EVALUATION OF OFFSHORE DRILLING CUTTINGS MANAGEMENT TECHNOLOGIES USING MULTICRITERIA DECISION-MAKING

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By

©Worakanok Thanyamanta, B. Eng.

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ABSTRACT

This thesis presents an evaluation of drilling cuttings management technologies. A deterministic multicriteria decision-making approach was applied to help assess eight drilling cuttings management alternatives based on twenty five criteria. The eight evaluated technologies included a vertical centrifuge, horizontal centrifuge, thermal desorption, incineration, grinding, stabilization/sodification, bioreactor, and re-injection. The criteria included one threshold criterion of conformity with regulations and four categories of decision-making criteria: technical feasibility, rig compatibility, environmental impacts, and costs. The alternatives evaluated include existing technologies that are currently used offshore and those used onshore but with potential for offshore applications. The criteria were assigned weights corresponding to their importance. The total weights for each of the major aspects, technical, environmental, and cost, were approximately equal. The eight options were scored under each corresponding criterion according to the technologies' information obtained from various sources such as journal papers, personal communication with industry personnel, and questionnaires. To score the options, quantitative and qualitative scoring schemes were used. Quantitative data were normalized and, where quantitative data were not available, subjective rankings were used to qualitatively measure the option. The overall values of each option were then calculated using the Additive Value Model. Uncertainty analysis was also conducted to reflect uncertainty associated with the final results.

From the evaluation, the three optimum drilling cuttings management technologies are the vertical centrifuge, horizontal centrifuge, and re-injection. In the present study, the fourth-ranked bioreactor technology is considered the most promising onshore technology for offshore applications. However, due to lack of availability of data for bioreactor, this option is associated with larger uncertainties compared with the three optimum options. Sensitivity analysis, where weight distribution of criteria was varied, was also conducted. The three optimum options remained as the best scored options regardless of the changes in criteria weights. In addition, the dominating criteria in this evaluation were determined to be costs, energy consumption, treatment capacity, treatment efficiency, size, and weight. These are considered the most influential properties in selecting a management technology to be used offshore. The least significant criteria included the associated solid wastes, ease of repair and maintenance, impacts on other operations, and chemical requirement of the technology. Further, this study also reviewed some innovative technologies including microemulsion, supercritical extraction, and silica microencapsulation in terms of their general process, status of development, and potential for offshore applications.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND PROBLEM

In offshore operations, wastes generated in drilling activities have major environmental impacts. Due to their volume and toxicity, drilling fluids and drilling cuttings are considered the major drilling wastes that can pose environmental impacts. The level of physical and chemical impacts from drilling cuttings discharges on the marine environment depend on the types of drilling cuttings and the properties of drilling fluids retained on the drilling cuttings.

The main effects of drilling cuttings discharges include benthic smothering, sediment alteration, toxic threats, bioaccumulation and anoxic conditions in the sediment. Oil-based drilling fluids (OBFs) cause the most adverse effects on the environment. Therefore, management of drilling cuttings contaminated with these types of fluids is strictly controlled by regulations. Discharges into the ocean of oil-based cuttings are prohibited and, in most locations, the cuttings must be shipped to shore for treatment and disposal or re-injected onsite. In order to reduce environmental impacts and to comply with stringent discharge limits, synthetic-based fluids (SBFs) were developed to have drilling properties comparable to OBFs but lower toxicity and faster rates of biodegradation. However, some synthetic fluid systems are not significantly better than OBFs in terms of environmental impacts (UKOOA, 2001). Therefore, treatment and disposal requirements for these types of fluids depend on types of base fluids and vary from place to place. Synthetic-based cuttings may either be allowed to be discharged after sufficient treatment or instead must be disposed of in an alternate manner.

Generally, management technologies for the drilling cuttings wastes differ depending on types of drilling fluids and regulations. Drilling cuttings can be simply discharged into the ocean when drilling utilizes water-based fluids, which are the most environmentally friendly but least effective in drilling performance. On the other hand, oil-based and synthetic-based cuttings require higher levels of treatment and disposal technologies (landfarming, stabilization/solidification, onsite mechanical treatment and subsurface re-injection (USEPA, 2000a)). Due to the possible adverse effects associated with drilling cuttings discharges and the higher demand on environmentally acceptable activities, research on effects of drilling cuttings, drilling fluids, drilling cuttings management technologies, and use of treated drilling cuttings have been conducted by many investigators (e.g. UKOOA, 2001). Attempts were made to develop treatment technologies that are able to treat cuttings to comply with standards and minimize treatment costs. In addition, recycling and reuse of drilling cuttings have also been of interest.

Onshore and offshore management of drilling cuttings have different advantages and disadvantages. Due to the higher costs and risks associated with transporting waste cuttings to shore, the focus in the drilling cuttings treatment industry is on offshore applications. The offshore treatments, however, have limitations such as space, capacity, the capability of the treatment techniques to meet the discharge standards, and the requirement of post-treatment activities.

Because of different advantages and disadvantages of treatment alternatives, the proper selection of the cuttings treatment system that suits a specific drilling operation is critical in terms of technical, environmental, and economic issues. This research is meant to present a thorough study on available offshore drilling cuttings treatments and proposes a practical and comprehensive method to select the most suitable drilling cuttings treatment technology focusing on offshore applications.

1.2 THE SCOPE OF THE RESEARCH

In the first stage of this research, treatment and disposal technologies for drilling cuttings, both currently in use and under development, were studied in detail. Particular focus was given to:

- Technologies to manage synthetic-based cuttings during the on-going drilling operations
- Technologies suitable or having potential for offshore applications, and
- Technologies which are able to meet the standard discharge limits for SBF cuttings.

Multicriteria decision making was used to compare the selected management options. Technical feasibility, rig compatibility, environmental and safety, and cost aspects were the main factors used to compare options. Due to the large number of options, criteria, and unavailability of probabilistic distribution of data, deterministic decision making was applied with associated analyses including uncertainty and sensitivity analyses. Based on the presently available data, the evaluation was divided into two groups of existing and innovative technologies. The first group was evaluated according to the established set of criteria and the evaluation methodology proposed in this thesis. The most suitable offshore drilling cuttings management methods were then recommended and the dominating criteria were identified. In addition, innovative technologies whose complete data set are presently unavailable were reviewed.

1.3 Objectives of the Research

- To identify baseline treatment technologies for offshore drilling cuttings as well as some innovative treatment technologies.
- To evaluate selected treatment technologies for drilling cuttings using multicriteria decision making analysis. The focus of the evaluation is on offshore-based applications with consideration of technical, rig compatibility, environmental and safety, and cost issues.
- To recommend the optimum cuttings treatment technologies according to the evaluation conducted.
- To identify the most important factors affecting the ranking of drilling cuttings treatment technologies as a result of the evaluation. The factors may be considered as the dominating parameters in selecting the most suitable treatment method and allow more detailed evaluation.

1.4 Structure of the Thesis

This thesis consists of seven chapters. Chapter 1, Introduction, presents the background problem, scope of the study, and objectives of this research. In the next chapter, background, previous studies and other information which are related to this research are outlined. Information specifically on technologies used for drilling cuttings management are reviewed and presented separately in Chapter 3. As the main part of this thesis, Chapter 4 describes the evaluation methodology conducted to compare drilling cuttings management options. The obtained data and how the management options were scored are then presented in Chapter 5. Chapter 6 contains the results of this study and other relevant analyses performed in this research. This thesis is concluded in Chapter 7 where some recommendations for future work are also proposed.

CHAPTER 2

BACKGROUND

A number of studies have been conducted to address concerns about the environmental impacts associated with drilling cuttings management. The studies can be classified into two main categories: studies on the marine environmental impacts from cuttings discharges, and studies on drilling cuttings management technologies. Multicriteria decision making has been widely used as a decision tool in many fields of studies including engineering. The studies which are related to this research will be briefly discussed below.

2.1 DRILLING CUTTINGS AND THEIR ENVIRONMENTAL IMPACTS

2.1.1 What are drilling cuttings?

Drilling cuttings are fragments of rock generated when a well is drilled. The cuttings may also include other solid materials from the drilled formation (Bansal and Sugiarto, 1999). These drilling cuttings are generated continuously at a rate in proportion to the rate of penetration of the drill bit (USEPA, 2000a). The cuttings are then transported from the borehole to the surface by drilling fluids, which are the mixtures of base fluids, water, clays, and other additives, which are pumped down the centre of the drill string to lubricate the bit and remove the cuttings (e.g. Sadiq, 2001). The drilling cuttings, which are mixed with the drilling fluids, contain about 30% by volume of fluids and require separation before being disposed (Bansal and Sugiarto, 1999). Due to the high cost of the drilling fluids, the fluids separated from the cuttings are reconditioned and recycled to be used again in the drilling process (USEPA, 2000a). Some fresh drilling fluid is added to the circulating fluid system to attain its desired drilling properties and the displaced fluid is considered waste, which requires an appropriate disposal. The life cycle of the generated drilling cuttings and the drilling fluids in the drilling process is shown in Figure 2-1.

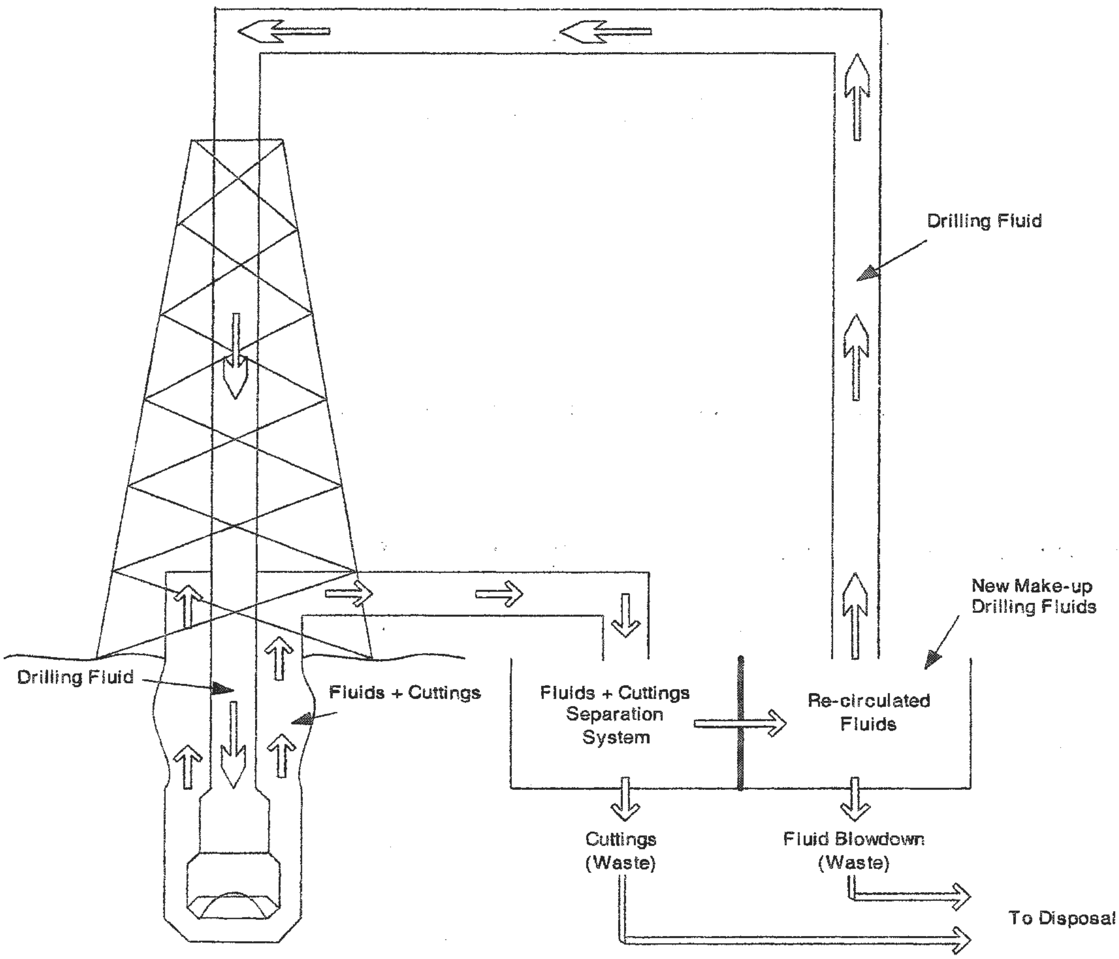

Figure 2-1 Drilling fluids circulation systems (USEPA, 2000a)

Drilling cuttings have different compositions, shape, texture and size, varying from fine silt to gravel, depending upon the types of the formation (Faulds, 1999; OLF, 2001). Even though the cuttings themselves have no particular environmental threat from a toxicological point of view, drilling cuttings can pose adverse effects on the marine environment by increasing turbidity and smothering benthic organisms. Moreover, even though most of the drilling fluids are removed from the cuttings to be used again, the cuttings are still coated with some retained drilling fluids and possibly some formation oil. Therefore, due to traces of organic and inorganic substances including heavy metals found on the cuttings, discharge of drilling cuttings can have adverse environmental effects and these are discussed later in this chapter (Patin, 1999).

2.1.2 What is on the cuttings?

Drilling cutting wastes, the cuttings separated from drilling fluids, consist of drilling cuttings, retained drilling fluid, and formation oil (USEPA, 2000a). According to Patin (1999), the properties and the composition of the cutting wastes may vary considerably depending on factors such as the type of formation and drilling regime, which in turn determine particle size and sorption capacity of the cuttings. Other major factors are the separation technologies used to clean the drilling cuttings and the contaminants adhering to the cuttings. The major sources of the contaminants on the cuttings are formation hydrocarbons and drilling fluid.

1) Drilling fluids

Drilling fluids, also known as drilling muds, are mixtures of chemicals. The chemicals in the drilling fluids significantly influence the composition of drilling cutting wastes and potential of hazards to the environment once the contaminated cuttings are discharged or disposed (Patin, 1999).

Drilling fluids are used in the drilling operations for many purposes, such as to transport cuttings from the bottom of the wellbore up to the surface, to lubricate, as well as to cool drill bits and drill pipes (Faulds, 1999; ERT and RF, 1999). Other functions of drilling fluids are maximizing drilling performance, preventing corrosion of the drilling equipment, stabilizing and sealing the sides of the wellbore, and controlling hydrostatic pressure to prevent blowouts (Faulds, 1999; ERT and RF, 1999). With these basic functions, different types of drilling fluids are used in different drilling conditions and can provide different drilling performance.

The basic properties of a drilling fluid are determined by the type of the base fluid. Depending on the base fluid, each type of drilling fluid provides not only different drilling performance but also different environmental impacts. The amount of pollutants in base fluids, such as Polycyclic Aromatic Hydrocarbons (PAHs), the most significant pollutants in base fluids, is used in toxicity classification of drilling fluids (Agha and Irrechukwu, 2002). According to Environment & Resource Technology Ltd. (ERT) and Rogaland Research (RF) (1999), drilling fluids can be classified into four major types according to the types of their base fluids.

- **Water-based fluids (WBFs)**

These types of drilling fluids consist of fresh or seawater or brine, such as KCl, functioning as the continuous phase and the suspending medium for solids (Patin, 1999). Other compositions include dissolved salts, a variety of additives, polymers, and dispersed clay and weighting material such as barite (Bansal and Sugiarto, 1999). WBFs are inferior to oil-based fluids and synthetic-based fluids in terms of performance. However, due to their dispersion ability and the chemical properties, WBF-cuttings are expected to pose less environmental impacts and are allowed to be discharged after being processed by solid separation units called solids control systems.

- **Oil-based fluids (OBFs)**

Oil-based fluids are inverted emulsion systems in which water (5-50%) is emulsified into a continuous oil phase with dispersed clay, weighting material and other additives (Patin, 1999). Oil in OBFs can be diesel, mineral oil or some other oils. OBFs contain 1-2% of PAHs while low toxic mineral oil (LTMO) based fluids contain 0.001-0.35% of PAHs (Agha and Irrechukwu, 2002).

