shore

Transporting the drill cuttings to shore could be undertaken by filling the hoppers on a cutter suction dredger vessel or similar. Once recovered to surface, the drill cuttings could simply be pumped into these hoppers and transported to shore where they could be pumped into tankers for transport to the disposal/treatment site. The largest of these vessels have hopper capacities in excess of 8,000 m^3.

The removed drill cuttings will have been fluidised to some extent and will have been pumped into a hopper in the form of a slurry. It is likely therefore that some form of separation system will be required. As the hoppers are large, the solid material will, over time, settle out from the water. This water may though contain some oil and will need to be treated in a similar fashion to produced water arising from oil and gas production operations. Skimmers may be employed to remove the top oily layers, while the less contaminated water may be discharged to sea.

An alternative to the above option would be to recover the cuttings to the surface, separate the solids from the liquid and containerise the solid material in drums or skips, while running the liquid through the platforms produced water treatment plant. However the quantities of drill cuttings being recovered would probably rule this out as a practical option.

8.3 Mechanical separation and centrifuge washing

Physical treatments require the segregation of the components contained within the waste stream. This can be achieved by the employment of various processes. Solid-liquid separation can be used to remove solid contaminants, in this case the drill cuttings, from the water. This can be achieved through various techniques such as coagulation and centrifugation, sedimentation and filtration.

The first stage in the treatment of oily cuttings is a solids-control system. High efficiency shale shakers are often used to remove as much of the solids as possible before mechanical attrition can wear the particles down in size. A shale shaker, under favourable conditions, should be capable of removing around 90 % (by weight) of the oily-drill solids.

De-sanders and de-silters are known not to be a good environmental or economic option. The reason for this is mainly the discard, or under-flow, which has a high oil content. To maintain acceptable fluids properties, centrifuges must be used to remove the fine particles that shale shakers are not able to separate. A primary centrifuge is run to recover barite and return it to the active mud system. A secondary centrifuge processes the liquid discarded by the first centrifuge, discarding solid waste and returning the salvaged liquid to the active mud system.

Solids and any associated liquid wastes discarded from the shale shakers, de-sanders, de-silters, mud cleaners and centrifuges may be treated in a number of ways.

- Spray wash system: cuttings from all or part of the solids control equipment are sluiced to a vibrating screen unit. As oversize cuttings travel along the screen, they are first sprayed with wash fluid and are then allowed to drain for the remainder of the screen.
- Immersion wash system: cuttings are sluiced from the solids-control system to an agitated tank containing diesel or aqueous-based wash fluid. The resulting slurry is then pumped over vibrating screens.

There are problems connected with washing disposal of oil-contaminated washing fluids.

8.4 Distillation

Distillation and evaporation can be used to separate the constituents of liquid mixtures. This works by applying heat to the liquid and extracting the components of that liquid as they evaporate at different temperatures. Distillation is a technique often used in the petrochemical industry and for solvent recovery. Evaporation serves to concentrate the non-volatile proportion of the liquid by extracting the more volatile components.

As far as treatment of drill cuttings are concerned, there are two processes of this kind available in the UK:

- Thermo-mechanical conversion and cracking: drill cuttings are subject to distillation/cracking process with water and oil being boiled off.
- Thermal stripping: operates on much the same principle by boiling off oil and water. The process does not however crack the oil, due to the lower temperatures used, and the oil can thus be reused. Unfortunately, the lower temperatures can not distil the older OBM's such as those which may have to be recovered from the seabed.

In Norway there are two facilities that treat drill cuttings by distillation, i.e. Resoil AS at Sotra and Thermtechs at Mongstad (see also Table 11).

The solid materials arising from these processes can be re-used in a variety of applications instead of merely being disposed of at a landfill, as seems to be the current standard practice. For example, Conoco have treated drill cuttings from their Murdoch project using thermal stripping and the solid materials have been used as road fill, in brick making and other construction projects. One problem however, is to lower the oil content in the solid materials to a level below the classification limit of hazardous waste in Norway. No solution has yet been found to this problem in Norway, and the solid materials are therefore considered unsuitable for reuse or recycling.

Problems in connection with distillation and evaporation are heavy metals and chloride slats. Some of the available options offer chloride stripping.

8.5 Stabilisation

Chemical treatment technologies do not necessarily destroy a waste but rather modify the chemical structure of the waste's constituents. These modifications may convert the waste into a useable form, such as a fuel, or render the material less hazardous. Such treatments may result in the total volume of waste increasing, by producing a sludge, but have advantages in that the processes generally produce minimal air emissions and can sometimes be conducted on site, or the equipment necessary can be transported as a mobile system.

Inorganic materials are most amenable to a technique called solidification. Otherwise known as stabilisation, this technique renders the waste less harmful by encapsulating it in a solid mass (such as concrete) which will not easily break down. This minimises the possibility of leaching from landfill sites.

There are a large number of processes which can be used to solidify or stabilise hazardous wastes, although as far as the UK is concerned, only one technique is widely used. A range of either organic polymers or inorganic material additives can be used to form silicate polymers (for example concrete with additives). Such methods, which rely on silicate polymer formation, can involve chemical reactions to improve the structural stability of the mass formed.

Most methods require the mixture of hazardous wastes to be pre-treated (often chemically) to optimise the characteristics of the resulting material. Chemical treatments can be used which do not necessarily alter the hazardous constituents of the waste but rather bind them together. Unfortunately, in practice, instead of rock-hard materials where hazardous wastes are trapped inside an inert block, a poorly controlled semi-sludge can result if the process is inadequately controlled.

Not all wastes can be treated by these processes. Those which cannot include wastes with a high proportion of organics, flammable or explosive compounds, environmentally persistent compounds like pesticides, carcinogenic wastes, organic wastes poisonous at low concentrations, wastes with toxic anions such as borates, those with high sodium chloride (salt) concentrations and wastes which liberate toxic gases on contact with water or alkali. The list contains some of the most difficult wastes for which alternative methods of disposal must be used. Once the waste has been treated, the solid mass is disposed of at a landfill.

The process used by Taylor Industrial Waste services in Aberdeen adds a fly ash mixture to the cuttings waste, which is then left to cure for about two days. The resulting solid material is disposed of at a landfill. The unit can process 2-30 tonne/h. The company are trying to obtain development funding to investigate using the final solid product in civil engineering applications.

8.6 Combustion

Incineration is a relatively inexpensive disposal option and is a good alternative for treating retrieved oily drill cuttings. The technique requires high temperature purpose-built plants, and is used for the disposal of organic waste which is highly toxic, highly flammable and/or resistant to biological breakdown in landfill sites. The process, other than for liquid wastes, normally leaves a solid residue or ash, which is finally disposed of at landfill.

In Norway there is one company, Sløåg Industriservice, that uses combustion for the treatment of oily cuttings. The plant has a capacity of 20,000 m^3/year of (wet) drilling muds and also 30,000 m^3/year of (solid) drill cuttings. As the energy requirements is directly related to water content, costs for incineration of materials such as drill cuttings, with a high water content, will be more expensive than those with a low water content.

Sløåg Industriservice uses a combustion method called the fluidised bed. This method runs at a defined temperature, thereby preventing the production of chloro-organic components as well as the production of toxic barium oxides. In addition, scrubbers and filters have been installed to reduce emissions to air. The plant fulfils the standards set by the EU.

The inorganic product of the combustion process is normally disposed of at a landfill. At Sløåg there is a separate landfill, though the intention is to reuse the remaining products of the treated drilling muds. So far the interest among Norwegian petroleum operators has been limited.

8.7 Biological treatments

Biological treatments (see also Chapter 4) do not generally alter inorganic wastes and so chemical or physical treatments may initially be required to remove them. There are bacterial products available on the market which are capable of treating a wide range of organic wastes, including chlorinated materials. These products are bred from naturally occurring materials which have evolved to tolerate heavy metals and degrade toxic organic compounds.

Other biological techniques include aerated lagoons, anaerobic digestion, stabilisation ponds and composting. They all operate on the principle of microbial breakdown of the waste with specific techniques for particular waste streams. The chief advantage of biological treatment methods is that they are environmentally benign and have little negative impact.

The Soil Recycling Centre (SRC) in Antwerp operates both physical/chemical treatment and bioremediation processes. Bioremediation processes speed up the natural decomposition process by controlling oxygen, temperature, moisture and nutrient parameters within the reactor (see also Section 4.4). The capacity for bioremediation at this plant is approximately 35,000 tonnes/yr.

8.8 Supercritical extraction offshore

8.8.1 Methods

Supercritical fluids can replace most organic solvents by manipulating the pressure and temperature conditions of the gas (fluid). A substance at its critical point has properties intermediate between those of a liquid and gas. It is compressible, has a density of a liquid, but with a gas-like viscosity and diffusivity. The solvent power of a supercritical fluid increases with density which can be changed by manipulated pressure and temperature. The high diffusivity provides rapid mass transfer and yields a fast rate of extraction from porous matrixes.

The use of supercritical extraction techniques to remove and recover oil from cuttings was first proposed in 1981 by Eppig *et al*. (1984) in US-patent 4,434,028. The process was based upon using liquid gas (i.e.CO_2, propane or freon) to extract the oil and to fully (99 %) recycle the gas. This process patent has been assigned to CF Systems (Woburn, Mass. USA). CF Systems also hold proprietary processes for supercritical extraction of hydrocarbon contaminants from contaminated soils and sediments. These processes have been scaled to a capacity of 240 tonnes per day using liquid propane as a solvent. Typical costs range between US$ 100 and $ 400 per tonne, primarily dependent on volume of material to be treated and concentration of the contaminants in the soil.

8.8.2 Process and equipment

8.8.2.1 System components

The following process description has been lifted from CF Systems` qualification brochure and as such, much of the following information should be regarded as proprietary.

This process description covers all systems required to operate the CF Systems' Solvent Extraction Unit. Specific choices of equipment vendors and system mechanical specifications will meet all client requirements.

The CF Systems soil remediation process (Figure 13) comprises the following systems:

- a feed delivery system;
- an extraction system;
- a raffinate removal system;
- a raffinate filtration system;
- a solvent recovery system;
- a vent gas recovery system;
- miscellaneous subsystems such as propane make up, utility supply, etc.;
- control room and MCC.

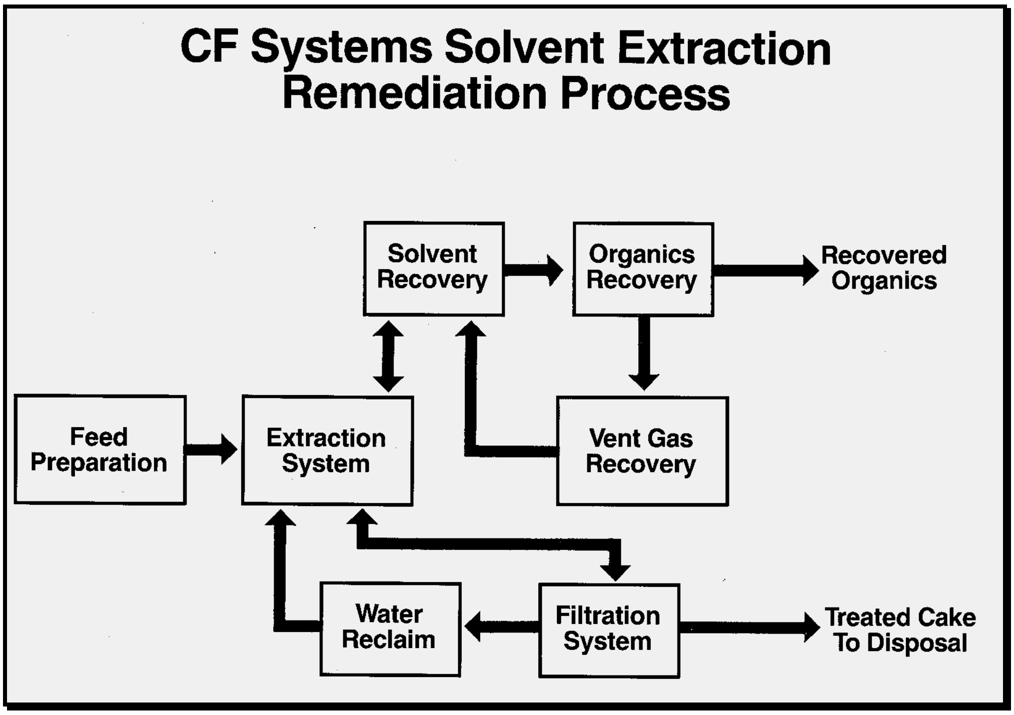


Figure 13*: General flow diagram of CF Systems' solvent extraction process.*

8.8.2.2 Feed Delivery

Feed delivery to the unit, by truck or other means, is screened to remove oversize material. Maximum acceptable particle size is about 1 mm. Oversize material is segregated and in many cases processed to acceptable size. The feed is then sent to the extractor(s) via a conveyor screw auger system.

8.8.2.3 Extraction System

The extraction system comprises a series of extractor stages where feed is extracted using propane solvent. The number of extractor, size of extractors, and power of the agitators in the extractors are all function of feed characteristics and the degree of organics removal required.

Material is fed to the extractors where it is contacted with propane solvent pumped from solvent surge. After extraction, the agitators are stopped, phase separation is allowed to occur, and used propane solvent is discharged to the extract surge. This process is repeated several times until extraction is complete. The final step utilises hot water to displace and evaporate residual propane. The water/solids slurry is then discharged to the filtration system.

8.8.2.4 Filtration System

This system includes the raffinate day tank, filter press, and all required drums and pumps for filter operation. Dewatered solids from the press that meet water content specifications can then go to disposal. Fixation of metals, if required for land disposal, can be conducted in conjunction with filtration.

8.8.2.5 Solvent Recovery System

This system contains an extract surge vessel, main solvent recovery still, propane condenser, propane solvent surge vessel, and main propane solvent recycle pump. Extract flows to the extract surge drum, on demand, and to the main solvent recovery still where the propane is vaporised using steam or other available source of heat.

The main still is refluxed using propane solvent from the discharge of the main solvent recycle pump. Propane vapour from the column is condensed against cooling water and flows to the propane solvent surge drum. The main propane solvent recycle pump takes suction from this drum and pumps propane solvent, on demand, to the extraction system.

From the main still reboiler, oil-rich extract flows to a low pressure still where residual propane solvent is removed from the extracted oil and sent to the vent gas recovery system. Recovered, de-propanised, oil is sent to product oil storage.

8.8.2.6 Vent Gas Recovery System

A low pressure compressor recovers low pressure propane vents from raffinate drums, extract and raffinate product storage, and the low pressure tower. The compressed recovered propane is returned to the main still for recycling. This system is not required if a refinery fuel gas recovery system is available to recover low pressure vents.

8.8.2.7 Utilities

All required utility sub-systems are included, as well as pH adjustment and propane make-up systems. A complete control room and MCC are provided, incorporating a full control system to meet client specifications.

8.8.3 Treatment costs

Typical charges for soil remediation range between $ 100 and $ 400 per tonne, primarily depending on the volume of material to be treated and the concentration of organics in the contaminated soil. Other factors which may affect price include the availability of utilities at the site, target treatment levels, and soil type. Bench scale testing is generally required by CF Systems in order to provide accurate pricing estimates for soil remediation. Pilot scale testing is recommended for firm, fixed-price quotations.

8.8.4 Future development: novel extraction process

One commercial drawback to supercritical fluids is that they require high pressure vessels for extraction in addition to distillation facilities to recover the solutes and to recycle the gas. The size of the extraction vessels are often relatively small since it is a rapid extraction process. The auxiliary equipment and utility requirements, such as facilities for gas storage, logistics, distillation and compressor equipment for gas (solvent) recovery, often though represent the largest part of the investment and operational costs.

Rogaland Research are in the process of filing a patent on a novel supercritical process for extraction of oil from drill-cuttings offshore. The process has been successfully tested in lab-scale, and it has the potential of reducing the investment and operating cost to a fraction of that which was proposed in the CF Systems` process as referenced above.

The novel process is distinct from other extraction processes in that all costs associated with "solvent-recovery" are eliminated. Overall, the new process also offers significant potential savings in logistics, chemicals costs and utility requirement, as compared with not only extraction processes, but also re-injection or on-shore disposal of drill-cuttings.

Since the filing of the patent is pending, the specific principles end elements of the process can be only be revealed to OLF under a specific confidentiality agreement.

8.9 Landfill

Landfill is currently the cheapest and most common waste disposal route, at least as far as the United Kingdom is concerned. There are many licensed sites in the UK capable of handling drill cutting materials.

8.9.1 Site availability

NORSAS are responsible for the tracking and permitting of hazardous waste disposal in Norway. Preliminary information regarding Norwegian waste disposal contractors licensed to accept drill cuttings is listed in Table 11.

***Table 11**: Norwegian disposal contractors for drill cuttings*

CONTRACTOR	LOCATION	MATERIALS ACCEPTED	TREATMENT
Resoil AS	Eide, Sotra	Drilling mud, drill cuttings	Separation of mud/water/oil
Sløvåg Industriservice AS	Dalsøyra	Drilling mud, drill cuttings	Combustion
Thermtechs	Mongstad	Drilling mud, drill cuttings	Separation of mud/water/oil

In other countries, different techniques for disposing of drill cuttings are available. For example, in the United Kingdom the majority of recovered drill cuttings material is disposed of at landfill sites either with or without prior treatment. There are numerous sites in the UK licensed to dispose of drill cuttings, however this option may not reflect the environmental philosophy of an offshore operator. Several waste management contractors operate their own licensed landfill sites:

- Owen Rae
- UK Waste
- Shanks and McEwen

Two distillation sites operate in the UK, Burgess and Garrick's site in Shetland (capacity is currently 1 tonne/hour) and Enaco's site in Great Yarmouth. Taylors Industrial Waste Services in Aberdeen offer solidification treatment in Aberdeen and SRC operate physical/chemical and bioremediation process on their site at Antwerp.

8.9.2 Trans-boundary waste shipment regulations

Under the principles of the "Basel Convention on the Control of the Trans-boundary Movements of Hazardous Wastes and Their Disposal", all wastes will be required to be treated or disposed of at the nearest suitable point to their origin. The import and export of wastes to/from countries of the EU for disposal, will be banned except to countries party to that convention and certain materials. Those on the "Red List" may only be transported with prior written authorisation.

8.9.3 Costs

Table 12 summarises the transportation and disposal costs calculated by Brown & Root (1997).

***Table 12**: Transportation and disposal costs (£1=NOK11)*

Transport: Offshore-Aberdeen-Shetland	
Hire of skip (4 tonne)	£2.35/day (NOK 25.85)
Supply vessel transport to shore	£50/tonne (NOK 550)
Local haulage supply boat-ferry	£10/skip (NOK 110)
Ferry transport (4 skips/trailer)	£847/trailer (NOK 9317)
Cleaning	£50/skip (NOK 550)
Disposal	
Landfill	£25 to 40 +£7 UK landfill tax /tonne (NOK 275 to 440 + 77)
Distillation	£180-200/tonne (NOK 1980 - 2200)
Solidification	£90-120/tonne (NOK 990 - 1320)

9 ENERGY BALANCE

9.1 Introduction

All proposed options for the treatment or disposal of cuttings piles will use energy. Activities such as offshore vessel operations, retrieving the material from the seabed, transporting the material to shore, and treating the material offshore or onshore will contribute directly to the use of energy. Other activities also related to the options include the energy used to produce materials to replace elements left on the seabed (for example oil "lost" as a result of leaving the cuttings pile *in-situ*.) A full assessment of the energy of treatment/retrieval options requires consideration of a wide range of activities. This report only considers significant sources of energy consumption (i.e. those that use more than 1 GJ energy per day).

Energy uses will be determined mainly by:

1. the energy used by vessels during recovery or transport operations;
2. the energy used in treatment operations offshore or onshore;
3. the energy used during surveys of the cuttings pile;
4. the energy used onshore to transport cuttings to final destinations; and
5. the energy used to produce materials to replace elements left on the seabed.

9.2 General Assumptions

All calculations are based on the treatment of a fictitious "reference pile" of known dimensions and weight. In order to further standardise conditions for energy consumption calculations, and make more relevant comparisons between options for cuttings pile treatment, the following assumptions have been made:

1. Assume reference pile is situated 2 days return journey from shore (this would apply to mob/demob operations and unladened vessels).
2. Assume reference pile is situated 3 days return journey from shore (this would apply to operations using ladened vessels).
3. Assume survey of cuttings pile would take 1 day to complete.
4. Assume drilling operations have ceased for all options.
5. Assume 1 day of down time for every 5 days of operations.
6. Once energy consumption is estimated for all retrieval operations, assume worst case scenario and apply greatest energy consumption to any option requiring retrieval.
7. Assume survey work will be required for each option prior to implementation of the operations. This element will not be included in the energy balance calculations as it would not suit comparative purposes.

***Table 13**: Energy use of vessels to be used during treatment/disposal operations*

Type of Vessel	Fuel Consumption (tonnes/day)1	Fuel Energy Rating (GJ/tonne)2	Energy Use (GJ/day)
Survey vessel	15 (during mob and demob)	45.4	681
	15 (during operations)	45.4	681
Trawling vessel	7 (during mob and demob)	45.4	318
	7 (during operations)	45.4	318
80 tonne bollard pull tug	15 (during mob and demob)	45.4	681
Supply vessel (DP equipped)	20 (during mob and demob)	45.4	908
	20 (during operations)	45.4	908
DSV	30 (during mob and demob)	45.4	1,362
	30 (during operations using DP)	45.4	1,362
Small capacity (1,000 tonne) gravel dump vessel	7 (during mob and demob)	45.4	318
	5 (during operations)	45.4	227
Large capacity (8,000 tonne) gravel dump vessel	12 (during mob and demob)	45.4	545
	10 (during operations)	45.4	454

Notes:

1 *Fuel consumption estimates were provided by CORDaH data*

2 *Fuel energy rating provided by J. Side et al, 1997*

The following energy consumption estimates for equipment have been identified by equipment manufacturers or suppliers:

- *The Jetprop 25,000 consumes 3 litres of diesel fuel per minute. This equates to 162 GJ/day of operation*
- *The Clay Cutter consumes 8 litres of diesel fuel per minute. This equates to 432 GJ/day of operation*

- *The Tramrod has a 600 Kwatt energy rating. At operating constraints of 15 hours/day, this would result in a daily energy consumption of 32.4 GJ.*

Energy calculations include energy consumed to produce materials to replace elements left on the seabed. These elements include:

- *oil: 44 GJ/tonne*
- *concrete: 7.3 GJ/tonne*
- *gravel (for gravel dump): 0.12 GJ/tonne*

source: CIRIA, 1995 and T. O'Riordan, 1995

9.3 Energy Calculations

Option 1: Leave undisturbed: 10,378 GJ

- Assume platform absence.
- Assume that a minimum of 2 surveys would be required within 5 years following completion of operations.

***Table 14**: Energy use of leave undisturbed option*

Option 1. Leave undisturbed	Energy (GJ)
1. Performance of 2 post-operations surveys	4,086
2. Energy "lost" in non-recovered oil	6,292
Total	**10,378**

1. Performance of 2 post-operations surveys: 4,086 GJ

- mob and demob survey vessel: (4 days * 681 GJ/day) = 2,724 GJ
- vessel operations to perform surveys: (2 days * 681 GJ/day) = 1,362 GJ
-

2. Energy "lost" in non-recovered oil: 6,292 GJ

- energy value of cuttings pile abandoned *in situ*: (143 tonnes oil * 44 GJ/tonne) = 6,292 GJ

Option 2: Cover the pile: 11,796 to 26,935 GJ

Option 2a: Entombment: 16,020 to 17,901 GJ

- Assume two scenarios for entombment option:
- Scenario 1: 5 m sandy layer over weak clay (enabling all operations to be undertaken by the Jetprop)
- Scenario 2: 5 m sandy layer over strong clay (both the Jetprop and the Clay Cutter will be required for operations)
- Assume equipment required for entombment option will require return transport to site
- Assume platform removed

- Assume that DSV crane fuel consumption will not be a significant contributor to overall fuel consumption for this option and therefore are not calculated
- Assume entombment silo will not be proud of seabed, eliminating need for survey

***Table 15**: Energy use of entombment option - scenario 1*

Option 2a. Entombment	Energy (GJ)
Scenario 1	
1. Excavate silo for disposal of drill cuttings	8,058
2. Relocate cuttings pile in silo	2,789
3. Backfill silo to cover cuttings	762
4. Energy "lost" in non-recovered oil	6,292
Total	**17,901**

Scenario 1. Sandy layer over weak clay 17,901 GJ

1. Excavate silo for disposal of drill cuttings: 8,058 GJ

- mob and demob DSV: (2 days * 1,362 GJ/day) = 2,724 GJ
- vessel operations to remove sandy layer and excavate silo using DSV-deployed Jetprop equipment: (3.5 days * 1,362 GJ/day) = 4,767 GJ
- use of Jetprop 25: (3.5 days * 162 GJ/day) = 567 GJ

2. Relocate cuttings pile in silo: 2,789 GJ

- vessel operations to relocate cuttings using a Tramrod system deployed from DSV: (2 days * 1,362/day) = 2,724 GJ
- use of Tramrod: (2 days * 32.46/day) = 64.8 GJ

3. Back-fill silo to cover cuttings: 762 GJ

- vessel operations to back-fill silo using DSV-deployed Jetprop equipment: (0.5 days * 1,362 GJ/day) = 681 GJ
- use of Jetprop: (0.5 days * 162 GJ/day) = 81 GJ

4. Energy "lost" in non-recovered oil: 6,292 GJ

- energy value of cuttings pile abandoned *in situ*: (143 tonnes oil * 44 GJ/tonne) = 6,292 GJ *Scenario 2. Sandy layer over strong clay: 16,020 GJ*

***Table 16**: Energy use of entombment option - scenario 2*

Option 2a. Entombment	Energy (GJ)
Scenario 2	
1. Excavate silo for disposal of drill cuttings	6,177
2. Relocate cuttings pile in silo	2,789
3. Backfill silo to cover cuttings	762
4. Energy "lost" in non-recovered oil	6,292
Total	**16,020**

1. Excavate silo for disposal of drill cuttings: 6,177 GJ

- mob and demob DSV: (2 days * 1,362 GJ/day) = 2,724 GJ
- vessel operations to remove sandy layer and excavate silo using DSV-deployed Jetprop and Clay Cutter equipment: (2 days * 1,362 GJ/day) = 2,724 GJ
- use of Jetprop: (0.5 days * 162 GJ/day) = 81 GJ
- use of Clay Cutter: (1.5 days * 432 GJ/day) = 648 GJ

2. Relocate cuttings pile in silo: 2,789 GJ

- vessel operations to relocate cuttings using a DSV-deployed Tramrod system: (2 days * 1,362 GJ/day) = 2,724 GJ
- use of Tramrod: (2 days * 32.46/day) = 64.8 GJ

3. Backfill silo to cover cuttings: 3,048 GJ

- vessel operations to backfill silo using DSV-deployed Jetprop equipment: (0.5 days * 1,362 GJ/day) = 681 GJ
- use of Jetprop: (0.5 days * 162 GJ/day) = 81 GJ

4. Energy "lost" in non-recovered oil: 6,292 GJ

- energy value of cuttings pile abandoned *in situ*: (143 tonnes oil * 44 GJ/tonne) = 6,292 GJ