OBFs can provide better drilling performance than WBFs due to their lower friction, better temperature tolerance, and lower reactivity with formation clays (Bansal and Sugiarto, 1999). Therefore, these types of fluids are used to provide efficient and cost-effective drilling in difficult drilling conditions, such as deviated wells, horizontal wells or active shales (Agha and Irrechukwu, 2002). In most cases, OBFs are used in combination with WBFs to drill the deeper part of the wells (Agha and Irrechukwu, 2002). Cuttings containing OBFs are not allowed to be discharged into the marine environment. The potential impacts are mainly because of their toxic composition, but other impacts including physical smothering, impacts on benthic fauna, and increases in the hydrocarbon content of sediment (Hinds et al., 1991). According to Hinds et al. (1991), some studies in the North Sea indicate that discharge of OBFs results in severe impacts on the benthic community and tainting of fish.

- **Enhanced mineral oil-based fluids (EMOs)**

Enhanced mineral oil, which is a product from crude oil, is the continuous phase for these types of drilling fluids with water as the dispersed phase. These types of drilling fluids were developed under the same regulatory and environmental demands as synthetic-based fluids. Therefore, they are less hazardous compared with OBFs due to the lower PAH content (0.001 or lower % weight) (Meinhold, 1998; Agha and Irrechukwu, 2002). However, the EMOs consist of petroleum products and must be treated as oil-based fluids (Meinhold, 1998).

- **Synthetic-based or pseudo-oil-based fluids (SBFs)**

Synthetic-based fluids having synthetic liquids as the continuous phase and brine as the dispersed phase were developed in the early 1990s to be an alternative to or to replace oil-based fluids (Cobby and Craddock, 1999; Meinhold, 1998). SBFs containing less than 0.001% of PAHs have comparable drilling performance to OBFs but provide higher worker safety and more environmentally friendly properties in terms of toxicity and biodegradability (Cobby and Craddock, 1999; Agha and Irrechukwu, 2002).

In addition to the base fluids, drilling fluids also contain some other chemicals which can be very hazardous. These chemicals or additives are added into the drilling fluids mainly to improve the properties of the fluids. Formulations of drilling fluids may vary considerably depending on specific situations, such as well conditions and regulations. The chemical additives used include weighting materials, viscosifiers, fluid loss control agents, emulsifiers, alkaline chemicals, lost circulation materials, shale control additives, lubricants, and biocides used to prevent some other additives from fermenting (ERT and RF, 1999).

From a toxicity point of view, the additive substances in drilling fluids can be classified according to their degree of toxicity and their relative proportion in the fluids (Patin, 1999). The first group includes weighting agents such as barite which are a large fraction of drilling fluids but have low toxicity. The second group includes the additives that have high toxicity but are present in the drilling fluids in a small proportion (usually less than 0.1%). These include corrosion and scale inhibitors, some of the defoamers and scavengers, and the most toxic biocides. Most heavy metals are also included in this highly toxic group. Trace heavy metals such as mercury, lead, cadmium, chromium, and zinc can be contained in the drilling cuttings themselves or in some components of the drilling fluids, such as barite and other weighting agents (Patin, 1999). The barite is the main source of barium, which appears in the drilling fluids in relatively high concentration compared with other trace metals (Agha and Irrechukwu, 2002). Other additives such as lubricants, emulsifiers, dispersants, viscosifiers, stabilizers, detergents, oil, and oil products are considered to have medium toxicity (Patin, 1999). Table 2-1 and Table 2-2 show typical compositions and properties of various drilling fluids respectively. Table 2-3 provides information on heavy metals contained in weighting materials.

Table 2-1 Example of drilling mud composition (ERT and RF, 1999)

Compound	WBM (% of weight)	OBM/SBM (% of weight)
Barite	57.6	69.5
Base oil		25.8
Bentonite	4.1	0.3
Calcium chloride		2.0
Caustic soda	1.2	
Emulsifiers		1.8
Oil wetting agent		0.1
Polyanionic cellulose (PAC)	1.2	
Salt	33.0	
Soda ash	1.0	
Starch	1.2	
Xanthan	0.5	
Other	0.2	0.5

Table 2-2 General properties of various drilling fluids (Meinhold, 1998)

Base Fluid	Density (g/ml)	Viscosity (cst at 40°C)	Flash Point (°C)	Aromatic Content (%)
Diesel	0.85	3-4	66	25
Conventional mineral oil	0.80	2-3	90-110	1-7
Purified paraffin oil	0.77-0.79	2-3	90-102	<1
Enhanced mineral oil	0.80	1.7-3	80-110	<0.01-<0.2
Ester ca. C_{26}	0.85	5-6	179	0
Ester ca. C_{20}	0.83	6.0	166	0
Acetal C_{20}	0.84	6.0	>139	0
Poly-alpha olefins C_{20}	0.80	5-7	155	0
Linear alpha olefins C_{14}- C_{16}	0.77-0.79	2.1	114	0
Linear alpha olefins C_{16}- C_{18}	0.77-0.79	3.1	146	0
Internal olefins C_{16}- C_{18}	0.78	3.1	137	0

Table 2-3 Heavy metals found in Barite (Modified from USEPA, 2000b)

Pollutant	Average Concentration of Pollutants in Barite (mg/kg)
Priority Pollutants, Metals	
Cadmium	1.1
Mercury	0.1
Antimony	5.7
Arsenic	7.1
Beryllium	0.7
Chromium	240.0
Copper	18.7
Lead	35.1
Nickel	13.5
Selenium	1.1
Silver	0.7
Thallium	1.2
Zinc	200.5
Non-Conventional Metals	
Aluminum	9,069.9
Barium	120,000
Iron	15,344.3
Tin	14.6
Titanium	87.5

2) Formation oil

In addition to drilling fluids, formation oil adhering to cuttings contains organic priority pollutants and also contributes to toxicity of cuttings containing SBFs (USEPA, 2000a). The amount of formation oil retained on cuttings is estimated to be 0.2% by volume of SBF cutting wastes (USEPA, 2000a). Pollutants in formation oil, including some organic priority pollutants, are shown in Table 2-4.

Table 2-4 Formation oil characteristics (Modified from USEPA, 2000b)

Pollutant	Average Concentration of Pollutants in SBF Contaminated with Formation Oil	
	mg pollutant/ ml formation oil	lbs/bbl of SBF*
Priority Pollutant Organics		
Naphthalene	1.43	0.0010052
Fluorene	0.78	0.0005483
Phenanthrene	1.85	0.0013004
Phenol (μg/g)	6	7.22E-08
Non-Conventional Pollutants		
Alkylated benzenes	8.05	0.0056587
Alkylated naphthalenes	75.68	0.0531987
Alkylated fluorenes	9.11	0.0064038
Alkylated phenanthrenes	11.51	0.0080909
Alkylated phenols (μg/g)	52.9	0.0000006
Total biphenyls	14.96	0.0105160
Total dibenzothiophenes (μg/g)	760	0.0000092

* Assumes 0.2% contamination from formation oil using diesel as an estimate of pollutant content

2.1.3 Environmental impacts from drilling discharges

As synthetic-based cuttings may be released into the ocean after appropriate treatment in some locations, in this study, where treatment technologies for drilling cuttings are investigated, particular focus was given on cuttings contaminated with synthetic-based fluids. In order to present the environmental impacts posed by this type of cuttings, the characteristics of SBFs were studied and are briefly described below.

1) Characteristics of synthetic based fluids

According to the Canada-Newfoundland Offshore Petroleum Board (1998), synthetic-based fluid is defined as a drilling fluid which has continuous phase that consists of one or more fluids generated from the reaction of specific purified chemical feedstock (instead of through physical separation processes such as fractionation, distillation and minor chemical reactions such as cracking and hydro processing). Generally, synthetic based fluids contain a total polycyclic aromatic hydrocarbon concentration of less (mostly significantly less) than 10 mg/kg, and most or all marine toxicity tests indicate non-acute toxic effects.

The major types of synthetic-based drilling fluids are long chain esters, ethers, acetals, and synthetic hydrocarbons including poly alpha olefin (PAOs), linear alpha olefin (LAOs), internal olefins (IOs), or PAOs/LAOs (ERT and RF, 1999; Meinhold, 1998).

Compared with OBFs, SBFs are environmentally preferable in many ways. Firstly, SBFs contain a negligible amount of polyaromatic hydrocarbons (PAHs), important toxic compounds in drilling fluids, very little or no aromatic content, and no priority pollutants (Sadiq, 2001). For this reason, SBFs tend to cause considerably less impact on the environment compared with OBFs in terms of toxicity. SBFs have lower accumulation and better biodegradation. Thus, from limited available data, SBFs are not likely to have impacts on marine ecology or on human health through seafood consumption (Meinhold, 1998). Despite this information, the discharge of SBF-cuttings has been phased out in many locations due to the potential environmental impacts on marine ecology associated with the discharge (Faulds, 1999). The potential environmental impacts are discussed later in this section and the summary of general characteristics of SBF drilling wastes is shown in Table 2-5.

2) Potential impacts from SBF-cuttings discharges

Drilling cuttings discharge can pose adverse effects on the environment in many ways. The extent of the effects substantially depends on the composition of cuttings which can be very complex and variable (Patin, 1999). The major impacts from drilling cuttings discharge are physical impacts and impacts from contaminants on the cuttings such as potential toxic effects and organic enrichment. The possible impacts from discharges of SBF-cuttings are briefly summarized in the section below:

- Physical effects

The major pollution loadings from discharge of drilling cuttings include total suspended solids (TSS). The first component contributing to the suspended solids in cutting wastes is the drilling cuttings themselves that are small bits of stone, clay, shale, and sand (USEPA, 2000a). The other component is the solids which are parts of the retained drilling fluids (USEPA, 2000a). In drilling fluid, a barite weighting agent and clays are added to control the density and the viscosity of the fluids and these are the main solid sources (USEPA, 2000a).

Due to the high TSS with large particles as the main content, discharge of drilling cuttings can cause physical environmental impacts including increase in turbidity. In addition, the rapid settling of the particles can cause benthic smothering of the benthic community and/or alteration in sediment grain size and composition (USEPA, 2000a; Patin, 1999). This will in turn have adverse effects on invertebrate populations, spawning grounds, and feeding habitats (USEPA, 2000a).

Table 2-5 SBF drilling waste characteristics (Modified from USEPA, 2000a)

Waste Characteristics	Value
SBF formulation	47% synthetic base fluid, 33% barite, 20% water (by weight)
Synthetic base fluid density	280 pounds per barrel
Barite density	1,506 pounds per barrel
SBF drilling fluid density	9.65 pounds per gallon
Percent (vol.) formation oil	0.2%
Pollutant Concentrations in SBF	
Conventionals	**lbs/bbl of SBF**
Total oil as synthetic base fluid	190.5
Total oil as formation oil	0.588
TSS as barite	133.7
Priority Pollutant Organics	**lbs/bbl of SBF**
Naphthalene	0.0010024
Fluorene	0.0005468
Phenanthrene	0.0012968
Phenol	0.000003528
Priority Pollutant Metals	**lbs/bbl of SBF**
Cadmium	1.1
Mercury	0.1
Antimony	5.7
Arsenic	7.1
Beryllium	0.7
Chromium	240.0
Copper	18.7
Lead	35.1
Nickel	13.5
Selenium	1.1
Silver	0.7
Thallium	1.2
Zinc	200.5
Non-Conventional Metals	**lbs/bbl of SBF**
Aluminum	9,069.9
Barium	588.000
Iron	15,344.3
Tin	14.6
Titanium	87.5
Non-Conventional Organics	**lbs/bbl of SBF**
Alkylated benzenes	0.0056429
Alkylated naphthalenes	0.0530502
Alkylated fluorenes	0.0063859
Alkylated phenanthrenes	0.0080683
Alkylated phenols	0.0000311
Total biphenyls	0.0104867
Total dibenzothiophenes	0.0004469

- Toxicity

As SBF-cuttings tend to sink to the bottom and do not disperse well in water, the toxicity in the sedimentary phase is usually the focus (USEPA, 2000b). The source of toxicity is primarily heavy metals in both barite, the weighting material, and formation oil. However, from studies by Meinhold (1998), most of the metals in drilling fluids are in insoluble forms and the easily leachable metals will be diluted quickly by seawater resulting in very low concentration of metals. In addition, the heavy metals in the barite are restricted by SBF stock limitations which determine characteristics of SBF that can be discharged (USEPA, 2000b).

Another factor affecting risk posed by toxic substances from cuttings discharges is the concentrations of harmful substances put into the marine environment. The concentrations can be estimated by studies on fate of drilling cuttings after discharge into the ocean. There are many studies regarding this issue. One example is the study by Niu (2003) who has conducted experiments on settling velocity and flocculation behaviors of different particle sizes of cuttings. These characteristics of drilling cuttings are important in predicting distribution of drilling cuttings and the retained chemical substances after discharge.

- Bioaccumulation

Bioaccumulation is the term indicating the increase in pollutant concentration when it is transferred from the environment to the first organism in a food chain. From studies by the USEPA (2000a), bioaccumulation is not a serious impact posed by synthetic base fluids due to its low bioaccumulation properties.

- Anoxic condition due to rapid biodegradation

This impact is considered the dominating impact of SBF-cuttings discharges as the largest proportion in the adhered drilling fluids is the base fluids which can cause organic enrichment (USEPA, 2000b). Therefore, the biodegradability of the base materials is an important parameter influencing the environmental fate and effects of SBF-cuttings discharges (USEPA, 2000b). Rapid biodegradation and oxygen utilization of these base fluid materials lead to "hypoxia" (reduction in oxygen) or "anoxia" in the immediate sediment once the drilling cuttings are discharged into the ocean (USEPA, 2000a). Basically, biodegradation of SBFs can be divided into two processes: aerobic degradation, which is limited to the sediment:water column interface, and an anaerobic process occurring in the deposited cuttings (USEPA, 2000b). Anaerobic activities can also occur to degrade base fluids after oxygen is depleted.

Organic enrichment and anoxic conditions which follow the initial smothering effect may occur only in a short-term period and the extent of the impact depends upon many factors including currents, temperature, and rate of biodegradation of the base fluids (USEPA, 2000a). However, biodegradable base fluids are preferred because re-colonization of the areas has been found to be more rapid when the base fluids biodegrade and disappear faster (USEPA, 2000a).

2.2 MANAGEMENT OF DRILLING CUTTINGS AND EVALUATION METHODOLOGIES

Management strategies for dealing with drilling cutting wastes vary depending mainly on types of drilling fluids used and regulations. For SBF-cuttings, there are now three basic categories of drilling cuttings management: ship-to-shore for treatment and disposal, treat offshore followed by marine discharge, and onsite re-injection. These three basic cuttings management policies are applied in compliance with local regulations which are discussed briefly below.

2.2.1 Regulations

Owing to the potential negative environmental impacts from discharges of SBF-cuttings, regulations regarding the discharge of SBF-cuttings are very strict worldwide. The regulation models, which differ from place to place, are driven by the industry's structure and experience, the marine environment's qualities and its policies, and political aspects (CAPP, 2001).

According to CAPP (2001), regulation models can be classified into two groups for different drilling cuttings disposal. The first model is guided by the regional OSPAR Convention (the Convention for the Protection of the Marine Environment of the North-East Atlantic) and has been applied among the North Sea European countries (CAPP, 2001; Wills, 2000). The countries applying the OSPAR model as the basis for national discharge regulations include Belgium, Denmark, Finland, France, Germany, Iceland, Ireland, the Netherlands, Norway, Portugal, Spain, Sweden and the UK (Wills, 2000). Under this regulatory model, the marine discharges which are the focus of the Convention are strictly controlled, focusing on biodegradability, toxicity or other hazardous properties, and the bioaccumulation tendency of the cuttings composition (Wills, 2000). All types of cuttings including WBF-cuttings must contain less than 1% by weight of oil (Wills, 2000). OBF- and SBF-cuttings are regulated more stringently than WBFs. These non-aqueous phase fluids

(NAPF; the drilling fluids with non-water soluble materials as the continuous phase and water or brine as the dispersed phase) retained cuttings must be shipped to shore or disposed of onsite using re-injection. Marine discharges are acceptable only when the cuttings are sufficiently cleaned and achieve 1% by weight of fluid retention on cuttings (Wills, 2000). Discharges of SBF-cuttings containing more than 1% drilling fluids may be possible with authorization. However, SBF-cuttings discharges are very restricted in some countries such as the UK where SBF-cuttings discharge was phased out (CAPP, 2001).

The second model is used in countries where the regulations are directed by national legislation (CAPP, 2001). These countries such as Australia, the United States, and Canada apply a more "holistic" methodology for drilling cuttings management (CAPP, 2001). SBF-cuttings management in this second model involves decision making of a disposal strategy after thorough study of technical, economic, and environmental issues (CAPP, 2001).

Western Australia has used an "objective case-by-case approach" to regulate SBF-cuttings. Technical issues of each project and environmental sensitivities are assessed without any approval system based on types of drilling fluids or chemical categories (CAPP, 2001).

Considering the impacts on the overall industry financial health associated with environmental regulations, the USEPA has issued guidelines and standards to control characteristics of base fluids, barite, and drilling cuttings discharges based on formation oil content and fluid retention (Wills, 2000). Two standard limits for the retention of base fluids on cuttings (ROC) were established for discharges from a cuttings dryer. There is a zero discharge for fines (USEPA, 2000a). The two levels of discharge limits are 9.4% ROC for

SBFs with the stock base fluid performance similar to esters and 6.9% ROC for those with the stock base fluid performance similar to C_{16}-C_{18} internal olefins (IOs) (USEPA, 2000a). These levels of retained fluids can be achieved by using one of the best available technologies (BAT).

During their early stage of development, offshore projects on the east coast of Canada are regulated by one of two regional boards, the Canada-Newfoundland Offshore Petroleum Board (C-NOPB) and the Canada Nova Scotia Offshore Petroleum Board (C-NSOPB) (CAPP, 2001). According to the guidelines, Offshore Waste Treatment Guidelines (OWTG) (NEB et al., 2002), WBFs and SBFs are preferred to OBFs, which can only be used in exceptional circumstances (when use of WBFs and SBFs is not technically practical) and upon approval. EMOs may be used upon approval provided that the fluids used are equivalent to or better than SBFs in terms of environment impacts and safety. Water-based drilling fluids may be discharged onsite without treatment while discharge of whole SBFs or EMOs is not allowed (NEB et al., 2002). Discharge of SBF contaminated cuttings is possible; however, operators are recommended to consider re-injection. Where re-injection is not feasible, SBF-cuttings may be discharged into the ocean after treatment by best available technology (NEB et al., 2002). According to the OWTG (NEB et al., 2002), at the time of publication, the best available technology is able to reduce the amount of base fluid on waste cuttings to 6.9 g/100 g or less oil on wet cuttings. This discharge limit may be adjusted when used in different locations such as in areas with more challenging formations and drilling conditions, or increased environmental impact potential (NEB et al., 2002).

2.2.2 Current cuttings management

After the cuttings are transported from the bottom of a drilled well to the surface, they are separated from the drilling fluid stream by a solids control system. As shown in Figure 2-2, a solids control system typically consists of a combination of separation equipment. The separation equipment includes primary and secondary shale shakers (vibrating screens), a "cuttings dryer" (shale shaker or centrifuge to further recover drilling fluids), a fines removal unit (high-G shale shaker or centrifuge to remove fine solids from the drilling fluid stream), and sand traps (USEPA, 2000a). According to the USEPA (2000a), the standard or baseline solids control systems include primary and secondary shale shakers in series with a fine removal unit. The shale shakers have the function of separating large solids from the drilling fluid stream and the fine removal unit is used to remove fines to maintain rheological properties of the drilling fluids. The cleaned fluid is then returned to the active mud system while the separated solids are considered wastes. This baseline solids control system can reduce the fluid retention to an average value of 10.2% (USEPA, 2000a).

A cuttings dryer is an additional treatment unit used to improve the solids control system. Using the cuttings dryer, drilling fluids are further separated from the treated drilling cuttings from the primary and secondary shale shakers (USEPA, 2000a). This higher level of solids and fluids separation is required due to the high cost of drilling fluids and stringent environmental regulations. After passing through the dryer the amount of drilling fluids retained on the cuttings can be reduced to around 3-8% (Montgomery, 2000). Therefore, where cuttings discharge is acceptable, such as in the US, cuttings dryers are used to reduce the fluid retention to a level below the standard limits before the cuttings are discharged into the ocean. The use of the cuttings dryer may return ultra fine solids to the mud system which will in turn increase the drilling waste volume due to the increased amount of fluid dilution (Montgomery, 2000). Therefore, the recovered SBFs from the cuttings dryer must pass through the fines removal unit before they can be returned to the mud system (USEPA, 2000a).

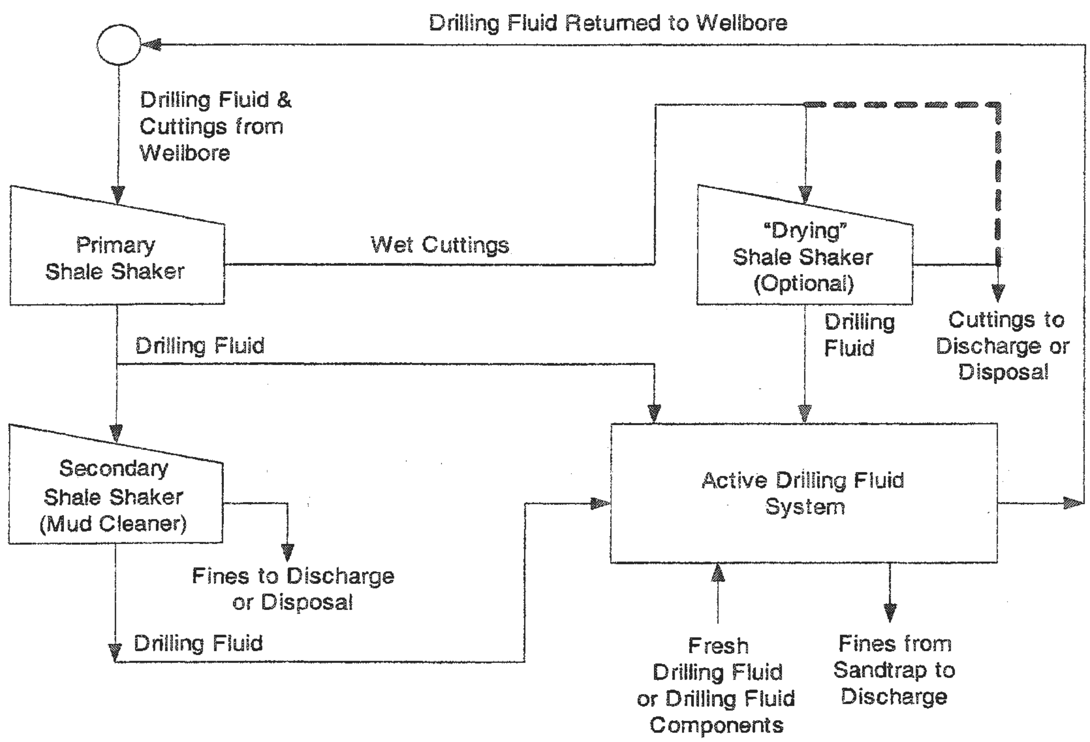

Figure 2-2 Generalized solids control system (USEPA, 2000a)

As previously mentioned, there are three ways to deal with drilling cuttings: ship-to-shore for treatment and disposal, marine discharge after offshore treatment, and onsite re-injection. These three options have different overall advantages and disadvantages resulting in different levels of compatibility with each specific project.

Ship-to-shore is currently the most practical management regime where cuttings discharges are not permitted. This is because of the limited feasibility of using offshore treatment and the availability of suitable formations for re-injection (OLF, 2001). However, where suitable formations are available and wastes from three or more wells are served, re-injection is a more cost-effective option compared with ship-to-shore methods (Montgomery, 2000).

1) Ship-to-shore for treatment and disposal

Under the zero discharge requirement, the most widely used approach to deal with drilling cuttings wastes is to transport the wastes to shore for treatment and disposal. Onshore, the SBF-cutting wastes may be treated at commercial land-based treatment and disposal facilities (USEPA, 2000a). In the US, the common onshore facilities are landfarming, stabilization/solidification (which bonds and changes drilling cuttings into construction material) and onshore re-injection (USEPA, 2000a). However, according to Montgomery (2000), the use of bioremediation, landfarming, stabilization, and soil washing using surfactants or enzyme solutions has been reduced considerably in the North Sea. This is because these technologies have some drawbacks, including their effectiveness and health and safety concerns regarding treatment and disposal of wastes on land such as long-term liability, possible migration of contaminants, and limitations on future use. Other potential onshore technologies are currently solvent extraction and thermal desorption (Montgomery, 2000). The solvent extraction process involves the use of light oil, hexane, or other solvents to extract oil from cuttings while in the thermal desorption process, where contaminants along with water on the cuttings are volatilized off by heat.

Even though it is a common practice and the environmental impacts are small, ship-to-shore transport of drilling cuttings has some disadvantages due to the increase in transportation cost and liability, requirement of temporary storage, potential long-term liability, limited number of treatment facilities, capacity of existing facilities, and potential co-mingling of wastes (Montgomery, 2000; OLF, 2001). Transportation, increase in energy consumption, air emissions, and risks of spills are potential environmental impacts associated with this practice (OLF, 2001).

2) Offshore treatment and disposal

Offshore treatment followed by ocean discharge, which avoids transportation of wastes to shore, has many advantages over the ship-to-shore option. Even though the mobilization and demobilization of the treatment process are higher than onshore installations, there is a minimum co-mingling of wastes and lower cost and liability compared to transportation of wastes to shore (Montgomery, 2000). The reduction of waste transportation results in less associated accidental risks and no or less wastes to onshore disposal sites (Ferrari et al., 2000). Space required for onsite storage and treatment processes is the main limitation of offshore treatment. Due to the limited space and weight constraints on offshore platforms, offshore treatment technologies are restricted to those simple technologies with a small footprint. Other environmental concerns associated with offshore treatment include energy use, atmospheric emissions, and disposal of waste streams including waste water, solids, and drilling fluids (Figure 2-3) (OLF, 2001). These concerns must be compared with those of the ship-to-shore process in order to develop a drilling cuttings management plan.

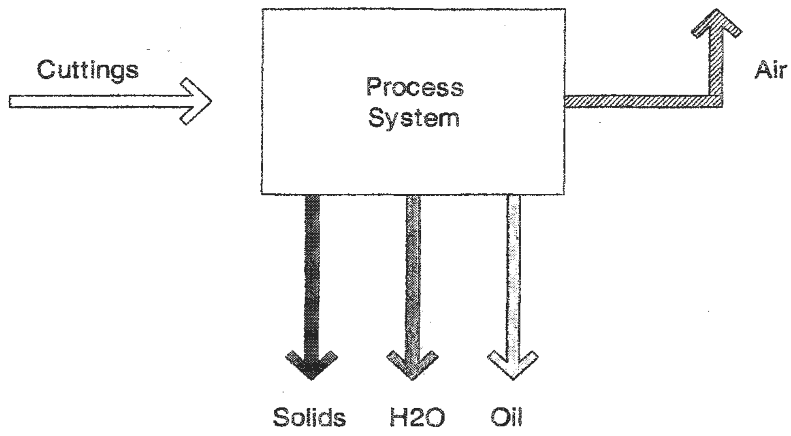

Figure 2-3 Waste streams from drilling cuttings management process (Montgomery, 2000)

Attempts are being made to develop technologies which can feasibly be installed on offshore platforms and can efficiently reduce the fluid retention on cuttings to the level below the standard limits. Studies have been conducted in Norway regarding offshore treatment technologies. Studies by the United Kingdom Offshore Operators Association (UKOOA; 2000) and Cripps et al. (1998) considered some existing onshore technologies with offshore potential as alternatives to ship-to-shore management.

3) Onsite re-injection

In the US, onsite re-injection as an alternative to land-based disposal has been of interest since 1993 (USEPA, 2000a). Re-injection (Figure 2-4) is the process in which drilling cuttings are ground, slurrified, and re-injected into a confined receiving formation. Re-injection may not be successfully employed at every site depending on the availability of the viable formations to confine the injected wastes (USEPA, 2000a). The wastes can be re-injected into a dedicated well, the annulus of the well previously drilled, or commercial re-injection facilities where "large-capacity receiving formations" reside are also available

(USEPA, 2000a). This method has been successfully used to dispose of drilling cuttings wastes for many offshore projects and provides minimal long-term liability once the injected waste is assured not to be release to the environment. However, high costs, air emission from the process, and the elimination of the possibility to recycle drilling fluids are important concerns.

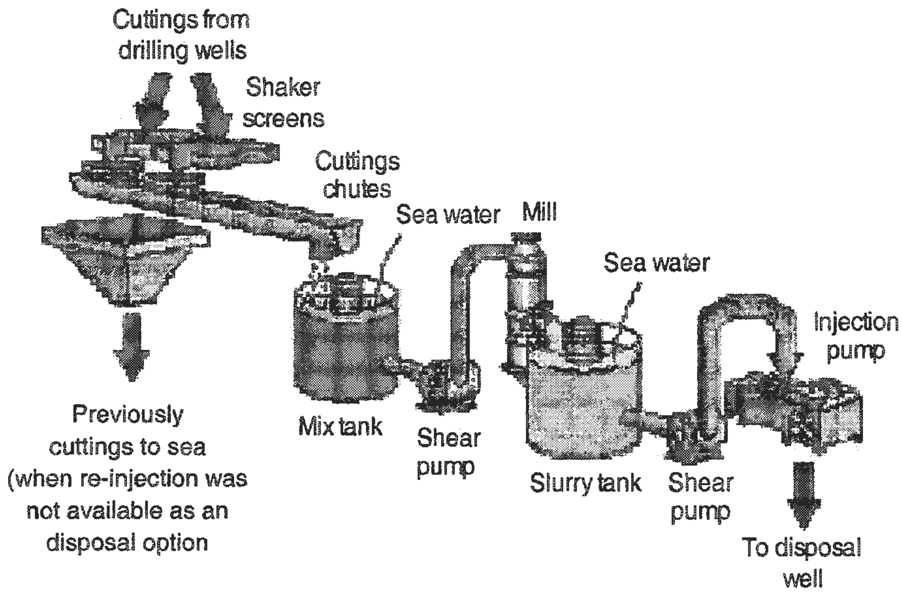

Figure 2-4 Drilling cuttings re-injection process (Wills, 2000)

Other than treatment and disposal of the cuttings wastes, the complete drilling cuttings management plan generally includes selection of drilling fluids and reduction of waste volume at source. An example of a waste management strategy is the 5 R's Strategy (Figure 2-5) which includes reduce, reuse, recycle, recover, and residual management.