<u>Option 2b: Capping: 26,935 GJ</u>

- Assume number of 4m x 5m concrete mats required to cover the reference cutting pile (surface area: 2,050 m^3) is 103
- Assume a further 32 mats will be required around the pile edge (circumference: 157m)
- Assume placing and anchoring of mats would take 9 days
- Assume no gravel dump is required to secure mats

Table 17: *Energy use of capping option*

Option 2b. Capping	Energy (GJ)
1. Transport concrete mats to cuttings pile using DSV	4,086
2. Place mats over cuttings pile and secure	12,258
3. Performance of 2 post-operations surveys	4,086
4. Energy "lost" in non-recovered oil	6,292
5. Replace "lost" concrete now covering cuttings pile	213
Total	**26,935**

1. Transport concrete mats to cuttings pile using DSV: 4,086 GJ

- mob and demob ladened DSV: (3 days * 1,362 GJ/day) = 4,086 GJ

2. Place mats over cuttings pile and secure: 12,258 GJ

- vessel operations to place mats over cuttings pile and install anchoring systems from DSV: (9 days * 1,362 GJ/day) = 12,258 GJ
-

3. Performance of 2 post-operations surveys: 4,086 GJ

- mob and demob survey vessel: (4 days * 681 GJ/day) = 2,724 GJ
- vessel operations to perform surveys: (2 days * 681 GJ/day) = 1,362 GJ

4. Energy "lost" in non-recovered oil: 6,292 GJ

- energy value of cuttings pile abandoned *in situ*: (143 tonnes oil * 44 GJ/tonne) = 6,292 GJ

5. Replace "lost" concrete now covering cuttings pile: 213 GJ

- manufacture concrete mats from raw feedstock: (163.48 tonnes * 1.3 GJ/tonne) = 212.5 GJ

Option 2c: Gravel Dump Cuttings Pile: 11,796 GJ

Table 18: *Energy use for gravel dump option*

Option 2c. Gravel Dump	Energy (GJ)
1. Offshore transport of gravel to cuttings pile	954
2. Perform gravel dump to cover cuttings pile	341
3. Performance of 2 post-operations surveys	4,086
4. Replace "lost" aggregate lying on seabed in gravel dump	123
5. Energy "lost" in non-recovered oil	6,292
Total	**11,796**

1. Offshore transport of gravel to cuttings pile using gravel dump vessel: 954 GJ

- mob and demob gravel dump vessel: (3 days * 318 GJ/day) = 954 GJ

2. Perform gravel dump to cover cuttings pile: 341 GJ

- vessel operations to gravel dump through use of fall pipe to cover cuttings pile: (1.5 days * 227 GJ/day) = 340.5 GJ

3. Performance of 2 post-operations surveys: 4,086 GJ

- mob and demob survey vessel: (4 days * 681 GJ/day) = 2,724 GJ
- vessel operations to perform surveys: (2 days * 681 GJ/day) = 1,362 GJ

4. Replace "lost" aggregate lying on seabed in gravel dump: 123 GJ

- 1,025 tonnes aggregate * 0.12 GJ/tonne = 123 GJ

5. Energy "lost" in non-recovered oil: 6,292 GJ

- energy value of cuttings pile abandoned *in situ*: (143 tonnes oil * 44 GJ/tonne) = 6,292 GJ

Option 3: Bioremediation: 15,500 GJ

- Assume land farming of recovered material is preferred bioremediation option
- Assume offshore bioreactor is not included in energy calculations as it was identified as too costly and time consuming for a 4,906m^3 reference pile. This option was also lacking information and energy consumption estimates and could not be calculated
- Assume retrieval operations will include use of high suction pump
- Assume land application site is 200 mile return trip from port-of-entry
- Assume transport lorries have 25 tonne load capacity
- Assume land application rate is 80 tonnes/day to spread the cuttings and plough them into the soil
- Assume tractor will consume 104 litres of diesel fuel per day
- Assume drill cuttings have undergone de-watering (additional undefined energy consumption)

Table 19: *Energy use of bioremediation option*

Option 3. Bioremediation (Land Farming)	Energy (GJ)
1. Retrieve cuttings from seabed	7,127
2. Offshore transport of cuttings to shore	1,022
3. Transport cuttings from port-of-entry to land application site	848
4. Spread and plough drill cuttings	211
5. Energy "lost" in non-recovered oil	6,292
Total	**15,500**

1. Retrieve cuttings pile using high suction atmospheric pump: 7,127 GJ

- mob and demob supply vessel: (2 days * 908 GJ/day) = 1,816 GJ
- mob and demob barge using 80 tonne BP tug: (1 day * 681 GJ/day) = 681 GJ
- vessel operations to retrieve cuttings to surface and transfer to barge: (5 days * 908 GJ/day) = 4,540 GJ
- use of pneumatic pump: (20 l/hr * 24 hr/day * 5 days * 0.8461 kg/l * 0.04433 GJ/kg) = 90 GJ
-

2. Transport cuttings to shore: 1,022 GJ

- transport cuttings to shore using 80 tonne BP tug: (1.5 days * 681 GJ/day) = 1,022 GJ
-

3. Transport cuttings from port-of-entry to land application site: 848 GJ

- transport 3,446 tonnes of de-watered cuttings to land application site:(3,446 tonnes ÷ 25 tonnes per load) = 173.4 loads
- transport 174 loads by lorry at 7 mpg to land application site: (174 loads * 200 miles = 34,800 miles ÷ 7 mpg) = 4,971.4 gallons of fuel consumed
- amount of energy in consuming 4,971 gallons of fuel: (4,971 gal * 4.546 litres/gal * 0.8461 kg/litre * 0.04433 GJ/kg) = 847.6 GJ
-

4. Spread and plough drill cuttings: 211 GJ

- days required for operations: (3,446 tonnes ÷ 80 tonnes/day) = 54.2 days
- estimated amount of fuel consumed: (54.2 days * 104 litres/day) = 5,637 litres
- amount of energy in consuming 5,637 litres of fuel: (5,637 litres * 0.8461 kg/litre * 0.04433 GJ/kg) = 211.4 GJ

5. Energy "lost" in non-recovered oil: 6,292 GJ

- energy "lost" in non-recovered oil applied during land-farming operations: (143 tonnes oil * 44 GJ/tonne) = 6,292 GJ

Option 4: Retrieval Technologies: 5,085 to 8,149 GJ

- Assume pre- and post-operative surveys to be performed for all options. This element will not be included in the energy balance calculations as it would not suit comparative purposes
- Assume platform absence
- Assume operations are vessel based

Option 4a: Vessel Based Tracked Vehicle with Pump: 6,340 GJ

- Assume use of Tramrod pumping system
- Assume system will be deployed from a supply vessel through use of an ROV
- Assume pumping capacity of 150 m^3/hr, resulting in pump duration of 33 hours
- Assume Tramrod system operates 12 hours/day

***Table 20**: Energy use of ROV and pump operation*

Option 4a. Vessel Based Tracked Vehicle with Pump	Energy (GJ)
1. Retrieve cuttings pile using tracked vehicle with pump	5,318
2. Transport retrieved cuttings to shore	1,022
Total	**6,340**

1. Retrieve cuttings pile using tracked vehicle with pump: 5,318 GJ

- mob and demob supply vessel: (2 days * 908 GJ/day) = 1,816 GJ
- mob and demob barge using 80 tonne BP tug: (1 day * 681 GJ/day) = 681 GJ
- vessel operations to retrieve cuttings and transfer to barge using supply vessel-deployed Tramrod equipment: (3 days * 908 GJ/day) = 2,724 GJ
- use of Tramrod equipment: (3 days * 32.4 GJ/day) = 97.2 GJ

2. Transport cuttings to shore: 1,022 GJ

- transport cuttings to shore using 80 tonne BP tug: (1.5 days * 681 GJ/day) = 1,021.5 GJ

Option 4b: Pump fed fall pipe from gravel-dump vessel: 5,085 GJ

- Assume use of pneumatic pumping system
- Assume 40 m^3/hr pump capacity

***Table 21:** Energy use of gravel dump option*

Option 4b. Pump fed fall pipe from gravel-dump vessel	Energy (GJ)
1. Retrieve cuttings pile using ROV feeding transfer pump	2,905
2. Transport cuttings to shore	2,180
Total	**5,085**

1. Retrieve cuttings pile from gravel dump vessel fall pipe using ROV feeding transfer pump: 2,905 GJ

- mob and demob large gravel dump vessel: (1 day * 545 GJ/day) = 545 GJ
- vessel operations to retrieve cuttings to surface and transfer to vessel: (5 days * 454 GJ/day) = 2,270 GJ
- use of pneumatic pump: (20 l/hr * 24 hr/day * 5 days * 0.8461 kg/l * 0.04433 GJ/kg) = 90 GJ.

2. Transport cuttings to shore: 2,180 GJ

- vessel operations to transport retrieved cuttings to shore (2 trips) using gravel dump vessel: (4 days * 545 GJ/day) = 2,180 GJ.

Option 4c: Vessel Based High Suction Atmospheric Pump: 8,149 GJ

- Assume pump capacity of 40 m^3/hr

***Table 22**: Energy use of suction pump operation*

Option 4c. Vessel Based High Suction Atmospheric Pump	Energy (GJ)
1. Retrieve cuttings pile using high suction atmospheric pump	7,127
2. Transport cuttings to shore	1,022
Total	**8,149**

1. Retrieve cuttings pile using high suction atmospheric pump: 7,127 GJ.

- mob and demob supply vessel: (2 days * 908 GJ/day) = 1,816 GJ
- mob and demob barge using 80 tonne BP tug: (1 day * 681 GJ/day) = 681 GJ
- vessel operations to retrieve cuttings to surface and transfer to barge: (5 days * 908 GJ/day) = 4,540 GJ
- use of pneumatic pump: (20 l/hr * 24 hr/day * 5 days * 0.8461 kg/l * 0.04433 GJ/kg) = 90 GJ

2. Transport cuttings to shore: 1,022 GJ

- vessel operations to transport cuttings to shore using 80 tonne BP tug: (1.5 days * 681 GJ/day) = 1,021.5 GJ

Option 5: Reinjection of Cuttings: 10,922 GJ

- Assume reinjection location is on-site (i.e. no vessel transport required to transport cuttings)
- Assume overall fuel consumption of pumping equipment during re-injection operations is 100 tonnes
- Assume reinjection equipment is on site and deployed from platform
- Assume platform presence

***Table 23**: Energy use of reinjection option*

Option 5. Reinjection of Cuttings	Energy (GJ)
1. Retrieve cuttings from seabed	90
2. Slurrification and reinjection operations	4,540
3. Energy "lost" in non-recovered oil	6,292
Total	**10,922**

1. Retrieve cuttings pile using high suction atmospheric pump: 90 GJ

- use of pneumatic pump from platform: (20 l/hr * 24 hr/day * 5 days * 0.8461 kg/l * 0.04433 GJ/kg) = 90 GJ

2. Slurrification and reinjection operations: 4,540 GJ

- based on reported total fuel consumption of 100 tonnes of fuel: (100 tonnes * 45.4 GJ/tonne) = 4,540 GJ

3. Energy "lost" in non-recovered oil: 6,292 GJ

- energy "lost" in non-recovered oil in re-injected cuttings: (143 tonnes oil * 44 GJ/tonne) = 6,292 GJ

Option 6: *in situ* redistribution of cuttings pile: 8,200 to 13,906 GJ

- Assume pre- and post-operative surveys to be performed for all options. This element will not be included in the energy balance calculations as it would not suit comparative purposes

Option 6a: Redistribution of cuttings using trawling method: 8,200 GJ

***Table 24**: Energy use of spreading option*

Option 6a. Redistribution of cuttings using trawling method	Energy (GJ)
1. Spread cuttings over seabed using trawler	1,908
2. Energy "lost" in non-recovered oil	6,292
Total	**8,200**

1. Spread cuttings over seabed using trawler: 1,908 GJ

- mob and demob trawler: (2 days * 318 GJ/day) = 636 GJ
- trawl over cuttings to redistribute pile: (4 days * 318 GJ/day) = 1,272 GJ

2. Energy "lost" in non-recovered oil: 6,292 GJ

- energy "lost" in non-recovered oil: (143 tonnes oil * 44 GJ/tonne) = 6,292 GJ

Option 6b: Redistribution of cuttings using Jetprop and Trawler: 13,906 GJ

***Table 25**: Redistribution with jetprop and trawler option*

Option 6b. Redistribution of cuttings using Jetprop and Trawler	Energy (GJ)
1. Redistribute cuttings pile over seabed using jetprop deployed from DSV	7,296
2. Trawl over flattened cuttings pile to further decrease depth of pile	318
3. Energy "lost" in non-recovered oil	6,292
Total	**13,906**

1. Redistribute cuttings pile over seabed using Jetprop deployed from DSV: 7,296 GJ

- mob and demob DSV: (2 days * 1,362 GJ/day) = 2,724 GJ
- vessel operations to spread cuttings over seabed to average depth of 0.76 m using DSV-deployed Jetprop equipment: (3 days * 1,362 GJ/day) = 4,086 GJ
- use of Jetprop: (3 days * 162 GJ/day) = 486 GJ

2. Trawl over flattened cuttings pile to further decrease depth of pile: 318 GJ

- trawl over flattened cuttings pile: (1 day * 318 GJ/day) = 318 GJ

3. Energy "lost" in non-recovered oil: 6,292 GJ

- energy "lost" in non-recovered oil: (143 tonnes oil * 44 GJ/tonne) = 6,292 GJ

Option 7: Treatment or disposal: 12,314 to 18,188 GJ

The following options lacked information and energy consumption estimates could not be made:

- Distillation - thermal conversion and cracking technique
- Supercritical extraction
- Stabilisation/solidification

Based on the available information, the preferred options for treatment and disposal are:

- Distillation - thermal stripping technique
- Combustion (fluidised bed)
- Landfill

Assumptions:

- Assume retrieval operations will include use of high suction pump
- Assume treatment/disposal site is 200 mile return trip from port-of-entry
- Assume transport lorries have 25 tonne load capacity
- Assume drill cuttings have undergone de-watering (additional undefined energy consumption)

Option 7a: Thermal stripping: 18,188 GJ

- Assume recovery of 50% of oil in pile (Cordah data)
- Assume approximately 80% by weight solids recovered from treatment process (Cordah data)
- Assume processed material will be disposed of in landfill site
- Assume landfill site is 20 mile return trip from treatment site
- Assume energy to dispose of cuttings at the landfill site is minor in comparison to retrieval and transport operations and has not been included in the energy calculations

***Table 26**: Energy use of thermal stripping option*

Option 7a. Thermal stripping	Energy (GJ)
1. Retrieve cuttings from seabed	7,127
2. Offshore transport of cuttings to shore	1,022
3. Transport cuttings from port-of-entry to treatment site	848
4. Thermal stripping operations	5,977
5. Transport of recovered solids to landfill site	68
6. Energy "lost" in non-recovered oil (assume 50% recovery of oil)	3,146
Total	**18,188**

1. Retrieve cuttings pile using high suction atmospheric pump: 7,127 GJ

- mob and demob supply vessel: (2 days * 908 GJ/day) = 1,816 GJ
- mob and demob barge using 80 tonne BP tug: (1 day * 681 GJ/day) = 681 GJ
- retrieve cuttings to surface and transfer to barge: (5 days * 908 GJ/day) = 4,540 GJ
- use of pneumatic pump: (20 l/hr * 24 hr/day * 5 days * 0.8461 kg/l * 0.04433 GJ/kg) = 90 GJ

2. Transport cuttings to shore: 1,022 GJ

- transport cuttings to shore using 80 tonne BP tug: (1.5 days * 681 GJ/day) = 1,021.5 GJ

3. Transport cuttings from port-of-entry to treatment site: 848 GJ

- Transport 3,446 tonnes of de-watered cuttings to treatment site:(3,446 tonnes ÷ 25 tonnes per load) = 173.4 loads
- transport 174 loads by lorry at 7 mpg to treatment site: (174 loads * 200 miles = 34,800 miles ÷ 7 mpg) = 4,971.4 gallons of fuel consumed
- amount of energy in consuming 4,971 gallons of fuel: (4,971 gal * 4.546 litres/gal * 0.8461 kg/litre * 0.04433 GJ/kg) = 847.6 GJ

4. Thermal stripping treatment: 5,977 GJ

- fuel consumption to treat 3,446 tonnes cuttings: (4,336 tonnes * 24.6 kg/tonne fuel) = 106,666 kg fuel
- amount of energy in consuming 106,666 kg fuel: (106,666 kg fuel * 0.04433 GJ/kg) = 4728.5 GJ
- energy used by kettle rods located in furnace: (80 kW/tonne * 0.0036 GJ/kW * 4,336 tonnes) = 1,248.8 GJ

5. Transport of treated material to landfill site: 68 GJ

- Transport 3,469 tonnes of treated solids to landfill site:(3,469 tonnes ÷ 25 tonnes per load) = 138.7 loads
- transport 139 loads by lorry at 7 mpg to landfill site: (139 loads * 20 miles = 2,780 miles ÷ 7 mpg) = 397.1 gallons of fuel consumed
- amount of energy in consuming 397 gallons of fuel: (397 gal * 4.546 litres/gal * 0.8461 kg/litre * 0.04433 GJ/kg) = 67.7 GJ

6. Energy "lost" in non-recovered oil: 3,146 GJ

- energy "lost" in non-recovered oil (assume 50% recovery of oil based on Cordah data): (71.5 tonnes oil * 44 GJ/tonne) = 3,146 GJ

Option 7b: Combustion: 12,314 GJ

- Assume that fluidised bed combustion process does not require any fuel for operation, as drill cuttings with an oil content of 5-7% are utilised as the fuel source.
- Assume that the low oil-content cuttings would be mixed with higher oil-content cuttings to obtain the desired 5-7%.
- Assume fluidised bed combustion process is a quayside operation, eliminating the need for onshore transport of cuttings.
- Assume process rate of 4 tonnes/hour.
- Assume some energy recovery from the generation of heat at an output of 545 kWh (2 GJ) for every hour of operation; this is based on information from process operators that have achieved a 6,000 kWh output from the combustion of cuttings containing 22% oil content.
- Assume on-site landfill for solid waste disposal, eliminating the need for onshore transport of solid waste.
- Assume energy required to dispose of cuttings at on-site landfill is minor when compared to operations (i.e. cuttings retrieval) and has not been included in the calculations.

***Table 27**: Energy use of combustion option*

Option 7b. Combustion	Energy (GJ)
1. Retrieve cuttings from seabed	7,127
2. Offshore transport of cuttings to shore	1,022
4. Combustion treatment	-2,127
6. Energy "lost" in non-recovered oil	6,292
Total	**12,314**

1. Retrieve cuttings pile using high suction atmospheric pump: 7,127 GJ

- mob and demob supply vessel: (2 days * 908 GJ/day) = 1,816 GJ
- mob and demob barge using 80 tonne BP tug: (1 day * 681 GJ/day) = 681 GJ
- retrieve cuttings to surface and transfer to barge: (5 days * 908 GJ/day) = 4,540 GJ
- use of pneumatic pump: (20 l/hr * 24 hr/day * 5 days * 0.8461 kg/l * 0.04433 GJ/kg) = 90 GJ

2. Transport cuttings to shore: 1,022 GJ

- transport cuttings to shore using 80 tonne BP tug: (1.5 days * 681 GJ/day) = 1,021.5 GJ

3. Combustion treatment: -2,127 GJ (energy rebate)

- energy generated from the combustion of 4,336 tonnes cuttings: (4,336 tonnes * 1 hr/tonnes * 545 kWh/hr * 0.0036 GJ/kWh) = 2,127 GJ

4. Energy "lost" in non-recovered oil: 6,292 GJ

- energy "lost" in non-recovered: (143 tonnes oil * 44 GJ/tonne) = 6,292 GJ

Option 7d: Landfill 15,289 GJ

- Assume energy to dispose of cuttings on site is minor in comparison to retrieval and transport operations and has not been included in the energy calculations

***Table 28**: Energy use of landfill option*

Option 7d. Landfill	Energy (GJ)
1. Retrieve cuttings from seabed	7,127
2. Offshore transport of cuttings to shore	1,022
3. Transport cuttings from port-of-entry to land application site	848
4. Energy "lost" in non-recovered oil	6,292
Total	**15,289**

1. Retrieve cuttings pile using high suction atmospheric pump: 7,127 GJ

- mob and demob supply vessel: (2 days * 908 GJ/day) = 1,816 GJ
- mob and demob barge using 80 tonne BP tug: (1 day * 681 GJ/day) = 681 GJ
- vessel operations to retrieve cuttings to surface and transfer to barge: (5 days * 908 GJ/day) = 4,540 GJ
- use of pneumatic pump: (20 l/hr * 24 hr/day * 5 days * 0.8461 kg/l * 0.04433 GJ/kg) = 90 GJ

2. Transport cuttings to shore: 1,022 GJ

- vessel operations to transport cuttings to shore using 80 tonne BP tug: (1.5 days * 681 GJ/day) = 1,021.5 GJ

3. Transport cuttings from port-of-entry to landfill site: 848 GJ

- transport 7,570 tonnes of de-watered cuttings to landfill site:(4,336 tonnes ÷ 25 tonnes per load) = 173.4 loads
- transport 174 loads by lorry at 7 mpg to landfill site: (174 loads * 200 miles = 34,800 miles ÷ 7 mpg) = 4,971.4 gallons of fuel consumed
- amount of energy in consuming 4,971 gallons of fuel: (4,971 gal * 4.546 litres/gal * 0.8461 kg/litre * 0.04433 GJ/kg) = 847.6 GJ

4. Energy "lost" in non-recovered oil: 6,292 GJ

- energy "lost" in non-recovered oil in landfill: (143 tonnes oil * 44 GJ/tonne) = 6,292 GJ

9.4 Summary

As identified in Table 29, Option 6 (*in situ* redistribution using the trawling method) has the lowest energy consumption estimate:

Table 29*: Summary of energy consumption estimates*

Treatment/Disposal Option	Energy (GJ)
1. Leave undisturbed	10,378
2. Covering the pile:	
• Entombment	
· *Scenario 1. (Jetprop only)*	17,901
• *Scenario 2. (Jetprop plus Clay Cutter)*	16,020
• Capping	26,935
• Gravel-dumping	11,796
3. Bioremediation: land farming	15,500
4. Retrieval	
• Vessel based tracked vehicle with pump	6,340
• Pump fed fall pipe from gravel dump vessel	5,085
• Vessel based high suction atmospheric pump	8,149
5. Reinjection	10,922
6. *In situ* Redistribution	
• Trawling method	8,200
• Jetprop plus trawler	13,906
7. Treatment onshore or offshore	
• Thermal stripping (distillation)	18,188
• Combustion	12,314
• Landfill	15,289

10 ENVIRONMENTAL IMPACTS

10.1 Introduction and aims

Much information has been published regarding the environmental impacts of oil production in the North Sea in general (e.g. Kingston, 1992; Olsgard and Gray, 1995) and the impacts of drilling fluids and cuttings in particular (e.g. Anderson *et al.*, 1996). Much less quantitative independent information is available concerning the different options available for the handling and treatment of existing piles of oily cuttings (Kjeilen *et al*., 1996). Much of the information available in this latter field is theoretical or of a review nature, because few field studies yielding hard data have been performed.

In chapters 2 - 8 the different operations available for handling the piles have been described and evaluated. In this chapter, the potential positive and negative environmental impacts that may result from each individual operation will be proposed. These different individual *operations* can be linked in different combinations to produce a total handling *option*. For example, reinjection will require the material to have been retrieved from the sea-floor, but the retrieval operation used prior to reinjection could also be used to obtain material for onshore disposal. As the matrix describing the different options (comprised of various combinations of operations) is large, these operations will be treated separately until chapter 12 when they will be combined. The impacts of an operation will not vary with different operations that follow, so this method is a means to decrease complexity and repetition.

Note therefore that impacts in this chapter refer to specific operations and not total options. The latter will be presented in chapter 12.

Having proposed these impacts, a summary of the consequences applicable to the different operations will be presented. Where possible a semi-quantitative assessment of the extent of the consequences will be performed.

10.2 Defining acceptable options

In section 10.3 as many of the potential consequences of drill cuttings handling and treatment as possible have been defined. This must however only be considered as a starting point. Having defined the consequences that attention needs to be paid to, a second stage is to estimate or determine in the field which consequences apply to which handling scenario and to what extent. These can then be compared to predetermined environmental quality objectives, to indicate if the method proposed will adequately meet at least the minimum defined environmental acceptance criteria.

Three quality levels can be envisaged:

1. return the site to the condition it was in prior to the beginning of oil exploration in the North Sea, without discharges from treatment processes at other sites;
2. restore the site to a condition which does not hinder other industries from using the location;

3. restore the site to a condition which does not lead to the long-term harm or detriment of the endemic organisms or humans.

A variety of parameters will influence the quality level that is considered acceptable for that time and location. These will include:

- political pragmatism;
- public opinion;
- technical feasibility;
- financial constraints.

These views or constraints are incorporated into the Best Possible Environmental Option (BPEO) in which practically achievable environmental goals are set within realistic budget constraints.

The return of the sea floor to a virgin condition (quality level 1 above), is not a realistic option within current technical and economic constraints. Cuttings piles may be patchily distributed, spread over a wide distance and/or form a gradual gradient with natural sediments. As such it would not be feasible to locate and remove or alter all material that originated from drilling operations.

Restoration of the site to a condition suitable for other industrial uses (quality level 2) may be considered by some to be a reasonable practical option. The industries most likely to reuse the site after the original platform has been removed will be the petroleum industry itself at a later date, and commercial fishermen. In order for the site to be suitable for fishermen then level 3 will need to be adopted. In view of this and political pressure resulting from public opinion, it would appear that quality level 3 above should be the aim of the BPEO for cuttings pile handling. The environmental implication of the different handling methods described in this report will therefore be judged against these environmental acceptance criteria.

10.3 Potential impacts

The following is a list and short explanation of the potential consequences. It should be noted that not all the handling methods will have all these impacts associated with them. Some of the impacts will refer only to the presence of the piles, irrespective of handling method. Further apportioning of the consequences to the methods will be proposed in the following section.

Contamination - surface sediments

1. Raised levels of hydrocarbons (THC) in the vicinity of the oily piles (Melberg, 1991; Davies and Kingston, 1992; Gray, 1992; Kingston, 1992; Reiersen *et al*., 1988) as a result of leaching or resuspension of material during decommissioning or retrieval.

2. Local organic enrichment as indicated by raised Total Organic Carbon (TOC) levels resulting from raised THC levels around piles (Hannam *et al*., 1987).

3. Anaerobic conditions as a result of microbial (sulphate reducing bacteria) activity using the organic enrichment (Moore *et al.*, 1987; Sanderes and Tibbetts, 1987; Dicks *et al*., 1988; Dow et al., 1990).

4. Raised and variable levels of toxic hydrocarbon components around piles, as opposed to the total hydrocarbon levels irrespective of the toxicity of the fractions.

5. Raised heavy metal content around piles. Primarily barium (Melberg, 1991; Olsgård and Gray, 1995), which is a relatively inert, low toxicity component of the drilling muds (Anderson *et al.*, 1996), but also other more toxic heavy metals such as mercury, zinc (Boothe and Presley, 1988), cadmium, lead and iron (Jørgensen & Mannvik, 1994).