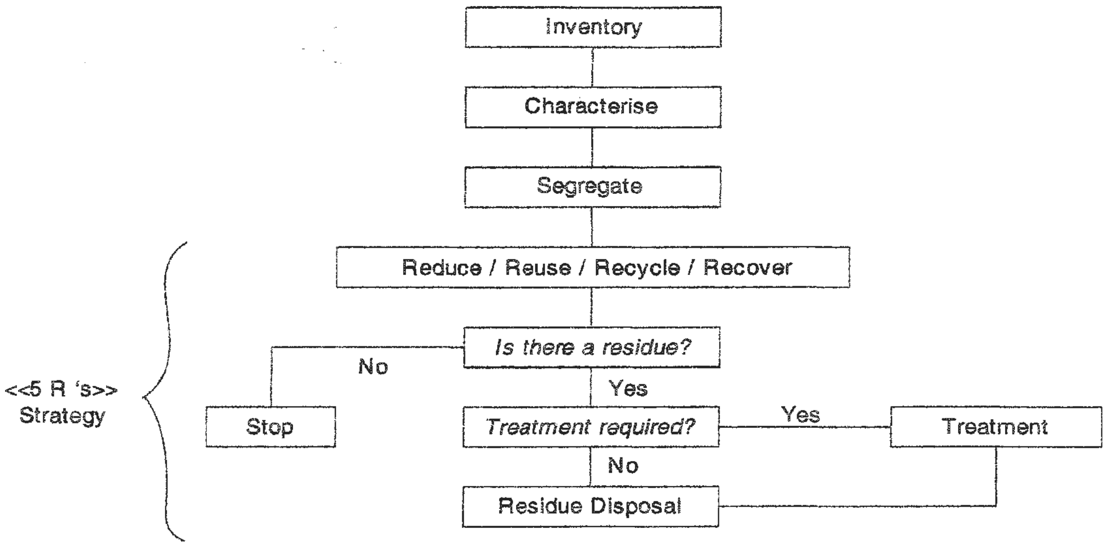

Figure 2-5 TotalFinaElf's key waste handling, minimization and disposal decision, "5 R's strategy" (Morillon, et al., 2002)

In addition to the studies on treatment technologies for drilling cuttings, there is now interest in reuse of treated cuttings. According to the Norwegian Oil Industry Association (OLF; 2001), treated cuttings can be used as construction materials such as bricks, roofing tiles or in asphalt production. The possibility of reusing treated drilling cuttings depends on the treatment technology used for the cuttings as it is limited by the cuttings' chemical characteristics and compositions such as salt, hydrocarbon, and heavy metal contents (OLF, 2001).

2.2.3 Evaluations of drilling cuttings management options

As the selection of the drilling cuttings management is critical, treatment and disposal technologies have been widely studied and evaluated. In the management of drilling cuttings in ongoing drilling processes, Husky Oil Operations Ltd. (2001) has conducted a study to compare drilling cuttings disposal options for the White Rose Oilfield Development. A risk analysis was used to obtain the "integrated risk index" values which reflect the properties of the considered options. The United Kingdom Offshore Operators Association (UKOOA; 2000) and Cripps et al. (1998) also conducted studies to identify cuttings treatment technologies and provide an analytical assessment of the different options to assist in selection of the optimum management option for drilling cuttings piles in the North Sea. Due to various advantages and disadvantages of each option, option ranking and recommendation of a specific system were avoided. Only comparative ratings were provided and a case-by-case analysis was recommended by the studies.

In this study, multicriteria decision making is applied to help assess and compare the drilling cuttings management alternatives involving conflicting and uncertain data. Multicriteria decision making (MCDM) is the method used for problems concerning multiple and usually conflicting criteria (Hwang and Yoon, 1981). This approach can be used for complicated decision making problems with diverse units of measurement including qualitative (e.g. intangible factors) and quantitative values. (Hwang and Yoon, 1981; Papatyi et al., 1997; De and Hipel, 1987). Therefore, it is commonly used to select the best over all criteria from a specified set of alternatives as it makes the decision making process more objective and transparent (Grelk et al., 1998). The common usage of multicriteria decision making includes choosing one or more best alternatives or ranking the alternatives completely or partially, or assessing the acceptability of the alternatives (Lahdelma et al., 2000).

Some common terms used in multicriteria decision making are listed below (Kirkwood, 1997):

- **Criteria** Factors to compare alternatives
- **Evaluation Measure** Scale to measure the degree to which an alternative attains an objective
- **Level or score** Specific numerical rating of the evaluation measure
- **Scoring function** A "single dimension value function" assigning a value to an evaluation measure
- **Value Model** A mathematical model of the value structure that includes scoring functions and weights
- **Weights** Relative preference for criteria and evaluation measures

A multicriteria decision making framework has also been used in selecting treatment technologies for wastes similar to drilling cuttings. The methodology used by the United States Department of Energy (DOE), as shown in Figure 2-6, is based on the Comprehensive Environmental Response, Compensation, and Liability Act, or USEPA CERCLA guidance (Parnell et al., 2001). The selection of the best soil remediation alternatives used by DOE was the basis method applied to drilling cuttings in this study.

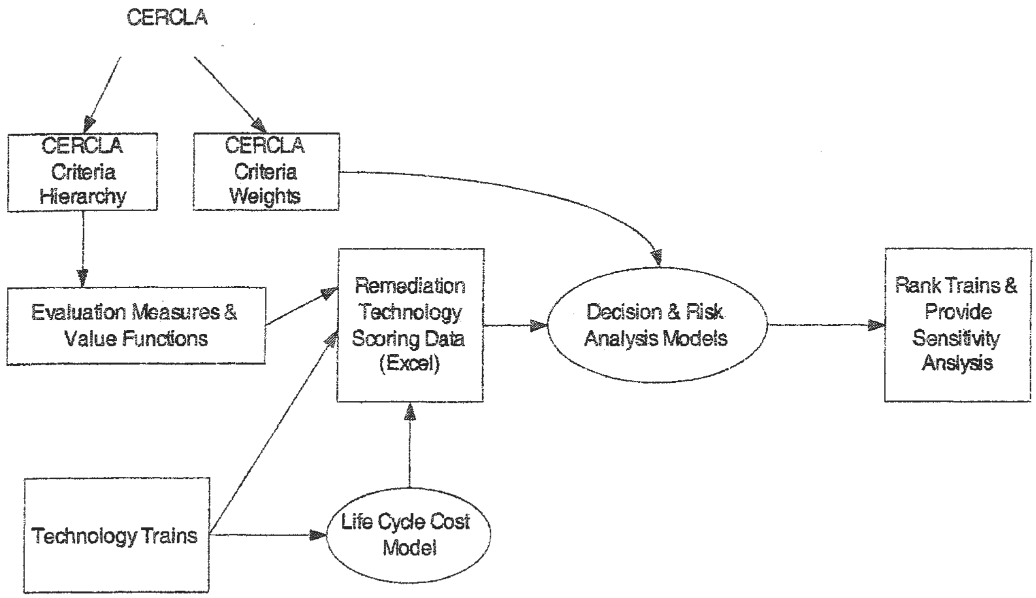

Figure 2-6 DOE's Decision and Risk Analysis Methodology

(Modified from Grelk et al., 1998)

In addition to the DOE's methodology, there are various multicriteria decision making techniques to be used in selecting the best option. Some examples of these techniques are discussed below.

- **Simple additive weighting method** (SAW; Hwang and Yoon, 1981)

This method is a very widely used method which involves weighting attributes, scaling attribute values, and then calculating the total score, which is the sum of the products of weights and scores for all the attributes. The option attaining the highest score is the one to be selected. According to Hwang and Yoon (1981), the most preferred option (A*) is selected such that:

$$A^* = \left\{ A_i \mid \max_i \sum_{j=1}^{n} w_j x_{ij} / \sum_{j=1}^{n} w_j \right\} \tag{2.1}$$

where x_{ij} is the level the i^{th} option attained for the j^{th} criterion on a numerically comparable scale. The weights (w_j) normally add up to 1 or $\sum_{j=1}^{n} w_j = 1$ (Hwang and Yoon, 1981).

This method may be extended to include hierarchical consideration of criteria as in the method called Hierarchical additive weighting method (Hwang and Yoon, 1981) where the criteria are classified into levels and the weights of criteria in the lower levels are assigned based on the weights of the criteria in the above levels.

- **Goal programming** (GP; Hobbs and Meier, 2000)

In this method, weights are given to criteria and the target level (goal) of each criterion is identified. The options are compared based on the weighted deviation from the goals (Hobbs and Meier, 2000). The selected option is the closest to the goals or has the least distance from the goals (equation 2.2) (Hobbs and Meier, 2000).

$$\left\{ \sum_{i=1}^{I} \left[w_i \left| G_i - V_i\left(A_{ij}\right) \right| \right]^P \right\}^{(1/P)} \tag{2.2}$$

where w_i is the weight for attribute i, G_i is the goal for attribute i (the desired value of $V_i(A_i)$), and P is a positive parameter indicating the impacts of the deviations on the option preferences (usually set to 1, 2, or ∞) (Hobbs and Meier, 2000).

- **Power law**

The steps in conducting this method are quite similar to the simple additive weighting method except that the overall value is calculated by using the equation below (Hobbs and Meier, 2000):

$$Totalvalue = \prod_{i=1}^{I} V_i\left(A_{ij}\right)^{w_i} \tag{2.3}$$

where w_i is the weight for attribute i and $V_i(A_{ij})$ is the value of attribute i for alternative j.

- **Utility functions**

Utility functions are the more general form of the simple additive weighting method. In this method, the expected value of the utility functions ($E[U(A_i)]$) is used to compare options. The utility functions ($U_i(A_i)$) are developed in such a way as to reflect the decision maker's risk attitude (risk neutral, risk averse, or risk seeking). The risk neutral decision maker prefers the option with the highest expected values regardless of the risk associated. On the other hand, for risk averse decision maker, the option with the best expected values of criteria may not be chosen as it may have higher risk associated. The expected value of a utility function for each criterion can be calculated using equation 2.4 (Hobbs and Meier, 2000):

$$\int P_{ij}\left(A_{ij}\right) U_i\left(A_{ij}\right) dA_{ij} \tag{2.4}$$

where $P_{ij}(A_{ij})$ is the probability density function of criterion I for alternative j

The calculated expected values are then used to calculate the expected overall utility using either multiplicative or additive utility functions as shown below (Hobbs and Meier, 2000):

$$\text{Additive form: } Maximize \sum_{i=1}^{I} w_i U_i\left(A_{ij}\right) \tag{2.5}$$

$$\text{Multiplicative form: } Maximize \left\{ \left[\prod_{i=1}^{I} \left(1 + K w_i U_i\left(A_{ij}\right)\right) \right] - 1 \right\} / K \tag{2.6}$$

where K is the scaling parameter which makes the overall values lie between zero and one.

According to Hobbs and Meier (2000), the additive form is used when the sum of the weights is one. More details on this concept can also be found in various literature such as Keeney and Raiffa (1976) and elsewhere.

- **Outranking methods**

These methods use comparisons of two options to screen out the less preferred options. An example of these methods is the Elimination et Choice Translating Reality method (ELECTRE; Hwang and Yoon, 1981) where two options are compared and the option which is superior under a "solid majority" of criteria are preferred (Hobbs and Meier, 2000).

From various multicriteria decision making methods discussed above, a deterministic multicriteria decision making similar to that used by the US DOE (Parnell et al., 1999) was used in this study to evaluate drilling cuttings management. This method utilizes deterministic value functions to score options instead of the complex utility functions where the decision maker's risk attitude and the probability distributions of the data are considered.

According to Hobbs and Meier (2000), different scaling methods for the evaluation scores make little difference in the results. In addition, the deterministic value functions can be used instead of the utility functions when the level of each criterion for each option is a single number (not a probability distribution) and when the decision maker is relatively risk neutral (Hobbs and Meier, 2000). However, when uncertainties are not included, the accuracy of the results depends on the sensitivity of the model and a sensitivity analysis should be done when a deterministic model is applied to make sure that there is no difference in the results or the ranking of the evaluated options (Hobbs and Meier, 2000). Therefore, as the obtained data are mostly single numbers with no probability distribution associated, a deterministic approach was used along with a sensitivity analysis after the evaluation was completed. The deterministic multicriteria decision making, including the US DOE's method, generally includes the following basic steps.

1) Criteria Selection and Definition

Criteria or attributes are factors used to compare alternatives by providing numerical measures for all corresponding properties of different options (Lahdelma et al., 2000). According to Keeney et al. (1994), identifying criteria is the first step in decision making followed by selection of alternatives. Using this "value-focused thinking" approach, the focus is given to the decision maker's values instead of the preliminary set of alternatives (Grelk et al., 1998). This methodology is known to provide better understanding or "the foundation for interest" (Keeney, 1992) in any decision situation, which in turn provides better decisions. After criteria are carefully and appropriately selected, a set of alternatives can be identified.

The criteria constructed should be (Kirkwood, 1997; Parnell et al., 1999)

- Complete – the criteria must include all issues in the evaluation and measure the attainment of each alternative.
- Non-redundant.
- Independent – the property of the alternatives measured under one criterion does not depend on that under other criteria.

Evaluation measures, which present the degree of attainment of the alternative, are then defined for each criterion. According to the evaluation measures, each option was measured on one of the scales below (Jordaan, 2001):

- Nominal – In this scale, a number is used for the purpose of categorization, such as type 1, type 2, etc. The number does not specify size or any other property.
- Ordinal – In this scale, a number is also used as a classification. However, the classifications are determined based on a common characteristic of the considered entity. An example of the value on this scale is grades of concrete where grade 1 is stronger than grade 2.
- Interval – This scale is an ordered set of numbers where the equal differences at different points on the scale represent the same difference in the considered attribute. An example of this scale is temperature. Zero is arbitrary in this case and general statistics (such as mean, standard deviation, etc.) of the values on this scale can be calculated.
- Ratio – This scale is similar to the interval scale but the zero is fixed as "an absolute" or "natural" zero.

From related studies, it was found that the basic groups of parameters important in assessing offshore management technologies for drilling cuttings include technical feasibility, rig compatibility, environmental impacts, and costs. These parameters are used as the groups of criteria which can be sub-divided into levels of criteria consisting of smaller criteria groups or individual sub-criteria. The criteria and their levels can then be presented as a "value hierarchy" or criteria hierarchy (Kirkwood, 1997). The complete set of criteria, their evaluation measures, and the hierarchy used to evaluate drilling cuttings management technologies can be found later in Chapter 4 of this thesis.

2) Define Alternatives

Alternatives are the options to be evaluated and from which the best will be selected. The most important thing in selecting alternatives is that there are significant differences in the types and the properties of selected options (Hobbs and Meier, 2000).

3) Screening

Screening is the process of using value judgments to reduce the size of a large alternative set. The more practical, smaller number of potential alternatives can then be studied in detail. According to Hobbs and Meier (2000), screening is applied for two purposes:

- To eliminate alternatives which are not likely to be selected so more focus can be given to other potential alternatives,
- To provide decision makers alternatives which are superior in various aspects. The set of alternatives after screening should not have similar values under a specific criterion.

4) Scoring

During decision making evaluation, data on each alternative are gathered according to the criteria or the evaluation measures. These data are then changed to interval scaled numbers or "scores" which can then be calculated using a value model to yield some indexes for comparing alternatives. Generally, in order to use overall value models to calculate the indexes, the data for each criterion must be converted to dimensionless interval scale values which are on an equivalent scale (Hobbs and Meier, 2000; Parnell, et al., 1999; Rudin et al., 1993). The dimensionless values are called utilities in the case that the evaluation measure levels are uncertain (Parnell et al., 1999).

There are two types of collected data and evaluation measures: qualitative and quantitative. Qualitative values are on an ordinal scale providing subjective rankings such as low, medium, high, higher. These qualitative values can then be subjectively converted into interval scaled values given a specific range, such as from zero (for the least preferred level) to ten (for the most preferred level). An example of a systematic qualitative rating scheme is shown in Table 2-6.

Table 2-6 Qualitative ratings of importance based on Saaty's concept (Saaty, 1988)

Intensity of Importance	Definition
1	Equal importance
3	Weak importance
5	Strong importance
7	Demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values

The second type, on the other hand, provides quantitative values which can be translated (or normalized) to interval scaled values using single value functions (Parnell et al., 1999). According to Hobbs and Meier (2000), the single value functions can be either discrete or continuous and either linear or non-linear. The types of the functions used, linear or non-linear, do not significantly affect the final alternative ranking, but the assumption of linearity should not be used without careful consideration (Hobbs and Meier, 2000). The functions should be selected based on the decision maker's comfort and it is beneficial to involve some technical experts in scaling of technical issues (Hobbs and Meier, 2000). Figure 2-7 below shows possible continuous value functions:

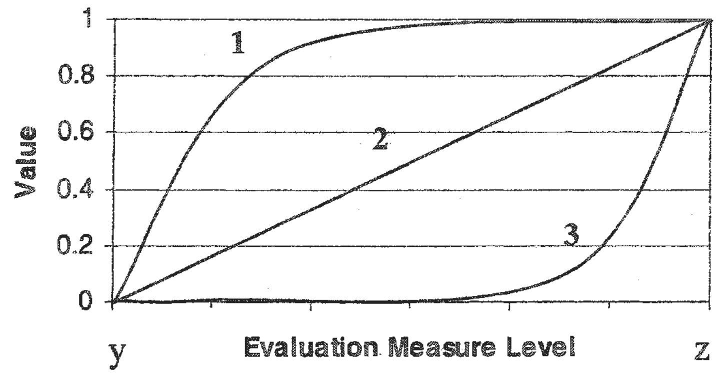

Figure 2-7 Scoring functions: Monotonically increasing

(Modified from Parnell et al., 1999)

The figure shows monotonically increasing value functions where the evaluation measure levels always increase or remain constant. These evaluation measures include those considered benefits (the higher value is preferred) such as treatment efficiency, and ease of operation. In the figure, the value increases from zero to one as the evaluation measure level increases from y to z. Line 2 represents a linear value function while line 1 and line 3 represent non-linear functions in which the value has marginally decreasing rates of return and marginally increasing rate of return respectively (Parnell et al., 1999).