6. Removal of sea floor debris along with cuttings material - a positive impact.

Contamination - water column

7. Raised hydrocarbon concentrations resulting from leaching from the cuttings piles or resuspension as a result of retrieval or decommissioning activity. Very little information available, possibly because of the low concentrations resulting from the high flushing and dilution rates in the North Sea (Kjeilen *et al.*, 1996). Raised levels as a result of the handling or treatment process are covered under discharges.

8. Raised heavy metal concentrations resulting from resuspension. These are commonly adsorbed onto particles which tend to sediment out of the water column. As such they are not present in high concentrations in the water column as such, but tend to be bound to the sediments or the biota.

9. Increased sediment loads as a result of resuspension during decommissioning of the platforms or retrieval of the pile.

Contamination - biota

10. Changes in macro, meio and micro benthic populations:
    - changes in the numbers of individuals and density of populations, i.e. low numbers or complete absence in acutely toxic areas, increased numbers in impoverished area with a highly modified fauna (Reish, 1973);
    - changes in the richness and diversity of species in a population (Shannon and Weiner, 1963; Davies et al., 1988; Gray, 1992)

11. Changes in the microbial populations:
    - greater quantities of oil degrading micro-organisms (Atlas, 1995);
    - raised THC breakdown capacity (Massie et al., 1985);
    - fewer species of out-competed natural endemic micro-organisms (Sanders and Tibbetts, 1987);
    - anaerobic conditions (see 3 above) as a result of microbial activity using up the available dissolved oxygen.

12. Prevention of benthic and nektonic plankton settlement on oil polluted sediments (Anderson, et al., 1996).

13. Raised levels of contaminants in the bottom biota and fish. Levels may be increased by a process of bio-magnification as they are passed up the trophic levels.

14. Taint in fish, though none significant has been found to date.

15. Reduction in the quantity and/or distribution of feed species for commercial fish (Olsgård and Gray, 1995).

Discharges

16. Drainage of materials from storage.

17. Emissions of CO_2 NO_x and SO_x as a result of handling and transport machinery or treatment processes.

18. Discharge of by-products of the treatment process.

19. Discharge of treated cuttings material with residual contamination.

20. Smothering as a result of handling, relocation or discharge from treatment processes, not from the original discharge of cuttings material. This could cause sessile organisms to be completely covered, or may clog the feeding or respiratory apparatus.

Resource use

21. Energy consumption as a result of:
    - transport of cuttings, equipment or expendables;
    - treatment process equipment;
    - retrieval technology.

22. Land fill usage.

23. Water use - potable or sea water.

24. Retrieval of underlying sediments along with the cuttings pile material.

Nuisance

25. Noise by onshore treatment facilities.

26. Increased road transport of material and cuttings.

27. Aesthetic aspects of onshore treatment or disposal.

Other

28. Increased corrosion of jacket structures as a result of contact with decomposing cuttings piles.

29. Hindrance to fishing activities after removal of the associated protecting jacket structure. Of primary importance will be the residual debris in a cuttings pile if it is left *in situ*.

30. Contamination of fishing gear as a result of trawling through a cuttings pile. Though this is considered unlikely, as attempts to redistribute a pile using trawling gear were largely unsuccessful (see Chapter 7).

10.4 Evaluation of impacts

Having defined the potential environmental impacts that could occur, Table 54 (Appendix 2) was used to assist in the qualitative evaluation process. The impacts have been semi-quantitatively graded using a severity index (SI), loosely defined below (Table 30). Adopting a precautionary principle, the most severe grade (highest value) of the criteria categories has been adopted in each case. SI values are necessarily loosely defined because of the broad nature of the different handling options and hence their potential impacts, and because of the lack of quantitative data available for many of the options. This method is designed to at least give a estimate of the impacts that are likely to occur and a general indication of their severity. Hard data, from field trials, will be required to give a more quantitative estimate of impact severity.

***Table 30**: Broad definitions of the criteria used to attribute each severity index score.*

SE index	Concentration	Persistence	Effect on biota	Distribution	Discharges / emissions
2	high	long-term	acute/ highly toxic	wide / global	high volume
1	low	short-term	chronic/measurable effects	local / restricted	low volume
0	negligible / not detectable	not measurable	negligible / not detectable	highly restricted/ not discernible	negligible

Table 54 summarises a general estimate of environmental impacts of the different handling strategies. High values indicate greater impacts. In order to avoid the over-representation of some impacts, and thus to achieve a more balanced assessment, the number of impacts used in the assessment has been reduced to only the main parameters.

Care should be taken in interpreting these data as they are necessarily only semi-quantitative and refer only to the individual operations, not the total options (which comprise several operations). The Table has been used as a tool for summarising the likely impacts. It was used as a basis for the following short evaluation and should not be used as a quantitative estimate on its own. Hence, it has been placed in an appendix because it represents a part of a method of evaluation, not a result in itself.

10.5 Qualified impacts

The following is a summarised description of the possible environmental impacts associated with each cuttings pile operation.

Leave in place - disturbed. As the pile is defined as being damaged, possibly during the jacket removal operation, some contamination or enrichment of the local sediments and bottom living benthos is expected. Less contamination of the water column and biota therein is likely, due to flushing. The pile will remain on the sea floor and as such will, to some extent, represent a hindrance to bottom trawling activity and a risk of bioaccumulation. Overall impact evaluation - medium.

Leave in place - undisturbed. As the pile is defined as being undamaged, impacts, specifically contamination, of the local sediments and biota would be expected to be far less than if it was disturbed. Any contamination or enrichment of sediments will arise as a result of leaching through surface layers, which is considered to be minimal if a surface crust does in fact develop. The pile will remain on the sea floor and as such will, to some extent, represent a hindrance to bottom trawling activity and a risk of bioaccumulation. Overall impact evaluation - low.

Entombment. The acts of digging out disposal channels and transfer of the pile material into the channels is likely to cause significant levels of resuspension. There will be a subsequent risk of contamination or enrichment of local sediments, the water column and fauna in both these zones. There will be a risk of bioaccumulation. Overall impact evaluation - medium.

Capping. As this involves the careful placement of mats that will seal in contaminants, thus reducing leaching from the piles, contamination and enrichment of the ambient environment is expected to be far less than for other sub-sea disposal options. The mats will require transport on land and by sea. Their prolonged presence on the sea floor must constitute a risk of hindering bottom trawling activity, though this should not be great because the matting and final profile will be designed to minimise disturbance. Overall impact evaluation - medium.

Gravel dumping. This involves the placement of gravel material onto the piles, primarily to restrict physical damage, and to a lesser extent to reduce leaching. The particle size of the covering material and the method of placement will greatly influence the damage to the pile and subsequent resuspension of material. The method described in this study combines gravel size particles delivered to the sea-floor by fall-pipe, which is the least damaging combination. Nevertheless some resuspension with contamination or enrichment and some smothering can be envisaged. Both of these will though be highly localised and short-term. Additionally the covering material will need to be quarried, transported and will form a hindrance (though unlikely to snag) to bottom trawling. Adjustment to the pile profile should reduce this latter impact. Overall impact evaluation - medium.

Bioremediation in situ. As this requires the placement of a covering membrane there will be some smothering of the few organisms present on the surface of the pile, during the renovation operation. Any discharges from chemical washing operations will be restricted but may need to be treated as special waste, either offshore or on land. Overall impact evaluation - medium.

Bio-reactor. Impacts of this process alone (i.e. not the operations required to retrieve the material and its final disposal), are restricted to processes discharges that may require further treatment or final disposal. Overall impact evaluation - low.

Land-farming. Requires transport to the spreading site, may be aesthetically poor, releases some air emissions and restricts further land use. Sites, at least in Norway, are limited. Overall impact evaluation - medium.

Mechanical dredging. Substantial amounts of pile material and natural sediments are expected to be resuspended during dredging operations, with subsequent contamination, smothering and enrichment of the sea-floor water column and local biota. Energy usage is expected to be high. Overall impact evaluation - high.

Suction pumping. Whilst the pumping and retrieval equipment will be designed to entrain as much of the solids as possible, it is expected that there will be some losses during the digging, slurrification and suction operation, hence some limited local contamination and enrichment is expected. Loss of natural sediments may also occur. Overall impact evaluation - medium.

Crawler retrieval. As for suction pumping. It is further predicted that resuspension will be greater if the retrieval operation is conducted with the jacket structure in place. Overall impact evaluation - medium.

Reinjection. Few environmental impacts of reinjection as an operation and an end point have been identified. Energy is required for the operation. It is assumed that if a suitable well is chosen, there will be no leakage. Overall impact evaluation - low.

Respreading. It is expected that this operation will cause large quantities of pile material to be resuspended, resulting in contamination or enrichment of ambient sediments, water column and biota. Bottom fauna in the respreading area will also be smothered. Overall impact evaluation - high.

Mechanical separation. This process will consume energy and water. A discharge (possibly toxic) requiring further treatment or disposal will be produced. Overall impact evaluation - low.

Distillation. As per mechanical separation. Overall impact evaluation - low.

Stabilisation. This will also require energy. The stabilised material will be greater in mass than the material to be stabilised. This will require transport to, and disposal in, a land fill. Overall impact evaluation - low.

Combustion. Transport is required to the treatment site. Depending on the characteristics of the piles to be processed, some pre-treatment, such as de-watering, may be required. Assuming the oil content of the cuttings is sufficiently high, externally derived energy for combustion should not be required. The plant conforms to EU standards, so air emissions should be minimal. Some discharges may need to be treated as special waste. Overall impact evaluation - low.

Supercritical extraction. Few environmental impacts of this proposed process have been identified. Both consumables are taken from, and discharges returned to, the produced water. Overall impact evaluation - low.

Landfill. As an end-point, this option represents a significant discharge on land, with associated air emissions. Road transport to the dump site will be required and valuable landfill volume and land surface area will be consumed. Overall impact evaluation - medium.

11 Summation and categorisation

11.1 Clarification

In Chapters 2 - 8 the technical and other information relating to the different handling operations has been compiled. The information was presented in as standard a format as possible to enable evaluations to be made by the reader. Due to the complexity of the data and its multi-disciplinary nature, some variation in style was inevitable. To further aid comparisons and to assist in the drawing of objective conclusions, this chapter will aim to draw comparable information together and, if possible, to categorise the methods within the different parameters examined.

As described in section 10, the handling operations could be divided into 4 main categories:

- ss - sub-sea, those that are conducted without lifting the piles above the water surface;
- r - retrieval, methods purely for retrieving and transporting the cuttings to the surface for further handling;
- t - treatment, on-shore or offshore methods for the treatment of the retrieved cuttings, including transport to land if necessary;
- d - disposal, the final disposal options for either the cuttings or residues from treatment processes.

By adopting this division of operations it should then be possible to evaluate them against each other within a group, e.g. different retrieval technologies. In the following Chapter 12 the most appropriate (based on a range of defined criteria) operation within each group of operations is combined with other types of operation required to comprise a total handling option, e.g. crawler retrieval could be combined with reinjection. It should be stressed then that in this Chapter 11, evaluations are maintained separate, e.g. combustion does not include retrieval or transport.

11.2 Methods

***Table 31**: Summary of methods (categorising not appropriate).*

Type	Technique	Method summary
ss	Leave in place - disturbed	Do nothing. Allow surface layer to encrust, sealing in contamination and allowing natural remediation processes.
ss	Leave in place - undisturbed	As above, but assuming minimal damage to the pile on removal of platform
ss	Entombment	Dig trench in vicinity. Fill with cuttings. Cover with natural sediment. Spread remaining sediment.
ss	Capping	Cover piles in situ with impermeable synthetic membrane / mats. Various mats proposed.
ss	Gravel dumping	Cover piles in situ with gravel.
ss	Bioremediation in situ	Injection of chemical and air/oxygen into diffuser pipes within in situ piles to increase microbial breakdown of contaminants.
t	Bio-reactor	As above, but conducted in a more controlled, intensive reactor offshore.
t	Land farming	Spread on land and use natural soil bacteria to degrade hydrocarbons and partially stabilise heavy metals
r	Mechanical dredging	Retrieval by cutting and digging into the piles followed by transport to the surface.
r	Suction pumping	Break down of pile followed by use of pressure differential to raise loose material to surface.
r	Crawler retrieval	Use of a sub-sea ROV with cutting head to dig into piles and pump material to surface.
d	Reinjection	Slurrification of retrieved cuttings followed by pumping into the annulus between the casing of an existing well into a suitable fractured formation.
ss	Respreading	Spreading out a pile to form a thin layer for improved natural decomposition and to reduce height of pile.
t	Mechanical separation	Separation of solids from water using shakers, de-sanders or centrifuges followed by washing. Solids to disposal, liquids to active mud treatment.
t	Distillation	Heat liquid wastes and separate off evaporated volatile components.
t	Stabilisation	Modification of wastes by binding into a stabile matrix.
t	Combustion	Incineration in high temperature facilities to break down resistant chemicals.
t	Supercritical extraction	Manipulation of temperature and pressure to form a solvent to recover oil from cuttings.
d	Landfill	Final disposal by dumping of treated or untreated wastes in a suitable landfill site.

11.3 Operation and equipment

***Table 32**: Summary of operations (categorising not appropriate).*

Type	Technique	Operation summary
ss	Leave in place - disturbed	Do nothing.
ss	Leave in place - undisturbed	Do nothing.
ss	Entombment	Cut trench with digger or water jets. Dredge up pile and pump into trench. Cover and spread with digger or water jets.
ss	Capping	Divers to locate interlocking mats with help of crane. Anchors to secure. ROV final survey.
ss	Gravel dumping	Dynamically positioned vessel depositing gravel in bulk through hatches or fall pipe.
ss	Bioremediation in situ	Drilling and installation of diffusers. Waste collection system installation with divers/ROV. Chemical and O2 injection. Collection and separation of waste material. Spreading on sea floor.
t	Bio-reactor	After retrieval to barge operated bioreactor. Continuous mixing and reacting in a vessel of wastes, chemicals and nutrients. Treated material ready for disposal.
t	Land farming	Retrieved cutting transported to land and spread on soil. Chemicals, nutrients and pH maintained optimal especially in composting. Treated material ready for disposal.
r	Mechanical dredging	Grab or cutter machinery deployed offshore and sub-sea. Piles cut/dug into and broken down. Loose material transported to surface by pump or grab.
r	Suction pumping	Compressed air driven positive displacement pump used to transport loose cuttings to surface via suction and discharge hoses. Surface and remote video control.
r	Crawler retrieval	Tracked, remote operated dredger with telescopic auger cutting and suction head and centrifugal pump.
d	Reinjection	Slurrification of retrieved cuttings. Injection pumping into existing well. Ship, barge or platform based slurrifier, storage and pumps.
ss	Respreading	Spreading out of piles using harrowing (trawl dragging), water jetting or dredging. Repeated crossings of pile or spiral cutting. Spread to a cuttings depth of 10 cm.
t	Mechanical separation	Spreading of retrieved cuttings on a shaker or sieve to separate 90% of solids. Separated particles spray or immersion washed then drained. Fluid to further treatment or disposal, cleaned solids to disposal or return to sea floor.
t	Distillation	Refinery based cracking or thermal stripping of fluids, e.g. from mechanical separation. Chloride and heavy metal slats to disposal.
t	Stabilisation	Organic polymers or inorganic additives used to form silicate polymers (e.g. with concrete) which stabilise the waste. Then to disposal.
t	Combustion	High temperature onshore or vessel based incinerator. Contaminated ash to disposal.
t	Supercritical extraction	Feed delivery, extraction, filtration, solvent recovery and vent gas recovery systems to separate organic components from retrieved cuttings. Disposal of extract in process stream. Solids to disposal.
d	Landfill	Transport of treated or untreated cuttings by barge to land. Road transport to available suitably licensed landfill site.

11.4 Technical status

***Table 33**: Categorised summary of technical status of the cuttings handling methods*

Type	Technique	Technical status
r	Mechanical dredging	ca
r	Crawler retrieval	ca
ss	Respreading	ca
t	Land farming	ca[1]
d	Landfill	ca
t	Mechanical separation	ca
t	Distillation	ca
t	Combustion	ca
d	Reinjection	ca
ss	Gravel dumping	a[2]
r	Suction pumping	a
t	Bio-reactor	a
t	Stabilisation	a
ss	Capping	a/u
ss	Leave in place - disturbed	u
ss	Leave in place - undisturbed	u
ss	Entombment	u
ss	Bioremediation in situ	n/a
t	Supercritical extraction	n/a

Key: ca = commercially available; a = available but not applied to cuttings handling; u = untested; n = novel technique under development; [1] = not conducted in Norway; [2] = not yet applied to cuttings piles but used on offshore pipelines. Retrieval techniques untested at >100m depth.

11.5 Capacity and rates

***Table 34**: Categorised summary of the process capacity and rates of the cuttings handling methods.*

Type	Technique	Capacity	Rate	Rate: m^3cuttings/h	Approx. predicted h per 4906m^3 ref. pile
ss	Entombment	u	100-500m^3/h-cuttings	300	16 h
r	Mechanical dredging	75-400m^3/h	75-400m^3/h	250	20 h
r	Crawler retrieval	18h/day, 200m depth	150 m^3/h	150	33 h
d	Landfill	Available licensed landfill sites	= retrieval rate	= retrieval rate	=retrieval rate e.g. 33 h
r	Suction pumping	200m depth	85 m^3/h	85	58 h
d	Reinjection	Max to date 54,000m^3	36-105m^3/h	70	70 h
ss	Re-spreading - trawling	4-5 days/pile	50m^3/h	50	98 h
ss	Re-spreading - dredge & spread	Including blockages	40-45 m^3/h	43	114 h
ss	Re-spreading - jet propulsion	5-9 passes/pile	13 d/pile	21	234 h
t	Supercritical extraction	u	240tonnes/day	9	545 h
ss	Capping	Unlimited	43 days/standard pile	6	774 h
t	Combustion	Dependant on water content	20,000 m^3/yr	ca. 3	1600 h
t	Stabilisation	Dependant on cuttings characteristics	2-30 tonnes/h	2	2500 h
t	Bio-reactor	Related to number of reactors	Few 100tonnes/yr	0.04/reactor	Dependant on number of reactors used.
t	Land farming	100ktonnes/yr	100ktonnes/yr	7.4	Dependant on land area available.
ss	Gravel dumping	18ktonnes / vessel	600-1000tonnes/h	u	u
ss	Bioremediation in situ	u	u	u	u
t	Mechanical separation	Dependant on cuttings characteristics	u	u	u
t	Distillation	u	u	u	u
ss	Leave in place - disturbed	Unlimited	na	na	na
ss	Leave in place - undisturbed	Unlimited	na	na	na

Key: na = not applicable; u = unknown/untried. Density = 1540kg/m^3. 18h/working day

11.6 Limitations

Table 35*: Summary of the main technical limitations involved with each method (categorising not appropriate).*

Type	Technique	Limitations
ss	Leave in place - disturbed	Not feasible if large scale demolition required.
ss	Leave in place - undisturbed	Permission may be required from authorities.
ss	Entombment	Trench collapse.
ss	Capping	Diver intervention. Limited working space.
ss	Gravel dumping	Uncertain at depths >300m. Fall-pipe system required.
ss	Bioremediation in situ	No experience. R&D required.
t	Bio-reactor	Capacity constraints.
t	Land farming	Available land area.
r	Mechanical dredging	<300 m depth untested. Difficult with platform present.
r	Suction pumping	<50m. >200m under development and so untested. Difficult with platform present.
r	Crawler retrieval	Weather. Surface operated. Difficult with platform present.
d	Reinjection	Well fracture capacity. Deep well or barrier. Buffer storage capacity.
ss	Respreading	Control of spreading and achievement of thin layer. Difficult with platform present.
t	Mechanical separation	Capacity. Separation efficiency.
t	Distillation	Access to waste treatment facilities.
t	Stabilisation	Volume requiring disposal.
t	Combustion	Process volume.
t	Supercritical extraction	R&D required.
d	Landfill	Limited acceptance capacity.

11.7 Man-hours

***Table 36**: Categorised summary of the man-hours involved with each method.*

Type	Technique	Man-hours / reference pile
ss	Leave in place - disturbed	0
ss	Leave in place - undisturbed	0
d	Reinjection	1200
r	Crawler retrieval	1900
t	Bio-reactor	Dependant on number of reactors used.
t	Land farming	Dependant on technical level.
ss	Entombment	cc
ss	Capping	cc
r	Mechanical dredging	cc
ss	Respreading	cc
ss	Gravel dumping	u
ss	Bioremediation in situ	u
r	Suction pumping	u
t	Mechanical separation	u
t	Distillation	u
t	Stabilisation	u
t	Combustion	u
t	Supercritical extraction	u
d	Landfill	u

Key: u = unknown; cc = commercially confidential.

11.8 Health and Safety and risks

Safety and risks to personnel were assessed according to criteria defined in Anderson *et al*. (1996), i.e.: "where possible, safety risk were identified, although not quantified. Significant factors included the requirement for diver intervention. Options with risks considered significantly greater than routine, ongoing production operations were assigned low scores. In all cases, detailed Safety Assessments will be required."

Safety issues are not considered quantifiable enough to reliably rank.

***Table 37**: Summary of health and safety*

Type	Technique	Operational safety risk
ss	Leave in place - disturbed	Negligible.
ss	Leave in place - undisturbed	Negligible.
ss	Entombment	Medium to high.
ss	Capping	Medium to high if divers required.
ss	Gravel dumping	Medium - comparable with offshore operations.
ss	Bioremediation in situ	u
t	Bio-reactor	Medium - comparable with offshore operations.
t	Land farming	Medium, but many aspects involved.
r	Mechanical dredging	High.
r	Suction pumping	Medium - comparable with offshore operations.
r	Crawler retrieval	Medium - comparable with offshore operations.
d	Reinjection	Medium
ss	Respreading	High especially if divers required.
t	Mechanical separation	Medium - comparable with offshore operations.
t	Distillation	Medium - comparable with offshore operations.
t	Stabilisation	Medium - comparable with offshore operations.
t	Combustion	High as many aspects involved.
t	Supercritical extraction	u
d	Landfill	High as many aspects involved.

11.9 Marine discharges

***Table 38**: Summary of marine discharges arising from the different methods.*

Type	Technique	Marine discharges
ss	Leave in place - disturbed	Leaching rates unknown, but greater if pile disrupted.
ss	Leave in place - undisturbed	Leaching rates unknown.
ss	Entombment	Re-suspension of material on transfer to pits.
ss	Capping	None through cap. Percolation through sediment unknown.
ss	Gravel dumping	Resuspension during operation. A per capping.
ss	Bioremediation in situ	Unknown. Leaching reduced by sealing layer.
t	Bio-reactor	Reclaimed solids to sea floor. Liquid phase contaminants to further treatment or disposal.
t	Land farming	Some leakage of liquid phase from land site possible.
r	Mechanical dredging	Resuspension and increased leaching during operation.
r	Suction pumping	Resuspension and increased leaching during operation.
r	Crawler retrieval	Resuspension and increased leaching during operation.
d	Reinjection	None. Small spillage risk.
ss	Respreading	Resuspension and increased leaching.
t	Mechanical separation	As per bio-reactor.
t	Distillation	Possibly none. Discharge into process stream.
t	Stabilisation	None. Stabilised solids to land-fill.
t	Combustion	None. Ash to land-fill.
t	Supercritical extraction	Possibly none. Discharge into process stream.
d	Landfill	None if licensed site properly sealed.

11.10 Transport

***Table 39**: Categorised summary of cuttings transport required.*

Type	Technique	Cuttings transport
ss	Leave in place - disturbed	None.
ss	Leave in place - undisturbed	None
ss	Bioremediation in situ	None.
ss	Capping	None. Transport of membrane or mats from production site
ss	Gravel dumping	None. Transport of covering material from quarry.
ss	Entombment	Sub-sea. Replacement from pile to pit in vicinity.
ss	Respreading	Sub-sea. Spreading out of pile at existing site.
t	Bio-reactor	Retrieval to offshore surface facility.
d	Reinjection	Retrieval to surface. Preferably local pumping , but possibly vessel transport to remote reinjection well.
r	Mechanical dredging	Retrieval to surface. Only part of total process.
r	Suction pumping	Retrieval to surface. Only part of total process.
r	Crawler retrieval	Retrieval to surface. Only part of total process.
t	Stabilisation	Retrieval to offshore surface facility. Only part of process.
t	Mechanical separation	Retrieval to offshore surface facility. Only part of process.
t	Supercritical extraction	Retrieval to offshore surface facility. Only part of process.
t	Distillation	Retrieval to surface. Vessel transport to land. Road to cracking facility.
t	Land farming	Retrieval to surface. Vessel transport to land. Road to site.
t	Combustion	Retrieval to surface. Vessel to land. Road to incinerator.
d	Landfill	Retrieval to surface. Vessel to land. Road to site.

11.11 Energy

The following Table 40 refers to the energy consumption associated with handling the reference cuttings pile (Table 1). Values have been transferred from Table 29 (Section 9.4).

***Table 40**: Categorised summary of energy usage arising from the different methods*

Type	Technique	Energy (GJ)
ss	Leave in place - disturbed	10,378
ss	Leave in place - undisturbed	10,378
ss	Entombment	16,961 (ave.)
ss	Capping	26,935
ss	Gravel dumping	11,796
ss	Bioremediation in situ	*
t	Bio-reactor	*
t	Land farming	15,500
r	Mechanical dredging	5,085
r	Suction pumping	8,149
r	Crawler retrieval	6,340
d	Reinjection	10,922[a]
ss	Respreading	11,053[b]
t	Mechanical separation	*
t	Distillation	18,188
t	Stabilisation	*
t	Combustion	12,314
t	Supercritical extraction	*
d	Landfill	15,289

* = Energy consumption estimates could not be calculated due to lack of information, though the minimum consumption for retrieval would be ca. 9,000 GJ for offshore treatment and ca. 10,000 GJ for onshore treatment, in addition to the operation.
a = Energy consumption would be greater if transport to another site required.
b = Average of redistribution with trawler (8,200 GJ) and trawler + jet prop (13,906 GJ).

11.12 Costs

Costs have primarily been drawn from calculations in this report and from Brown and Root (1997) and must be considered only representative. Prices vary considerably with conditions and time, so an estimate for a specific project should be obtained direct from the service supplier.