Value functions can be monotonically decreasing where higher evaluation levels are translated to lower values (Parnell et al., 1999). The evaluation measures requiring this type of value functions are undesirable properties of alternatives or costs, such as the cost of operation, and size. In this case, the value decreases from one to zero when the evaluation measure level increases from y to z.

5) Assigning Weights

Weights represent the relative importance of criteria (Hobbs and Meier, 2000). The assigned weights are higher for the criteria that are more important (Parnell et al., 1999). All of the weights must add up to one or 100 percent (Parnell et al., 1999).

Assigning weights is an important process as it can make a significant difference in the results (Hobbs and Meier, 2000). According to Hobbs and Meier (2000), proper weights should be constant with tradeoffs that decision makers are willing to make among criteria. In other words, weights should represent the value that the decision maker willingly trades off one criterion for another or the relative importance of unit changes in the criterion values. Different weighting methods can possibly give different weights and, in turn, different results (Hobbs and Meier, 1986; Weber and Borcherding, 1993). Commonly used weighting methods are such as:

- **Equal weights**

This method is the method which considers all criteria equally important thus equal weights are assigned to all of them. This method is the simplest; however, it is not quite realistic that all the criteria have the same importance (Hobbs and Meier, 2000; Parnell et al., 1999).

- **Direct weighting**

Using this method, the decision makers directly assign weights according to their judgment. This method is simple but requires careful judgment. Examples of various ways to directly assign weights are point allocation, categorization of criteria based on their importance, ranking before assigning weights, defining ratios of importance of each pair of criteria, and rating or scaling the criteria (Hobbs and Meier, 2000).

In case of a large number of criteria, a "hierarchical approach" can be applied to help in this process (Hobbs and Meier, 2000). In this approach, criteria are grouped into major categories and weights are then assigned to each criterion. This method is better than the non-hierarchical method and provides more variable weights. However, some factors, such as the structure of the hierarchy, which can affect the defined weights, make this method not completely valid in measuring priorities (Hobbs and Meier, 2000). Therefore, careful considerations are essential in applying this method.

- **The Analytic Hierarchy Process** (AHP; Saaty, 1980)

This method requires decision makers to compare "every possible pair of criteria" and provide their importance ratio (Hobbs and Meier, 2000; Papatyi et al., 1997). Some scales are suggested to help in the comparisons such as that the decision maker may give "1" when the two attributes are considered equally important, "2" when attribute I is slightly more important than attribute II, etc. (Hobbs and Meier, 2000). With n criteria, n(n-1)/2 comparisons must be conducted and the same number of ratios can be obtained. The ratios can then be input in a matrix and the weights can be solved by using eigen vector analysis (Hobbs and Meier, 2000). Similar to the direct weighting method, hierarchical methods can also be applied. There might also be difficulties in applying this method when a large number of criteria are involved.

- **Swing weights**

Using this method, criteria are compared by considering a hypothetical alternative which has been assigned the worst values for all criteria (Hobbs and Meier, 2000; Clemen, 1996). Another hypothetical alternative is then set up to have the same property as the previous one, but has one most preferred criterion "swung" from the worst to the best. The process is then repeated for the second most preferred criterion and so on. After ranking the alternatives according to preference, weights (or "magnitude of preference" (Parnell et al., 1999)) are then assigned to alternatives such that 100 is assigned to the most preferred alternative and zero is assigned to the worst (Parnell et al., 1999). The weights for the criteria can then be calculated by modifying the weights proportionally so that the total weight of one is obtained. One of the advantages of this method is that considering and ranking the criteria makes it not too difficult for decision makers (Hobbs and Meier, 2000).

- **Pricing out and indifference tradeoff weights**

Pricing out weighting is to ask decision makers the amount they are willing to pay to increase a benefit or to decrease an undesirable property of an alternative. An example of this method is paying 1 million dollars to increase the treatment efficiency from 95% to 99%.

Another similar method is called indifference tradeoff. This is an indirect weighting method where decision makers are asked to make tradeoffs and calculate weights by using the equation (Hobbs and Meier, 2000):

$$\frac{w_h}{w_i} = \frac{-[V_i(A_{iX}) - V_i(A_{iY})]}{[V_{hi}(A_{hX}) - V_h(A_{hY})]} \qquad (2.7)$$

where X and Y are 2 alternatives which differ in only 2 criterion h and i. $V_i(A_{ij})$ is the value of criterion i for alternative j.

Although this method is preferred as the obtained weights correctly represent tradeoffs, it is quite a difficult task to define tradeoffs between each pair of criteria.

6) Overall value model

Overall value models or overall value functions are mathematical models used in an amalgamation method which is conducted to evaluate alternatives consistently with the preferences of the decision maker (Clemen, 1996). Some of the models, such as the additive value function, provide a single index which enables the decision maker to rank alternatives.

The additive value function is the most commonly used function as it is simple and easily understood. Sensitivity analyses can also be broadly utilized (Steward, 1995). This function is basically a weighted average of scoring functions $v_1(x_1),..., v_n(x_n)$ for n evaluation measure levels x_1 to x_n (Parnell et al., 1999). The evaluation measures for each criterion were linearly averaged to provide a single number or index which represents the decision maker's preferences and can then be used in comparison (Rudin et al., 1993; Papatyi et al., 1997). The function can then be presented as (Modified from Parnell et al., 1999):

$$v(x_1,\ldots,x_n)=\sum_{i=1}^{n} w_i v_1(x_i) \qquad (2.8)$$

where w_i represent weights for each attribute i and add up to one (Keeney and Raiffa, 1976).

2.3 SUMMARY

The extent of environmental impacts from drilling cuttings discharge depends on the composition of adhered contaminants. Sources of the contaminants on the cuttings include retained drilling fluids and formation oil. The potential environmental impacts from cuttings discharge include benthic smothering, toxic impact, bioaccumulation, and organic loading. Therefore, the cuttings must be properly managed to avoid adverse environmental effects. The management of drilling cuttings wastes is controlled by regulations, which differ from place to place. Other than a solids control system, which provides basic fluid separation, various technologies, such as cuttings dryers, may be used to sufficiently reduce the retained amount of fluids on the cuttings before ocean discharge. In cases where no discharge is allowed, the cuttings must be either transported ship-to-shore for treatment and disposal, or re-injected onsite.

In this study, selected technologies to deal with drilling cuttings wastes including treatment technologies and re-injection, a disposal method, were assessed using multicriteria decision making. The multicriteria decision making approach is widely used to help in decision making problems when conflicting criteria are involved. Even though this approach may be performed in various ways, it has a few basic and required steps which include identifying criteria, identifying alternatives, screening, scoring, assigning weights, and overall value calculations (or alternative ranking).

CHAPTER 3

REVIEWS OF DRILLING CUTTINGS MANAGEMENT TECHNOLOGIES

This chapter presents reviews of the technologies used for drilling cuttings management that were considered as options in the evaluation. Emerging technologies are also reviewed.

3.1 CENTRIFUGES

A centrifuge is a mechanical treatment used to separate drilling fluids from drilling cuttings. Developed in the coal industry, dryer centrifuges combine the fine screen of a shale shaker with a rotating basket of a centrifuge (CAPP, 2001). Therefore, they can dry drilling cuttings more efficiently than conventional centrifuges and reduce waste volume. The cuttings dryer centrifuges only require a small deck space and have been successfully used offshore. However, there is concern regarding disposal of the large amount of fines created during the process. These fines are removed from the returned fluid by using a high speed decanting centrifuge and require proper disposal (CAPP, 2001). There are basically two types of the cuttings dryer centrifuges: vertical basket and horizontal basket.

3.1.1 Horizontal Centrifuge

The screen basket used in this type of centrifuge is oriented horizontally (Figure 3-1). An example of this technology is called a "Duster Cuttings Dryer" supplied by Swaco and Hutchison-Hayes International. The process starts with a conveyor transferring drilling cuttings from shale shakers to the dryer unit. The cuttings are distributed evenly on the high g-force rotating screen where the cuttings are transported through the centrifuge by a screw conveyor and separated from the fluid. After the drying process, the cuttings, which retain between 3 to 5% by weight of fluid on cuttings are then transferred to an effluent tank (Swaco, 2002). The efficiency depends on the effective g-force, screen area at g-force, residence time on screen, and cuttings thickness on screen (Swaco, 2002). The capacity of the system varies from 30 tons (continuously) to 90 tons (intermittently) of cutting waste per hour (Swaco, 2002).

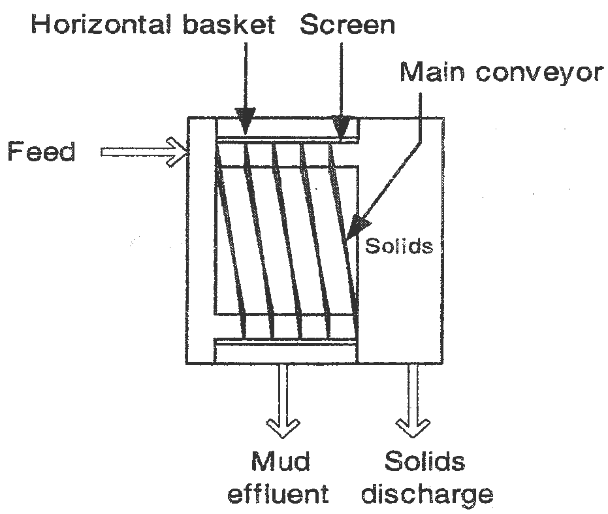

Figure 3-1 Horizontal centrifuge unit (Modified from Swaco, 2002)

3.1.2 Vertical Centrifuge

This technology uses the same concept as the horizontal centrifuge, but with a vertically oriented basket centrifuge. The components of the system are shown in Figure 3-2. The treatment process is similar to that of the horizontal centrifuge. However, the cuttings processed by the vertical centrifuge exit the centrifuge unit by gravity (Oiltools, 2002b). The treatment efficiency varies from 1.8 to 4.4% fluid retention (Apollo, 2002;

Oiltools, 2002b). Some systems can process cuttings waste from 32 to 60 tonnes per hour (Oiltools, 2002b; Swaco, 2000). Vertical centrifuges have been used offshore; however, as the waste exits the centrifuge unit from the bottom, most of the systems require a stand for the centrifuge which can add up to four meters to the height, which is undesirable on an offshore platform.

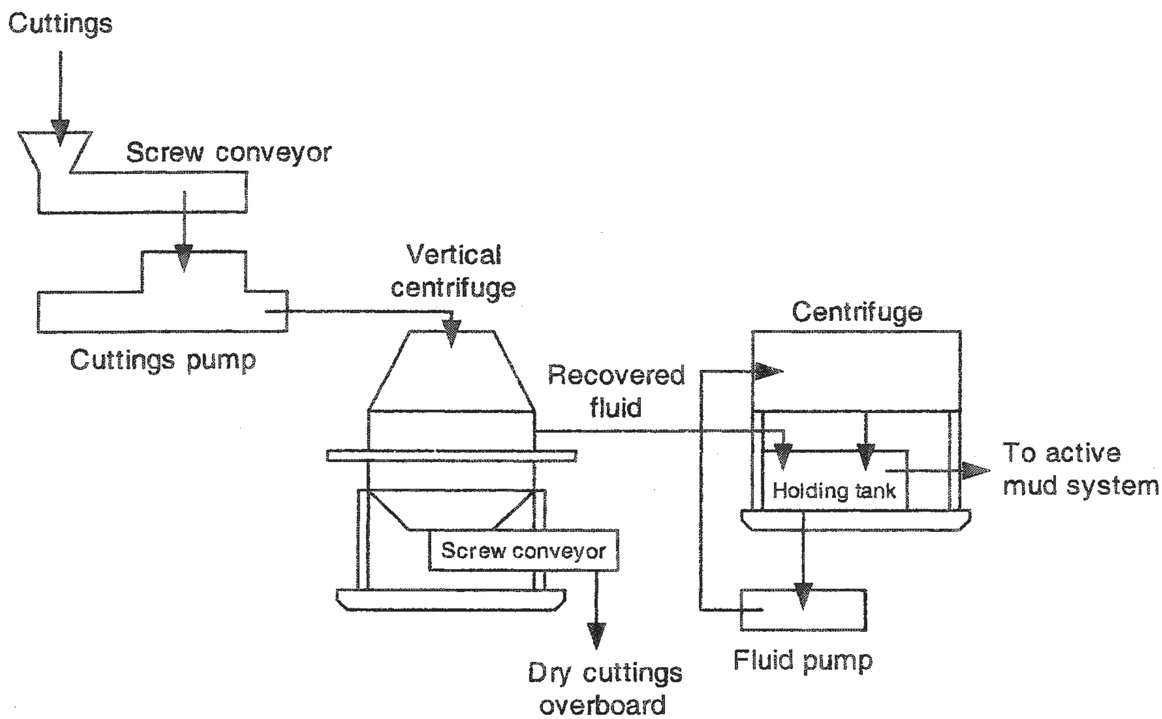

Figure 3-2 Vertical centrifuge process schematic (Oiltools, 2002b)

3.2 THERMAL TREATMENT

3.2.1 Thermal Desorption

Thermal desorption is a process to treat solids by using heat to volatilize and physically separate organic contaminants retained on the solids. Oxidation of contaminants might occur during the process; however, this process is not designed to destroy contaminants. The volatilized water and the contaminants are transported by either a carrier gas or vacuum system to the gas treatment system where the entrained particulates are removed by conventional equipment, such as wet scrubbers and fabric filters (FRTR, 2003; Anderson, 1993c). Typically, the contaminants can then be either destroyed by using a combustor or catalytic oxidizer, or removed by condensation followed by carbon adsorption (FRTR, 2003). However, most of the thermal desorption systems for drilling cuttings are designed to recover oil in the vapor stream using a phase-separation process (Oiltools, 2002a). The typical thermal desorption process is shown in Figure 3-3.

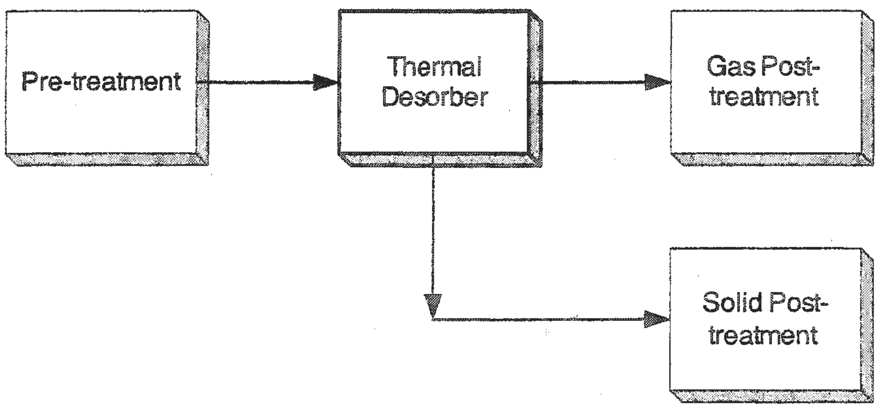

Figure 3-3 Thermal Desorption Schematic (Anderson, 1993c)

Typically, thermal desorption is used to treat various kinds of solid wastes including drilling cuttings. It is used to remove contaminants such as petroleum hydrocarbons (fuels), non-halogenated volatile organic compounds (VOCs), and semi-volatile organic compounds (SVOCs) (FRTR, 2003). According to Bansal and Sugiarto (1999), it is more difficult to treat heavier compounds such as PAHs using thermal desorption. The effectiveness of the treatment to remove different kinds of contaminants depends on the operating temperature, which varies from 320 to 560 °C for high temperature thermal desorption and from 90 to 320 °C for low temperature thermal desorption (FRTR, 2003). Rotary dryers and thermal screws are the two common designs of thermal desorption units (FRTR, 2003).

The thermal desorption process can be divided, based on the heating method used, into two major types: direct-heated and indirect-heated. In the direct thermal desorption process, the combustion gases directly come into contact with the cuttings. In contrast, indirect thermal desorption processes do not involve direct contact of the cuttings waste and the combustion gas or heat transfer fluid. The heat is transferred to the cuttings by convection and radiation, thus, smaller capacity gas treatment units are required (Anderson, 1993c). The heat transfer fluid can be used again in the desorption process to provide a closed loop system (Oiltools, 2002a).

Thermal desorption systems might require pre-treatment to reduce water content in the wastes to be treated. The water content is an important parameter affecting the energy used and costs of the process. For efficient thermal desorption operation, the water content should be between 20 to 50% (Anderson, 1993c). Characteristics of wastes such as particle size also have influences on the process's efficiency and applicability; thus crushing and/or screening of the cuttings may also be required (Anderson, 1993c).

Thermal desorption is now used to treat cuttings onshore and some systems are available in portable form. The United Kingdom Offshore Operators Association (UKOOA; 2000) has included an indirect thermal desorption system as a technology with potential for offshore use due to its "compact design and robust track record". However, there are still some general restrictions for offshore applications of thermal desorption. The main restriction is the size (footprint) of the system including the storage required prior to the treatment process. In addition, the application of this technology is limited by health and safety issues including oil vapor emissions, dust, and risks associated with the high temperature processes (UKOOA, 2000). Heavy metals and low specific activity scale retained on the treated cuttings are also factors to be considered (UKOOA, 2000). In the presence of heavy metals, some toxic by-product may be formed during the treatment process (UN, 2000).

Figure 3-4 shows the indirect thermal desorption process by Oiltools which has been successfully used to treat drilling cuttings. The porcupine process is a low temperature indirect thermal desorption system using a maximum temperature of 340°C (Oiltools, 2002a). The volatilized water and oil vapors are condensed and phase separated in the "vapor recovery unit" (UKOOA, 2000; Oiltools, 2002a). The recovered water is further treated before it is used to spray the treated cuttings for re-hydration or discharged (Oiltools, 2002a). The amount of oil on the cuttings after treatment is less than 1% which makes the cuttings possible to be reused, e.g. as construction meterials (Oiltools, 2002a). The properties and rheology of the recovered oil are similar to the original oil (Oiltools, 2002a). This is one of the advantages of thermal desorption over other processes, such as incineration, where valuable base oil is destroyed.

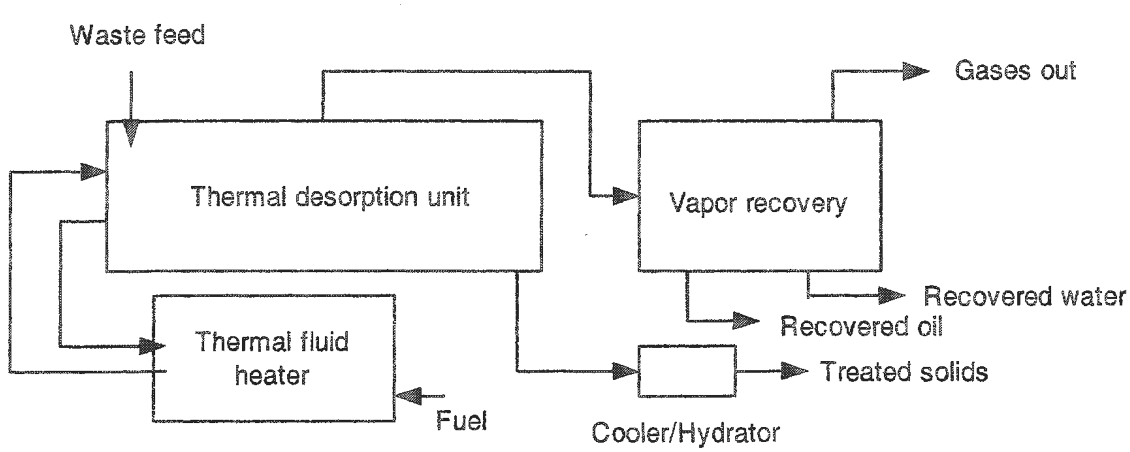

Figure 3-4 Thermal desorption process (Modified from Oiltools, 2002a)

3.2.2 Incineration

Incineration technology is used to treat drilling cuttings by volatizing and combusting contaminants with oxygen (UN, 2000). It is normally used to treat highly toxic, flammable, and organic wastes resistant to biological break down (Cripps et al., 1998). There are four typical types of incinerators: rotary kiln, liquid injection, fluidized bed, and infrared (UN, 2000). In the incinerator, the contaminants are combusted at higher temperature than that in thermal desorption, ranging from 850 to 1,200°C to provide sufficient combustion of unwanted combustion gas such as dioxins (UN, 2000). The higher temperature results in higher energy use and costs than thermal desorption. As the process involves volatilization and combustion of water and contaminants, the costs of operation or energy required is directly related to the water content in the drilling cuttings waste. Gas treatment equipment is required for off-gases and combustion residuals generated from the process (Cripps et al., 1998; FRTR, 2003). The ash or solid residue is then disposed of by landfilling.

Concerns associated with the application of this technology to treat drilling cuttings are quite similar to other thermal methods. Volatile heavy metals can be released with flue gases or remain in the treated solid (FRTR, 2003). In addition, combustion may result in by-product compounds which are more volatile or more toxic, such as chloro-organic compounds or barium oxides (UN, 2000; Cripps et al., 1998). Other issues regarding offshore applicability include size, air emissions and risks associated with use of a high temperature processes. Combustion of the drilling fluids on the cuttings eliminates the opportunity to recycle base fluids.

3.2.3 Grinding

Grinding uses "frictional grinding" to treat drilling cuttings. One of the suppliers is Burgess and Garrick licensed as TCC Technology (UKOOA, 2000). According to United Kingdom Offshore Operators Association (UKOOA; 2000), the technology has been used at two onshore sites since 1995 and a "containerized version", which is more suitable for offshore applications, is now being developed. The process, outlined in Figure 3-5, involves treatment of drilling cuttings by mechanical grinding in a sealed chamber. The friction in the grinding process provides sufficient heat to volatilize oil and water retained on the cuttings. The temperature in the process varies from 250°C to 270°C. After the process, the cuttings are in the form of "oil-free powder" which are then bagged and disposed (UKOOA, 2000). The entrained solid in the vapor stream is removed using cyclones. In the first condensation stage, the oil vapor is condensed and reused. The water vapor is condensed in the second stage and discharged.

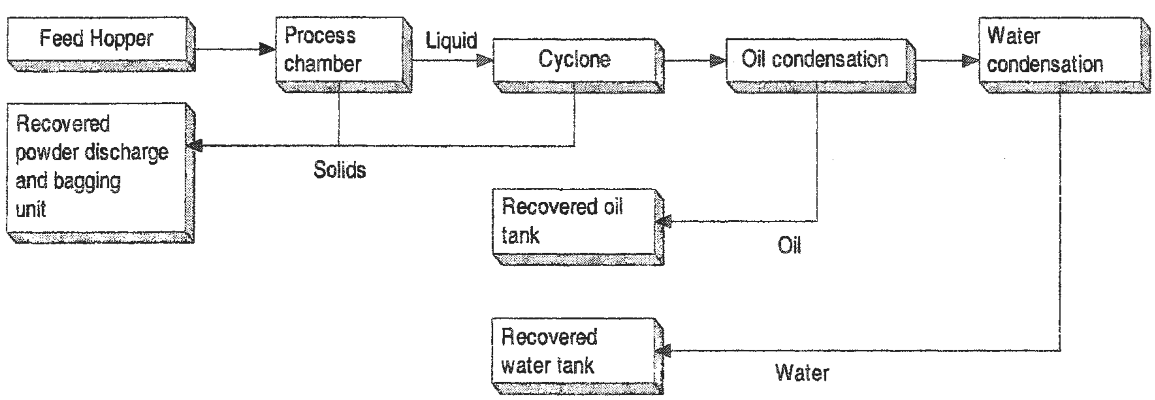

Figure 3-5 Schematic of the grinding process (UKOOA, 2000)

This process is similar to the process called "Hammermill" which is being used onshore in the UK (CAPP, 2001). The process uses the same mechanism of frictional grinding to heat contaminated drilling cuttings up to a temperature between 270°C and 290°C (CAPP, 2001). The treated cuttings contain less than 0.1% oil and allow recycling of the recovered oil (CAPP, 2001).

Similar to other thermal treatment processes, concerns in the grinding process include increase of fire risk due to high temperatures, dust, and air emissions (oil and VOCs) from the process (UKOOA, 2000).

3.3 STABILIZATION/SOLIDIFICATION

According to UN (2000), solidification is the process where contaminants are physically bound or enclosed in a low-permeability mass and stabilization is the process where chemical reactions are induced between a stabilizing agent and contaminants to diminish their mobility. Stabilization and solidification are two different processes which may both employ chemical, physical, and thermal processes to reduce toxicity of waste (UN, 2000). However, the two processes differ. In the stabilization process, the contaminants in the hazardous waste are changed into another form with reduced solubility, mobility, or toxicity (Anderson, 1993b). On the other hand, solidification involves encapsulation of the waste into "monolithic solids with high-structural integrity" such as concrete where migration of contaminants is limited through reduction of leaching surface area or isolation of waste (Anderson, 1993b; Cripps et al., 1998). Various organic polymers or inorganic additives can be used in the process to bind the waste (Cripps et al., 1998). Some wastes, such as those containing a high proportion of organics, flammable or explosive compounds, may cause difficulties in the treatment. Further, pre-treatment may also be required to ensure the desired properties of the resulting material (Cripps et al., 1998).

An example of the stabilization process is the use of a fly ash mixture to stabilize the cutting wastes at a rate of 2-30 tonnes/hour before disposal in a landfill (Cripps et al., 1998). The advantages of this technology are that it is a relatively inexpensive, simple method that produces minimal air emissions (Cripps et al., 1998; UN, 2000). However, this technology may result in an increased total volume of waste (Cripps et al., 1998). In addition, the contaminants are not removed from the cuttings. Therefore, there is an associated future liability (UN, 2000).

3.4 BIOREACTOR

Bioremediation (Figure 3-6) is the process using specific kinds of microorganisms to degrade organic content in the wastes to non-toxic products such as carbon dioxide, water, and biomass (Anderson, 1993a). In biological treatment, appropriate conditions are required to enhance the microbiological activity. The basic parameters affecting the efficiency of the treatment include moisture content, pH, temperature, and nutrients. (Kellems et al., 1991). The biological treatment is conducted in a bioreactor.

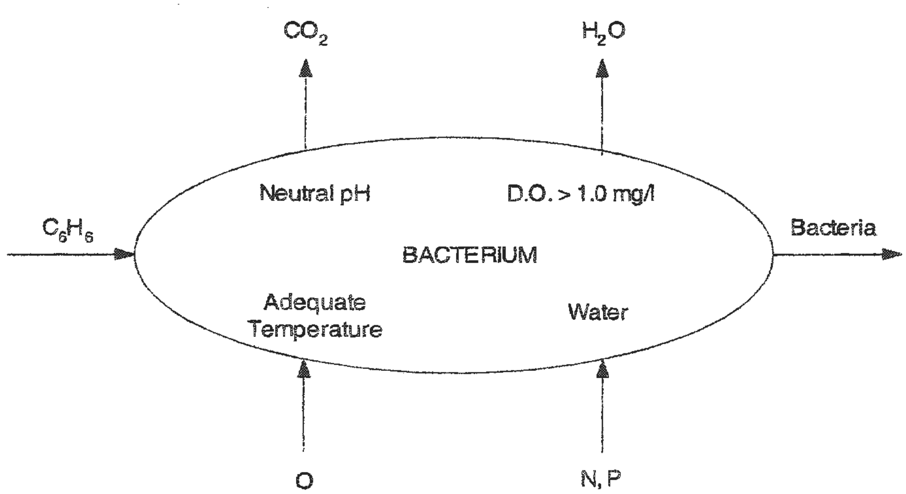

Figure 3-6 An aerobic design: biochemical process (Anderson, 1993a)

Bioreactor technology or "slurry-phase treatment" is one such technology to treat drilling cuttings in a sealed reactor (Anderson, 1993a). In the slurry-phase bioreactor, the waste is mixed with nutrient-adjusted water to maintain an aqueous slurry form generally containing 30-50% dry solids by weight to achieve the maximum efficiencies (Anderson, 1993a). Mechanical mixing is used to maintain solid suspension and aeration equipment is used to provide sufficient oxygen for aerobic degradation. An off-gases control system may also be needed for some systems to control volatile material releases. This method is better than other types of biotreatment (e.g. landfarming) since it requires less space and enhances the mass transfer rate between contaminants and microorganisms leading to faster treatment. The treatment conditions can be better controlled and the addition of water helps reduce the concentration of the contaminants in the waste which might have adverse effects on the process (Kellems et al., 1991).

Bioreactors generally require pre-treatment since the biological process is not able to remove inorganic wastes. Therefore, chemical or physical treatments are required as a pre-treatment in the presence of inorganic contaminants (Cripps et al., 1998). In addition, pre-treatment is required to adjust the environmental conditions to be the most suitable for biological activities. Thus, the pH of the waste might need to be adjusted (Kellems et al., 1991). Some oversized material may need to be removed before the cuttings enter the reactor (Anderson, 1993a). Moreover, biological treatment may also be susceptible to toxic substances in drilling fluids such as biocides and some systems may be limited by concentration of contaminants in the feed. Even though the biological process has relatively less environmental impacts, limitations on offshore application mainly include the capacity of the process, which results in a temporary storage requirement, and the time required by the treatment process.

3.5 RE-INJECTION

Drilling cuttings re-injection (CRI), also known as "slurry fracture injection", is the technique in which drill cuttings and other oilfield wastes are mixed into slurry with water and re-injected under high pressure (at or above formation fracture pressures) down an injection well (Wills, 2000; TTI, 2002). This method is considered a disposal technique where the re-injected drilling cuttings waste is contained in the confined area without migration into the environment through the seabed or water resources (Figure 3-7). CRI has been successfully applied since the 1980's in several areas around the world such as in North America and the North Sea area (Abou-Sayed and Guo, 2002).

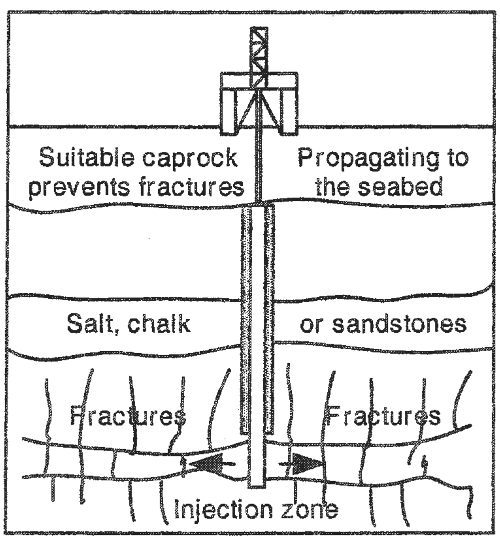

Figure 3-7 Cuttings re-injection (Modified from Swaco, 1999)

The cuttings wastes can be re-injected into the formation through an annulus of an existing production well or a purposely drilled well called a dedicated well. Normally, re-injection is conducted at the platform where the cuttings are produced (UKOOA, 2000). However, as a suitable formation is critical, remote re-injection is also possible where cuttings are transported to the re-injection site (UKOOA, 2000).