***Table 41**: Summary of costs associated with the different methods (categorising not meaningful).*

Type	Technique	Operational costs (NOK)	Investment costs (NOK)
ss	Leave in place - disturbed	0	0
ss	Leave in place - undisturbed	0	0
ss	Entombment	> 12M/pile	
ss	Capping	ca. 36M/pile	Mat costs
ss	Gravel dumping	Ship-time + gravel material	
ss	Bioremediation in situ	u. Site dependant.	u. Site dependant.
t	Bio-reactor	ca. 3.8M/standard pile	
t	Land farming	u	u
r	Mechanical dredging	cc. Site specific.	cc
r	Suction pumping - platform - vessel	192k/day 497k/day	cc cc
r	Crawler retrieval - platform - vessel	288k/day 657k/day	cc cc
d	Reinjection	247-772k/standard pile	7.8M depending on equipment available
ss	Respreading - trawling - jetting - dredging	43k/standard pile[1] ca. 8.3M/standard pile ca. 7M	-- -- --
t	Mechanical separation	u	u
t	Distillation	17M/standard pile	--
t	Stabilisation	9.5M/standard pile	--
t	Combustion	u	u
t	Supercritical extraction	u	u
d	Landfill	3.6M/standard pile in UK	--

Key: u = unknown; cc = commercially confidential; [1] = assuming the method functions (doubtful). NOK12 = £1. NOK7.05=US$1

11.13 Environmental impacts

***Table 42**: Summary of the impacts associated with the different cuttings handling methods categorised according to an estimate of their overall impact[1].*

Type	Handling method	Summary of possible main impacts[1]	Overall evaluation
ss	Leave in place - undisturbed	Leaching, enrichment, resuspension, hindrance by debris, contamination of fishing gear, bioaccumulation.	low
t	Bio-reactor	Energy use, process discharges.	low
d	Reinjection	Energy use.	low
t	Mechanical separation	Energy & water use, process discharges.	low
t	Distillation	Energy, process discharges.	low
t	Combustion	Energy, discharges, transport, landfill, emissions.	low
t	Supercritical extraction	Energy use.	low
t	Stabilisation	Energy, process discharges, transport, landfill.	low
ss	Leave in place - disturbed	Leaching, enrichment, resuspension, hindrance by debris, contamination of fishing gear, bioaccumulation.	medium
ss	Gravel dumping	Enrichment, resuspension, hindrance, transport of materials.	medium
ss	Entombment	Resuspension, smothering, enrichment.	medium
ss	Capping	Smothering, enrichment.	medium
ss	Bioremediation in situ	Smothering, enrichment, hindrance by debris, population changes.	medium
t	Land farming	Bioaccumulation, energy use, transport, emissions.	medium
r	Suction pumping	Resuspension, energy use, sediment loss.	medium
r	Crawler retrieval	Resuspension, energy use, sediment loss.	medium
d	Landfill	Transport, energy, nuisance, landfill.	medium
r	Mechanical dredging	Resuspension, energy use, sediment loss.	high
ss	Respreading	Leaching, resuspension, energy use, smothering, enrichment, population changes.	high

[1] = Impacts refer to only the specific operation or endpoint indicated, not a complete option, which may comprise several operations and end points. For details on overall evaluation see section 10.4 and Appendix 2.

12 Assessment of the overall advantages and disadvantages of different options.

12.1 Introduction

The previous sections of the report have described, and where possible quantified, the performance of a range of "*operations*" that may be carried out to recover, treat or dispose of drill cuttings, and the "*end-points*", or consequences of such operations. These individual operations and end-points are components of possible decommissioning "*options*", i.e. a complete decommissioning option would consist of one or more related operations, performed in a logical sequence, leading to the achievement of at least one main end-point. This section now draws together the operations and end-points that form possible logical total decommissioning options for drill cuttings piles, and evaluates their overall advantages and disadvantages, in relation to certain stated criteria.

12.2 Possible total decommissioning options for cuttings piles

The operations and end-points examined in this study may be logically combined to form 35 different decommissioning options, as shown in Table 43, that fall into eight "generic" groups. The eight groups are:-

- Leave *in situ*
- Bioremediate *in situ*
- Cover *in situ*
- Spread on sea-floor
- Entomb
- Recover and re-inject
- Recover and treat offshore
- Recover and treat onshore
- Dispose of onshore untreated

Table 43. The 35 possible decommissioning options derived from the combination of operations and endpoints examined in this study.

A3 Excel sheet in here

12.3 Method

Table 43 was examined to determine which operations or end-points distinguished or differentiated the different options within each generic group. The data presented in Chapters 2 to 10 of the study, and summarised in Section 11, were then used to assess the performance of the key operations or end-points, in terms of the criteria of environmental impact, energy use, safety, cost and technical feasibility. The "performance" of the key operations and end-points was examined on the basis of these criteria, both when taken individually and when taken in various combinations.

By examining the key operations and end-points, it was possible, in an ***intra-generic group comparison,*** to identify one specific decommissioning option which was judged to be the "best" or most "attractive" option for its particular generic category.

The performances of these selected options were then assessed in an ***inter-generic group evaluation,*** using the same criteria of environmental impact, energy use, safety, cost and feasibility, both individually and in combination.

The results of these evaluations permit the different options for cuttings piles to be examined with respect to their ability to meet those criteria, such as "clean seabed," "minimum overall environmental impact," or "lowest safety risk," that might be used to make management decisions about cuttings decommissioning.

12.4 Intra-generic group comparisons

12.4.1 Leave in situ

This group has one option, though the condition in which the piles might be left after the completion of decommissioning operations pertaining to the associated platform may vary. Therefore no further assessment of this group is warranted at this stage.

12.4.2 *In situ* bioremediation

There is only one option in this group and so it warrants no further examination at this stage.

12.4.3 Cover

This group has two options, differentiated by the type of operation used to cover or contain the cuttings, and the consequences of the resultant end-point. No further selection is therefore warranted at this stage.

12.4.4 Spread *in situ*

There is only one option in this group and so it warrants no further examination at this stage.

12.4.5 Bury in situ

This group has three options which are differentiated on the basis of the method used to move the cuttings from their original position to the site of burial in the seabed. The key differentiating feature of this group is therefore the operation *retrieval of cuttings*.

12.4.6 Re-inject

This group has three options which are differentiated on the basis of the method used to recover the cuttings from the seabed so that they may be re-injected. The key differentiating feature of this group is therefore the operation *retrieval of cuttings*.

12.4.7 Recover and treat offshore

This group has six options differentiated by the methods *retrieval of cuttings*, and o*nshore treatment.*

12.4.8 Recover and treat onshore

This group has fifteen options, and this results from the permutations of (i) different possible recovery methods, and (ii) different treatment methods onshore. The key differentiating features of this group are therefore the operations *retrieval of cuttings*. and o*nshore treatment*.

12.4.9 Recover and dispose of untreated cuttings onshore

This group has three options, differentiated by the key operation *retrieval of cuttings* and the key end-points *disposal in landfill* and *disposal on landfarm*.

12.5 Assessment of key operations and end-points

12.5.1 Retrieval of cuttings

Three methods were assessed for moving cuttings on the seabed or recovering them to the sea surface. The recovery of cuttings by a crawler with a pump would appear to offer advantages over the other two methods. It has a good environmental performance based on the fact that its pump is said to retain most of the disturbed cuttings and will thus minimise resuspension.. Its use of energy is comparable with the other two systems and it has a low safety risk. It is commercially available. It is therefore concluded that, for the purposes of conducting the inter-generic comparisons, those options that require the sub-sea movement, or retrieval to the water surface of the cuttings, would be evaluated on the basis of the recovery by the sea-floor crawler and pump.

12.5.2 Onshore treatment

Five methods were assessed for treating the cuttings onshore. Distillation may offer advantages over the other options. Environmental impacts and energy use are relatively low, and safety is acceptable. The technique is available and may have been used for cuttings treatment previously. It is one of only two options for which it has been possible to estimate cost data. It is therefore concluded, for the purposes of conducting inter-generic comparisons, those options that require onshore treatment of cuttings will be evaluated on the basis of treatment by distillation.

12.5.3 Covering

Two methods were assessed for covering cuttings piles *in situ*. They had somewhat different operations, and different end-points. The containment of cutting *in situ* by gravel dumping appears, overall a more attractive option than containment by capping. Gravel dumping certainly appears to use much less energy and is a technique that has been applied offshore, though not yet for the covering of piles of drill cuttings. The environmental impacts of gravel dumping are, however, judged to be worse than those of capping, and it has not been possible to calculate a cost for the gravel dumping on a standard pile. Nevertheless, because the performance of gravel dumping and capping does not differ greatly, the former technique appears preferable because of its proven commercial success in covering pipelines

For the purposes of conducting inter-generic comparisons, those options which require the containment of the cuttings pile offshore would be evaluated on the basis of gravel dumping with a fall-pipe.

12.5.4 Offshore treatment

Two methods were assessed for offshore treatment. Both would result in the endpoint of treated cuttings being re-deposited on the seabed, so the key differentiating factor is the operation offshore treatment.

The two techniques suggested for offshore treatment are both apparently available, but have not yet been applied offshore on cuttings piles. It was not possible to obtain data on energy use or safety for either method and no figure could be obtained for the cost of the super-critical treatment. Both treatment processes would appear to perform equally in terms of environmental impacts.

It is therefore concluded that, for the purposes of conducting inter-generic comparisons, those options that require the offshore treatment of cuttings would be evaluated on the basis of treatment by the bioreactor, purely because an estimate of the cost of this treatment was available.

12.5.5 Summary

Table 44 shows the option selected as best performer for its group. These are the options that will now be used to compare the different groups. It should be stressed that the choice of operations comprising the options was based on data presented in this study and was a means of simplifying an otherwise complex matrix of numerous operations and end-points that could comprise an option. Combinations of operations other than those evaluated below may also be suitable for specific decommissioning projects.

Table 44: *The generic decommissioning options studied, and the specific option identified as an overall attractive performer for the purpose of comparing the performance of the different generic options.*

Generic Description	Selected specific option
1. Leave in place	The pile is left in place after some degree of disturbance during removal of the associated jacket structure.
2. Bioremediate *in situ*	The pile is left *in situ* and treated by the bioremediation technique described previously.
3. Cover	The pile is left *in situ* and covered by gravel from a vessel with a fall-pipe system.
4. Spreading	The pile is spread out across the sea-floor by a sea-floor crawler and pump.
5. Entomb	The pile is moved and buried in a pit by the use of a sea-floor crawler and pump.
6. Retrieve and re-inject	The cuttings are slurrified and reinjected from the platform having been retrieved by the use of a sea-floor crawler and pump.
7. Retrieve and treat offshore	The pile are recovered to the platform by the use of a sea-floor crawler and pump and then treated on the platform by the bioreactor.
8. Retrieve and treat onshore	The pile is recovered to the sea surface by use of the sea-floor crawler and pump and treated onshore by the distillation technique.
9. Dispose of onshore untreated	The pile is recovered to the sea surface by use of the sea-floor crawler and pump and disposed of untreated onshore at a land-fill site.

12.6 Discussion of the performances of the different selected options

12.6.1 Introduction

The results of the analysis of the different operations and end-points for the disposal of drill cuttings piles (section 12.5) exhibit different advantages and disadvantages with respect to different parameters such as environmental impacts, energy use, safety, technical status and costs. The apparent overall performance of the generic options will now be briefly discussed. A summary of four selected management requirements that are, or are not, met by the option is also presented in each case.

12.6.2 Discussion of the performance of each option

Option 1: Leave in situ untreated

This option performed relatively poorly in terms of environmental impact, and very poorly in terms of technical status because, as yet, no operator has left a large drill cuttings pile *in situ* after removal of the platform above it. The option has a low use of energy, good safety performance (because of the lack of any operations) and apparently low cost. Leaching rates are unknown, so it remains to be seen whether the piles will become a long-term source of pollution into the surrounding environment and how they may react to periodic disturbance by mobile fishing gear. In addition it is not yet clear to what extent the operator of the site will be required to conduct periodic environmental surveys around the cuttings pile for the duration of its existence. The disturbance of the pile caused by removal of the associated platform is also a source of uncertainty. This option would satisfy the requirements listed in Table 45.

Table 45*: Management requirements satisfied by option 1, leave in situ untreated.*

Management requirements	Satisfied by option
1. acceptable level of environmental impacts	No
2. acceptable level of safety	Yes
3. unobstructed sea-floor	No
4. no ongoing liability	Yes

Option 2: Bioremediate in situ.

This option has a very good environmental performance because it elegantly has the potential to eliminate the hydrocarbon contaminants within the cuttings pile without the need to attempt to remove the cuttings pile from the water. Because of the relatively small number of operations envisaged in this option, it is likely to be relatively safe. It is also likely to use relatively little energy though no data were available to corroborate this. The technique is under development and so has not yet been applied on a large deep-water cuttings pile. It remains to be seen how effective this technique would be, and how much effort and time would actually be required by an operator to ensure that an *in situ* cuttings pile had been bioremediated to an acceptable degree. This option would satisfy the requirements listed in Table 46.

Table 46*: Management requirements satisfied by option 2, bioremediate in situ.*

Management requirements	Satisfied by option
1. acceptable level of environmental impacts	Yes
2. acceptable level of safety	Yes
3. unobstructed sea-floor	No
4. no ongoing liability	No

Option 3: Cover *in situ* by gravel dumping

This option had a moderate to good environmental performance by virtue of the presumed limited disturbance of the cuttings as the covering is put in place, and the localised nature of the impacts. The use of a fall-pipe system and gravel rather than the more commonly envisage rocks should though assist in minimising and resuspension of piles and bottom sediments. The technique remains untested on any pile, but is commonly used to cover offshore pipelines. It is not known if the cover would remain in place over a long period of time, nor to what extent the cover would restrict the leaching of hydrocarbons into the water column, if indeed such a purpose was required. This option would satisfy the requirements listed in Table 47.

***Table 47**: Management requirements satisfied by option 3, cover in situ by gravel dumping.*

Management requirements	Satisfied by option
1. acceptable level of environmental impacts	Yes
2. acceptable level of safety	Yes
3. unobstructed sea-floor	No
4. no ongoing liability	No

Option 4: Spread on sea-floor

This option has a relatively good performance in terms of its energy use and safety, but is relatively costly and a very poor performer in terms of environmental impact. Several attempts, not all successful, have been made to spread drill cuttings from a pile into a thin layer over the sea-floor in order to enhance natural degradation and reduce the height of the pile. Although there is some experience of this technique, and it is in theory commercially available, no-one has yet attempted to spread a very large cuttings pile from a multi-well site. Some experience suggests that this would in fact be extremely difficult to achieve and the exact extent, severity and persistence of the environmental impacts that would be caused by the resuspension of oily cuttings remains to be seen. This option would satisfy the requirements listed in Table 48.