The CRI process starts with selection of a suitable formation, or an injection zone, to contain the wastes. The selected receiving formation must have the capability of containing the specific volume of wastes to prevent break out of waste to the environment. Other factors influencing the well selection include well location, depth, and injection pressure (Oiltools, 2000). According to Saasen et al. (2000) and Bruno et al., (2000), the best receiving zone is under a highly porous sand formation with an underlaid impermeable layer to keep the injected waste in a confined zone. In the receiving formation, the high pressure of the slurry injection creates a fracture where the cuttings particles are retained while the fluid phase in the slurry leaks off through the sand layer (Saasen et al., 2000). This allows the formation to contain as much cuttings as possible and the sand zone above the fracture also serves as a "safety barrier" to prevent the fracture from extending upward (Saasen et al., 2000; TTI, 2002).

The drilling cuttings re-injection process consists of a few steps (Figure 3-8). First, the cuttings are transported to the slurrification unit where the cuttings wastes are mixed with water (usually seawater or waste water and maybe chemicals) and ground into fine particles with pre-determined sizes of less than 300 microns (Abou-Sayed and Guo, 2002). The solid concentration varies from 15 to 30% by volume (personal communication, Guo, 2002). Currently, ultrasonic processors have also been developed to reduce cuttings size in a slurrification system (Saasen et al., 2001). The specified cuttings particle size distribution is ensured by using a classification shaker (Cripps et al., 1998). The viscous slurry, which is stable and is maintained solid suspension, is then either kept in a storage tank until there is sufficient slurry, or directly injected downhole into the selected disposal zone (Wills, 2000). The rate of injection ranges from 0.6 to 1.75 m^3/min and at pressures ranging from 63 to 100 bars (Wilson et al., 1993). The cuttings are contained in the formation with no future cleanup liabilities.

According to the United Kingdom Offshore Operators Association (UKOOA; 2000), health and safety issues from CRI are comparable to normal offshore operations. However, there are risks associated with transportation when using remote re-injection. The major environmental concerns are related to migration of the re-injected wastes to the environment (UKOOA, 2000). In addition, according to Saasen et al. (2000), air emissions generated from power used in the process are also expected.

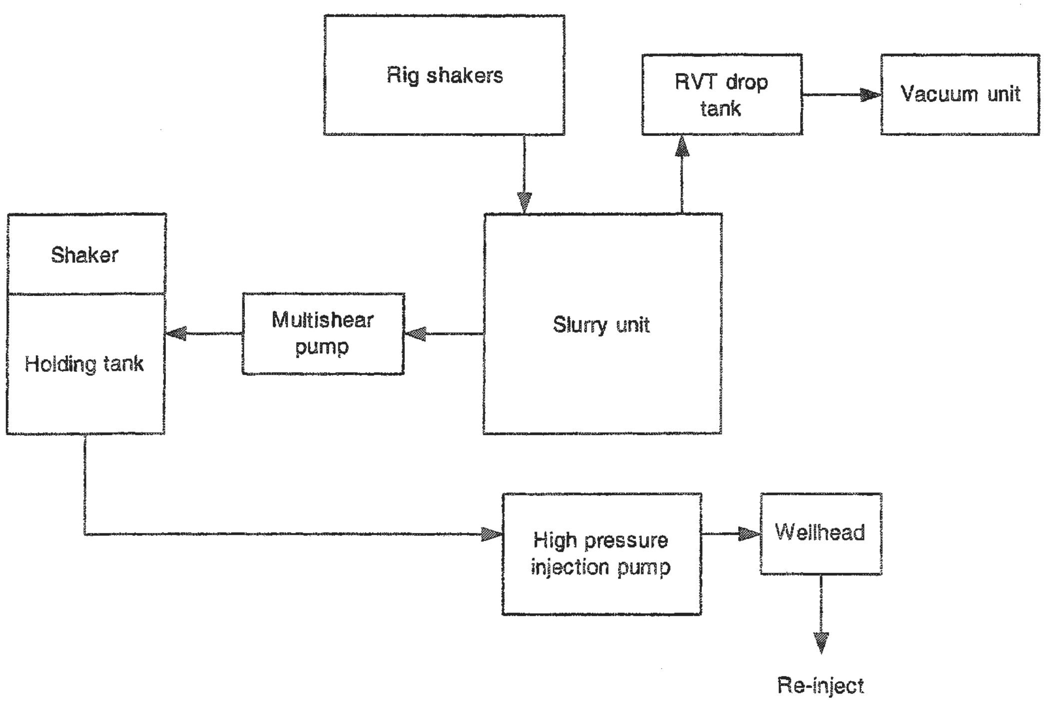

Figure 3-8 Cuttings slurrification and re-injection process (Modified from Swaco, 1999)

3.6 INNOVATIVE TECHNOLOGIES

The technologies in this section are new technologies which are currently under development. All of the reviewed technologies use some kind of chemical treatment and have the ability to reduce fluid retention on cuttings to less than 1%. Therefore, these technologies have very high potential for offshore use. However, as the technologies are under development, most information is confidential and data regarding field operations is not available.

3.6.1 Supercritical Extraction

Supercritical extraction is a process using supercritical fluids as solvents to extract fluids on drilling cuttings. The supercritical fluid is created by setting the pressure and temperature conditions of a substance beyond its critical point or in the critical region (Saintpere and Morillon, 2000). The supercritical fluid has the properties of both liquid and gas. It has liquid density but gas-like low viscosity and high diffusivity (Cripps et al., 1998; Saintpere and Morillon, 2000). The most important property of the supercritical fluid in drilling cuttings treatment is the ability to dissolve contaminants. The ability increases with density and can be achieved by adjusting its pressure and temperature condition. In addition, the gas-like properties enhances mass transfer and extraction rate from porous solids (Cripps et al., 1998). In this section, two supercritical extraction systems using two different supercritical fluids are discussed.

- **Supercritical Extraction using Hydrocarbons**

Cripps et al. (1998) has reviewed a supercritical extraction process called the CF system. The system uses liquid propane as the extraction fluid to extract hydrocarbon contaminants from soils and sediments. The process (Figure 3-9) starts with transportation of the feed to the extraction system. The maximum acceptable particle size is about 1 mm; thus, the oversize materials are separated and processed to the proper size before entering the extraction system (Cripps et al., 1998). In the extractor, propane solvent contacts the feed and extracts contaminants on the feed material. The mixture is then allowed to be phase-separated by reducing temperature and pressure below critical conditions. This process is repeated many times until the desired level of contaminant removal is achieved. Hot water is then used to displace and evaporate retained propane on the solids. The water and solid mixture is filtered in the filtration system. Fixation of metals may be required before disposal of the treated solids. The used propane is recycled by vaporization and condensation and returned to the extraction system. The extracted oil that is separated from the propane can be recovered. The typical charge of this process on soil remediation varies from US$100 to US$400 per tonne. The main disadvantages of this supercritical extraction process include risks of using combustible gas and high investment and operational costs (UKOOA, 2000, Cripps et al., 1998). Other concerns include air pollution from release of VOCs (UKOOA, 2000).

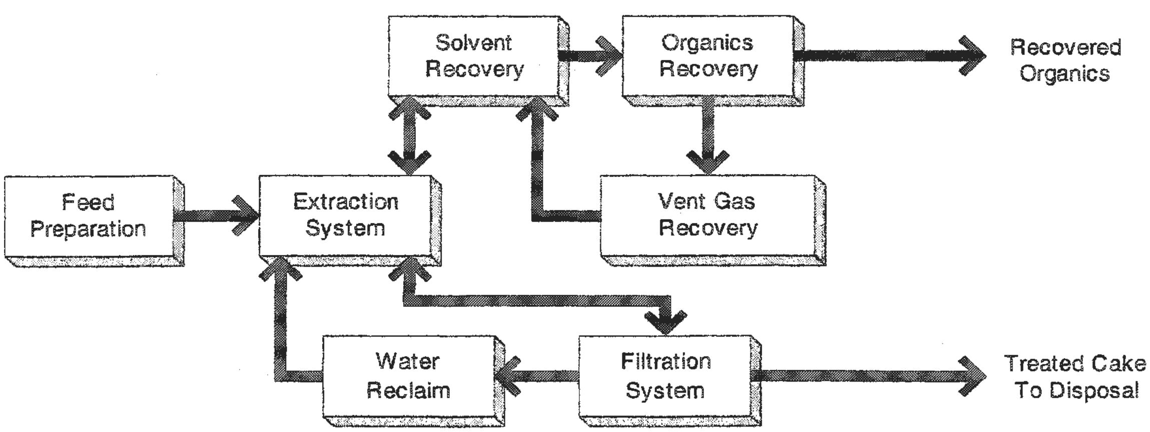

Figure 3-9 CF Systems Solvent Extraction Remediation Process (Cripps et al., 1998)

The United Kingdom Offshore Operators Association (UKOOA; 2000) reviewed another supercritical extraction method which uses a natural gas liquid system developed by Rogaland Research to treat drilling cuttings. The process has been stated to require no high pressure vessels and this makes the process more applicable to offshore operations (UKOOA, 2000). However, the process uses propane or butane at pressures up to 20 bar and room temperature (personal communication, Mönig, 2002). Therefore, the fluid used is not considered to be in supercritical conditions. The process is found to be not quite suitable for offshore application due to high costs, size, weight, and safety aspects (personal communication, Mönig, 2002). Other information regarding this system remains confidential.

Eldridge (1996) has presented results from pilot scaled supercritical extraction systems using propane and Freon as solvents. The experiments show that both Freon 134a and propane have very high efficiency in removing oil contaminants (more than 98%) (Eldridge, 1996). However, flammability of propane is the main concern for offshore application. Therefore, a commercial system (Figure 3-10) was designed for Freon and the cost estimate for the system shows reasonable installation cost compared with cuttings re-injection and the total cost of onshore management.

According to USEPA (2002), Freon 134a is a Hydrofluorocarbon which is used as a refrigerant to substitute CFC-12. The Freon 134a does not contain chlorine or bromine thus it does not deplete the ozone layer (USEPA, 2002; CMDL, 2003). In addition, Freon 134a does not pose a cancer or birth defects hazard based on current toxicity data (USEPA, 2002). However, this type of compound may cause adverse environmental effects (for example they are efficient absorbers of infrared radiation) and venting of Freon 134a is prohibited by the USEPA (USEPA, 2002; CMDL, 2003). Freon 134a is also flammable at elevated pressures (CMDL, 2003), thus use of this compound under supercritical condition might not be suitable for offshore oil and gas operations.

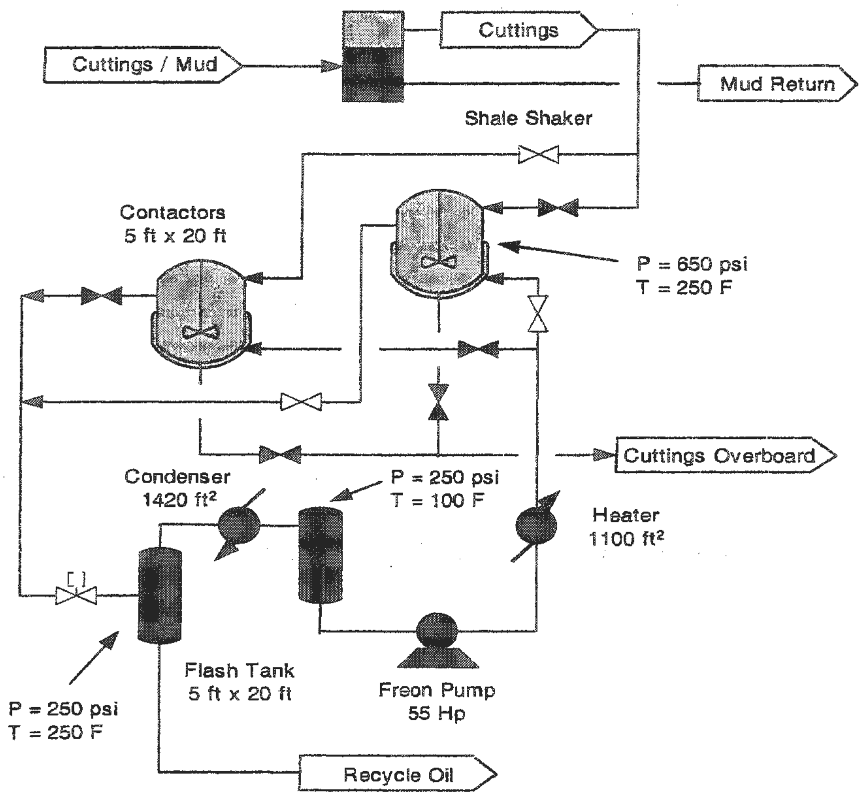

Figure 3-10 Commercial supercritical extraction process using Freon (Eldridge, 1996)

- **Supercritical Extraction using CO_2**

Supercritical extraction using CO_2 uses a similar process to that using hydrocarbons. The basic process of CO_2 supercritical extraction is shown in Figure 3-11. According to Saintpere and Morillon (2000), CO_2 is the most widely used supercritical fluid due to its easily achieved supercritical conditions (the critical point is 73.8 bars; 31°C) and high solvating ability (Saintpere and Morillon, 2000). In addition, CO_2 is non-flammable, non-toxic, inexpensive, and commercially available.

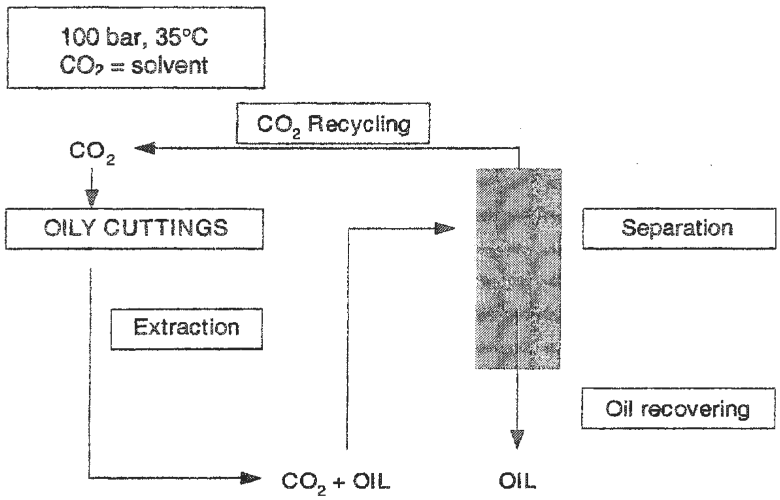

Figure 3-11 CO2 supercritical extraction principle (Saintpere and Morillon, 2000)

A supercritical extraction process using CO_2 has been developed by Separex to treat oil-based cuttings. Tests on a small scale system have proven successful to treat cuttings from Norway and Holland to 1% fluid retention (UKOOA, 2000). According to United Kingdom Offshore Operators Association (UKOOA; 2000), a demonstration plant with the treatment capacity of 100 kg of cuttings per hour has been designed for onshore and offshore applications. The process (Figure 3-12) includes crushing of drilling cuttings to the size of 0.1 to 2 mm in diameter and mixing the crushed cuttings with supercritical carbon dioxide at 20°C and 60 bar to dissolve or extract the oil on the cuttings (UKOOA, 2000). The extracted oil is separated from the mixture of fluid by using a high performance cyclone and can be recycled. The released gas is condensed to be used again in the process while the treated cuttings are removed as a slurry. In this process, there are health and safety concerns regarding use of high pressure gas, such as the potential for CO_2 to build up in confined spaces of equipment. Possible environmental concerns include release of CO_2 which is a greenhouse gas (UKOOA, 2000).