***Table 48**: Management requirements satisfied by option 4, spread on sea-floor.*

Management requirements	Satisfied by option
1. acceptable level of environmental impacts	No
2. acceptable level of safety	Yes
3. unobstructed sea-floor	Yes
4. no ongoing liability	No?

Option 5: Entomb

This option performed reasonably well in terms of environmental impact, safety and energy. It is though expected to be relatively costly and is a technique that has not yet been tested. Although several different types of equipment have, or could, be used to excavate cuttings piles and to excavate large pits or trenches in natural seabed sediment, no programme has yet been undertaken to attempt to move a whole cuttings pile across the seabed to a site for burial. It therefore remains to be seen whether burial, which is technically feasible, can in fact be achieved without causing substantial and unacceptable concurrent contamination of the adjacent water column and seabed. This option would satisfy the requirements listed in Table 49.

Table 49*: Management requirements satisfied by option 5, entomb.*

Management requirements	Satisfied by option
1. acceptable level of environmental impacts	Yes?
2. acceptable level of safety	Yes
3. unobstructed sea-floor	Yes
4. no ongoing liability	No?

Option 6: Retrieve and reinject

This option has a moderate level of environmental impact as a result of the requirement to retrieve the cuttings from the sea-floor and has a net energy consumption which appears to be in the middle of the range that was able to be determined for the nine generic options. In all other respects this option performs well or very well: it is safe, commercially available and affordable. It would therefore appear that reinjection would be an attractive option in those circumstances where the necessary well injection and buffer capacity storage facilities are available and most importantly the rock formation is able to accept sufficient quantities of the reinjected slurry. This option would satisfy the requirements listed in Table 50.

Table 50*: Management requirements satisfied by option 6, retrieve and reinject.*

Management requirements	Satisfied by option
1. acceptable level of environmental impacts	Yes
2. acceptable level of safety	Yes
3. unobstructed sea-floor	Yes
4. no ongoing liability	Yes

Option 7: Retrieve and treat offshore by bioreactor

This option requires the use of a technique that, though developed, has not yet been applied to a cuttings pile offshore, but which has been used for other applications onshore. It has a relatively poor environmental performance and there are no data available regarding its energy consumption. Fairly long-term topside based facilities would be required in the vicinity of the pile. It should be possible to return treated wastes to the sea-floor if legislation permits this. This option would satisfy the requirements listed in Table 51.

Table 51*: Management requirements satisfied by option 7, retrieve and treat offshore by bioreactor.*

Management requirements	Satisfied by option
1. acceptable level of environmental impacts	Yes?
2. acceptable level of safety	Yes
3. unobstructed sea-floor	No
4. no ongoing liability	No

Option 8: Retrieve by crawler and treat onshore by distillation

This option was judged to have a relatively poor environmental performance by virtue of the impacts that could occur in several different environmental parameters in many stages in the operations required to retrieve, ship, land, treat and finally dispose of the cuttings. Despite the fact that it would result in the recovery of a proportion of the oil and the possibility of being able to benefit from the energy value of this oil, the option has a high use of energy. It was judged that this option would be safe and that it would be feasible to apply to drill cuttings, though expensive. This option would satisfy the requirements listed in Table 52.

Table 52*: Management requirements satisfied by option 8, retrieve by crawler and treat onshore by distillation.*

Management requirements	Satisfied by option
1. acceptable level of environmental impacts	No
2. acceptable level of safety	Yes
3. unobstructed sea-floor	Yes
4. no ongoing liability	No

Option 9: Landfill disposal

The most attractive feature of this option is that the technique is commercially available, although doubt exists as to the acceptability of using the scarce resource of fully managed landfill sites for dealing with large volumes of difficult waste from offshore. The cost of this option lies in the middle of the range derived for all the generic options, but in all other measures the option performs poorly or very poorly in comparison with the other methods. This option would satisfy the requirements listed in Table 53.

***Table 53**: Management requirements satisfied by option 9, landfill disposal.*

Management requirements	Satisfied by option
1. acceptable level of environmental impacts	No
2. acceptable level of safety	Yes
3. unobstructed sea-floor	Yes
4. no ongoing liability	No

13 CONCLUSIONS

1. Of the specific cutting pile handling techniques evaluated using environmental impact, energy use, safety, technical status and cost criteria, gravel dumping using a fall-pipe appeared overall to offer the most advantages compared with other covering techniques, a sea-floor crawler the most appropriate retrieval technique, a bioreactor the most appropriate offshore treatment technique and distillation was judged a suitable onshore treatment technique.

2. Using these specific techniques in the evaluation of the different total handling options, retrieval, slurrification and reinjection appeared a promising commercially available technique. Bioremediation *in situ* appeared to offer much potential, but the method is currently not developed. Leaving in place also showed potential, but aspects such as decommissioning damage, hindrance, liability and a lack of field data (primarily on leaching rates) needs to be addressed.

3. Operations involving the sub-sea spreading out or sub-sea transport of the cuttings piles did not appear appropriate for reasons of either technical feasibility (in the case of spreading by trawl gear), or environmental impacts caused by resuspension of material from the disrupted piles.

4. All the handling options had advantages and disadvantages relative to the other options, so a case-by-case assessment of each pile is needed. For this reason, this study has avoided the ranking of operations, or the recommendation of any one specific operation, end-point or generic option. The methods and data presented in this study can be used to assist such assessment studies, as well as to tentatively indicate an overall policy.

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Appendix 1 - ELECTROKINETIC REMEDIATION TECHNOLOGY

The following is a description of a novel technology that the manufacturer claims may be suitable for the treatment of oily drill cuttings. Information was sourced too late for it to be evaluated, but is included here in order for it to be included in this study.

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ELECTRO-KINETIC REMEDIATION TECHNOLOGY

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Background

When an ionic contaminant is introduced into a substrate (soil, mud or sludge), some of the contaminant dissolves in the solution around the substrate particles, while the remainder adsorbs onto the surfaces of the particles. The amount of the contaminant adsorbed to the soil particles is directly dependent on the ion exchange capacity (EC) of the substrate. There is a direct relationship between the EC of the substrate and the equilibrium concentration of contaminant ions in the substrate. The soluble ions are relatively mobile and can be removed by a variety of remediation technologies. Removal of the adsorbed ionic contaminants is significantly more difficult than removal of the mobile ions, and is the principle factor preventing efficient substrate remediation with most remediation technologies.

The overall movement of both contaminants and water through a substrate is regulated by the coupling between the substrate's electrical, chemical, and hydraulic gradients. The two primary mechanisms by which the electro-kinetic transport of contaminants through a substrate takes place are electro-migration and electro-osmosis. In electro-migration, charged particles are transported through the solution surrounding the substrate particles. In contrast, in electro-osmosis water containing the contaminant ions moves relative to the substrate, carrying the contaminants along. Of the two mechanisms, the rate of electro-migration is approximately ten times greater than the rate of electro-osmosis. It is important to note that both phenomena operate simultaneously in electro-kinetic remediation, and both can be used successfully to remove contaminants from a substrate. However, electro-migration is normally used for removal of ionic species (e.g., metals and polar organic compounds), while electro-osmosis is used for removal of non-polar organic contaminants.

Method

Electrokinetic remediation can be applied as either an in situ or a batch process. In either case, the basic method is the same: an electrode array consisting of anodes and cathodes is positioned in the contaminated substrate, and a DC electric field is applied across the electrodes. Under such conditions, ions and water move towards the electrodes. Metal ions (e.g., cadmium, mercury, zinc, copper, and lead), ammonium ions and positively charged, soluble organic compounds move toward the cathode. Anions such as chloride, fluoride, cyanide, nitrate, and negatively charged organics move toward the anode.

The electrodes are not inserted directly into the substrate, but rather are positioned inside permeable casings which are inserted into the substrate. The annulus of each electrode casing is filled with an aqueous electrolyte. The electrolyte solution is circulated through an external processing system. Processing involves purifying the electrolyte by the removal and recovery of the contaminants, followed by return of the processed electrolyte to the electrode casings.

Equipment

The basic equipment required for the application of Batch Electro-kinetic Remediation (BEKR) includes a treatment cell, electrodes, power supply, electrolyte circulation and processing equipment, and a computer controller. A treatment cell may range in volume from 0.5 cubic meters to several hundred cubic meters. The size of the cell is dictated by the quantity of substrate to be remediated and the amount of time available in which to conduct the remediation.

Electrodes may take a variety of forms, ranging from plates to rods to tubes. Choice of electrode geometry again depends on the substrate quantity and amount of time available. The capacities of the power supply and the electrolyte circulation and processing equipment are determined by the number and size of electrodes required to perform the remediation. The computer control system is a general purpose process control system which has been developed to automatically monitor and control all aspects of the BEKR treatment process. In addition to the basic equipment, certain ancillary equipment such as dredges, conveyor systems, etc., may be required for handling the substrate. The nature of this ancillary equipment is determined by the contaminant(s), the substrate, and the site characteristics.

In situ applications of electro-kinetic technology use the same components, with the exception of the cell. The only changes made involve the method in which the components are packaged. For example, in situ applications use rod or tube electrodes rather than plate units.

Both electrode operating parameters (voltage and amperage) and the chemical composition of the electrolyte solutions can be tailored to the specific characteristics of the substrate. The pattern of electrodes (i.e., spacing and orientation) can also be changed to optimise contaminant removal for specific substrates.

Costs and Process Rates

Electro-kinetic remediation costs depend mainly on substrate-specific characteristics such as the identity and concentration of the contaminant(s) and the ion exchange capacity of the substrate. Highly polluted substrates with a high ion exchange capacity require a large amount of energy, thus increasing remediation costs. Since there are practical limits to the electric current which can be passed through a substrate, the duration of the remediation effort is determined by how much time is needed to pass the required amount of electrical energy through the substrate at the current limit to achieve the desired amount of contaminant removal.

Depending on specific substrate characteristics, the maximum cost for electro-kinetic removal of metal contaminants can be as high as $100 to $200 (US) per cubic meter, with the minimum cost as low as $20-$30 (US) per cubic meter.

For BEKR applications using high density electrode arrays, remediation process rates can be as low as 24 hours to achieve 99 % contaminant removal. For *in situ* applications, which typically use low density electrode arrays, remediation process rates are usually on the order of 1-4 months to achieve 95-99% reduction in contaminant concentration.

Discharge of Pollutants

Unlike most remediation technologies, electro-kinetic remediation is a proportional process. That is, the substrate continues to be cleaned of contaminants as long as electric power is applied to the electrodes. When the desired reduction in contaminant concentration is achieved, the power can be turned off and the substrate can be removed for reuse or safe disposal as non-hazardous material.

By using closed-loop electrolyte circulation and processing systems, the contaminants can be removed and recovered from the electrolyte. This feature even makes it possible to recycle the contaminants in some cases. It also means that there are no contaminants in the processed effluent produced by the technology. The only potential pollution produced by the technology comes in the form of gases or vapours which may be released during the remediation process. In many cases, these gases are non-polluting, or can be captured by currently available air purification technology.

Appendix 2: Environmental impacts severity estimates

The following table was used as a tool to semi-quantitatively estimate and summarise the likely environmental impacts of the different operations. An evaluation of the impacts is presented in section 10.4. Impact scores refer to the individual operations and not to a total option (that would include several operations). Care should then be taken not to compare operations from different phases in an option, e.g. retrieval by suction with combustion. Also, landfill, for example, does not include the operation to retrieve the material from the sea-floor, which is evaluated separately under various retrieval technologies.

***Table 54**: A semi-quantitative severity estimate of selected screened environmental impacts associated with each cuttings pile handling option (see section 10.3 for a definition of each impact type). Scores refer to individual operations, not total options.*

Technique	Contamination - surface sediments		Contamination - water column			Contamination - biota			Discharges		Resource use	Nuisance		Overall impact evaluation
	THC	Metals	THC	Metals	Solids	Benthos	Plankton	Fish	to land	to air	Land	Aesthetics & road	Hindrance	
Leave in place - disturbed	2	2	1	1	1	2	1	1	0	0	0	0	2	medium
Leave in place - undisturbed	1	1	0	0	0	1	0	0	0	0	0	0	2	low
Entombment	1	1	2	2	2	2	1	1	0	1	0	0	0	medium
Capping	1	1	1	0	1	0	0	0	0	1	0	1	1	medium
Gravel dumping	1	1	1	1	0	1	1	0	0	1	1	1	2	medium
Bioremediation in situ	1	1	1	0	0	1	0	0	2	1	0	0	2	medium
Bio-reactor	0	0	0	0	0	0	0	0	0	1	0	1	0	low
Land farming	0	0	0	0	0	0	0	0	2	2	2	2	2	medium
Mechanical dredging	2	1	2	2	2	2	1	1	0	1	0	0	1	high
Suction pumping	1	1	1	1	1	1	0	0	0	1	0	0	1	medium
Crawler retrieval	1	1	1	1	1	1	0	0	0	1	0	0	1	medium
Reinjection	0	0	0	0	0	0	0	0	0	1	0	0	0	low
Respreading	2	2	2	2	2	2	2	2	0	2	0	0	1	high
Mechanical separation	0	0	0	0	0	0	0	0	0	1	1	1	0	low
Distillation	0	0	0	0	0	0	0	0	0	1	1	1	0	low
Stabilisation	0	0	0	0	0	0	0	0	0	1	2	2	0	low
Combustion	0	0	0	0	0	0	0	0	0	2	1	1	0	low
Supercritical extraction	0	0	0	0	0	0	0	0	0	1	0	0	0	low
Landfill	0	0	0	0	0	0	0	0	2	1	2	2	2	medium