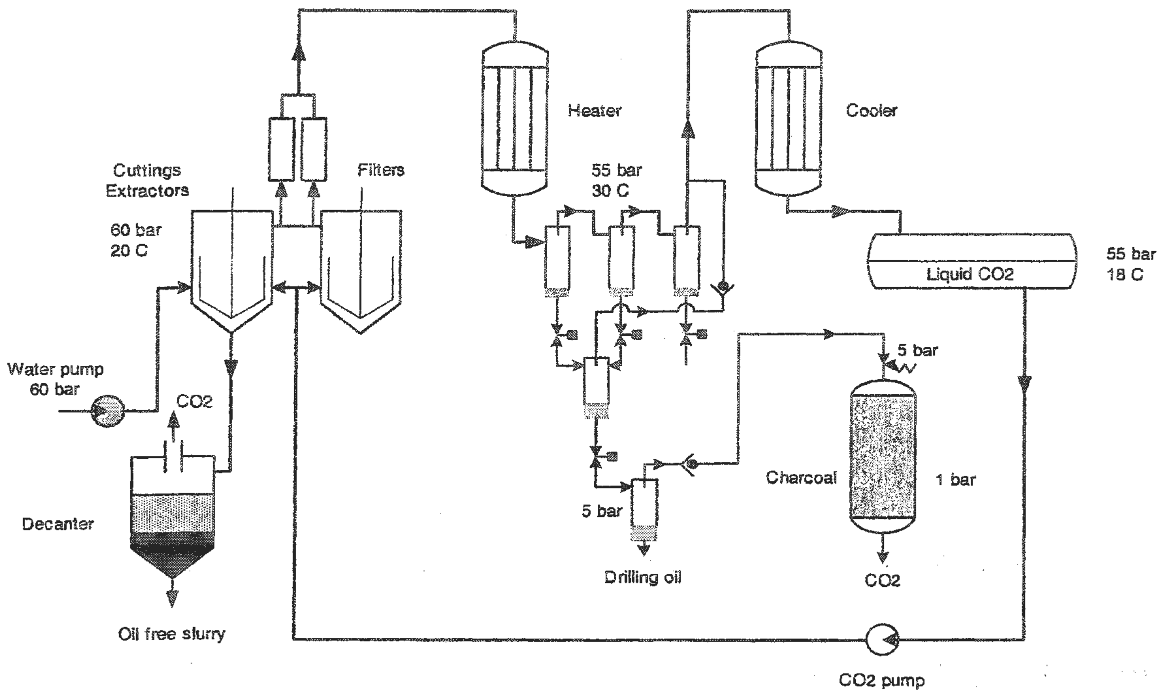

Figure 3-12 Supercritical extraction using liquid CO_2 (UKOOA, 2000)

3.6.2 Microemulsion

Microemulsion technology has been developed by Napier University, Edinburgh, Scotland. In the process, the cuttings from a solids control system enter the treatment unit with around 7-10% weight base fluid (UKOOA, 2000). An aqueous solution of a non-toxic, biodegradable microemulsion-forming surfactant is added at room temperature and pressure to clean the contaminated cuttings. This specialized surfactant rapidly extracts the oil on cuttings and form a colloidal oil in water microemulsion. The microemulsion and the clean cuttings are separated using conventional equipment such as a centrifuge. After the separation, there are still some traces of the microemulsion remaining on the solids. These can be removed using an aqueous or brine wash resulting in the washed cuttings containing lower than 0.5% of oil (UKOOA, 2000). The microemulsion is transported to a phase-separator unit which allows recovery of surfactant and oil.

According to UKOOA (2000), the process has been tested in a prototype using commercially available surfactants. The development of a surfactant which will allow more efficient separation and recovery of oil and surfactant, as well as the reduction of surfactant losses to less than 5% per cycle are now the focus for this technology.

Health and safety concerns associated with this microemulsion technology are handling of the emulsion and the aqueous wash effluent, which may require appropriate treatment and disposal (UKOOA, 2000).

3.6.2 Silica Microencapsulation

Silica microencapsulation (SiTEQ) developed by Baker Hughes INTEQ is a process where the retained oil on cuttings is physically encapsulated in amorphous silicate (SiO_2). The silicate droplet is insoluble and the encapsulated oils do not leach or biodegrade (Limia, 1999).

The process consists of the addition of an emulsifier into the oil-contaminated cuttings to emulsify the oil into "microscopic droplets" (Limia, 1999). The emulsification stage is performed in acidic conditions and different emulsifiers are used depending on the properties of the retained oil (Limia, 1999; Quintero, 2001). Water soluble silicate is then added to the mixture of the emulsified oil and cuttings to form silica gel around the oil droplets. The silica microencapsulated droplets are stable and have a size ranging from 1 to 300 microns. When discharged into the ocean, the encapsulated oil will be gradually leached off mainly through abrasion. This leaching is expected to be gradual and depends on many factors, such as the distribution of the droplet sizes and the thickness of the silica shell (personal communication, Quintero, 2002). According to Quintero (2001), a field test has been conducted using a 65 ft^3 unit. The results show that the contaminated cuttings with 12 to 17% by weight of retained oil were treated to less than 0.01% free oil. In addition, leaching tests show satisfactory results (less than 0.01% leached after a 150-day evaluation period) and lab-scale test results show that the treated material was thermally stable at temperature up to 150°F (66°C) (Quintero, 2001).

According to Limia (1999), this method will help reduce environmental impacts from drilling cuttings discharges in many ways. For instance, this method helps increase cuttings dispersion, which in turn reduces the potential for the seabed smothering impacts. Further, the encapsulated oil on cuttings is not bioavailable to marine organisms and does not cause organic enrichment. The slow release of oil also leads to very small amounts of oil which can rapidly biodegrade by natural mechanisms (CAPP, 2001). However, the treated cuttings using this technology are not allowed to be discharged into the ocean due to the current environmental regulations. In the North Sea, discharge of the encapsulated oil and cuttings is not permitted under zero discharge conditions (personal communication, Limia, 2002). Similarly, according to USEPA (2000c), this technology is incompatible with the method used to determine the amount of the retained fluids on cuttings due to the break down of the silica droplets under very high temperature. Therefore, the discharge of the treated cuttings can only be conducted when the amount of oil retained on cuttings is lower than 6.9% by weight (personal communication, Limia, 2002).

CHAPTER 4

EVALUATION METHODOLOGY

In this study, an evaluation methodology was developed to help select the most suitable management option for ongoing drilling operations. The simple additive weighting multicriteria decision making approach similar to the US DOE's methodology (Parnell et al., 1999) was used to evaluate the drilling cuttings management options as described in detail in this chapter. Less complex deterministic multicriteria decision making using "point estimates of decision variables" (Stansbury et al., 1999) instead of considering intervals with unknown probabilistic distribution was applied and uncertainty was considered separately.

4.1 IDENTIFY CRITERIA AND EVALUATION MEASURES

The first step of multicriteria decision making is to identify the evaluation criteria following the value-focused thinking approach proposed by Keeny (1992). The criteria are the controlling factors in which drilling cuttings management options will score in the evaluation. Therefore, the criteria must be chosen such that they accurately reflect the issues with respect to drilling cuttings management technologies. In this study, criteria were divided into two major types: threshold criterion and decision making criteria.

4.1.1 Threshold Criterion

The threshold criterion is used to screen out inappropriate options which are not likely to be selected as the optimum option at the end of the evaluation. The options not meeting the threshold were discarded and were not evaluated further. Conformity to discharge regulations was deemed to be the most appropriate threshold criterion due to its importance and because it provided ease of application. In this case, the discharge standard of 6.9% retention of base fluid on wet cuttings, which is the acceptable fluid retention level used in the USA and Canada (USEPA, 2000a; NEB et al., 2002), was used in the screening and the options that are not able to meet the regulatory discharge standard were rejected and not considered as evaluation options.

4.1.2 Decision Making Criteria

Decision making criteria are the criteria which were used to evaluate and compare options. These criteria provide tradeoffs of important factors that influence the decision making, such as tradeoffs between financial and environmental aspects. To achieve minimum environmental impacts, higher expenditure is required. To compare drilling cuttings management options, the decision making criteria were divided into four major categories: technical feasibility, rig compatibility, environmental and safety, and costs. The criteria hierarchy is shown in Figure 4-1. The numbers in brackets represent the weighting factors which will be described in section 4.5.

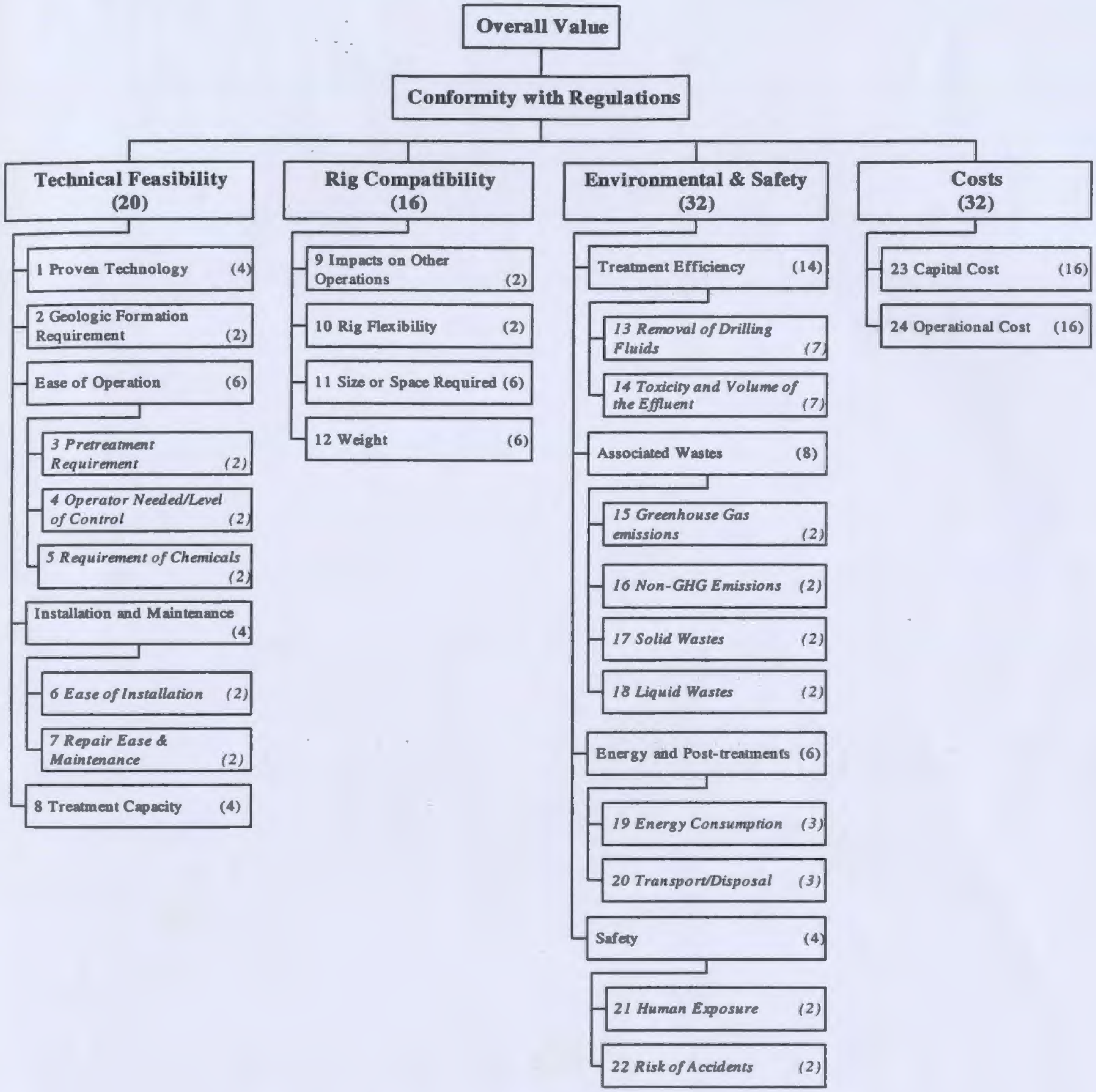

Figure 4-1 Criteria Hierarchy

The criteria used in this evaluation are briefly described below. The numbers in the brackets represent the identification number of the criteria which corresponds to the ones shown in Figure 4-1.

A. Technical feasibility

Technical feasibility is a criteria category used to assess the options in terms of their technical performance. This category was divided into five major criteria including proven technology, geologic formation requirement, ease of operation, installation and maintenance, and treatment capacity. Some of these criteria were also sub-divided into lower level criteria as discussed in this section.

A.1 Proven technology and availability (1)

Whether the technology is proven to be able to treat drilling cuttings, especially synthetic-based drilling cuttings, was the main focus in this assessment. Part of the evaluation measure was the previous application of the technology in treating drilling cuttings or similar kinds of solid wastes such as hydrocarbon contaminated soils. The applicability to offshore operations also considerably affected the rating of the technology under this criterion. This means that the technologies previously used offshore were given a higher score. In addition, the availability of the technology was also considered under this criterion.

A.2 Geologic formation requirement (2)

For some technologies, such as re-injection, the availability of a geologic formation is mandatory. In this case, these technologies were assigned a score of zero. The options where an appropriate receiving formation does not affect their operation or efficiency were assigned a score of ten. In other cases, the relative extent of the impact of an unsuitable formation on the operation of a cuttings management technique was the main issue to consider under this criterion.

A.3 Ease of operation

The ease of operation criterion was sub-divided into per-treatment requirement, operator needed/level of control, and requirement of chemicals.

A.3.1 Pre-treatment requirement (3)

The pre-treatment requirement is the demand of one or more processes, other than normal solids control systems, to prepare the feed for the treatment or disposal system. The considered pre-treatments included processes such as de-watering and removal of toxic substances in the case of biological treatment. This criterion indicates that the technology is not self-sufficient or does not provide complete processing of cuttings. A requirement of extra processes prior to the main treatment systems also implies more energy, space, costs, and complexity.

A.3.2 Operators needed or level of control (4)

This criterion shows how much control the technology needed in terms of operation supervision, which is specified by number of operators. Under this criterion the number of personnel-hours was used as the evaluation measure.

A.3.3 Requirement of chemicals (5)

The amount and types of chemicals needed in each treatment process differ and imply extra costs in operation and other difficulties associated with handling and storage of the chemicals. Chemicals required are, for example, those chemicals used in chemical treatment processes and basic chemicals, such as lubricants, needed in most systems.

A.4 Installation and maintenance

Installation and maintenance criterion was sub-divided into ease of installation, and repair ease and maintenance. These sub-criteria are described below.

A.4.1 Ease of installation (6)

This criterion evaluates the ease in installation and the mobility of a management option. The evaluation measure for this criterion was based on installation cost, time required, or the system's portability. The system which requires less installation cost or installation time was assigned a higher score. A system available in a portable form was also given a higher score than a fixed system as its installation was expected to be less complex and less expensive.

A.4.2 Repair ease and maintenance (7)

Repair ease and maintenance was measured by costs, time required for repair and maintenance, and their frequency. The simplicity to repair or maintain the treatment system is important as it may considerably affect the operational costs and time. A reliable system requiring less maintenance and causing shorter duration of downtime was assigned a higher score. The repair ease was rated depending on the components which require frequent reparation or replacement. For example, the option whose frequently replaced components are inexpensive and commercially available was given a higher score. In addition, the repair ease depended on the requirement of experts and special equipment which is often not available offshore.

A.5 Treatment capacity (8)

The capacity of the treatment system is a measure of the system's capacity to handle cuttings in a specified period. The evaluation measure was tonnes of dry cuttings treated per hour.

B. Rig compatibility

Rig compatibility is a criteria category consisting of sub-criteria used to assess the potential or the practicability of evaluation options to be installed and operated offshore. This category includes impacts on other operations, rig flexibility, size, and weight criteria.

B.1 Impacts on other operations (9)

Under this criterion, impacts caused by the operation of the cuttings management systems on other activities on the platform were considered. The impacts might be caused when the waste management system is under operation or during its downtime. For example, other activities on the rig or platform might cease during downtime of some cuttings management systems or during transferring treated waste to shore. On the other hand, other management systems might only cause difficulties on other operations due to the nature of the process such as its vibration or its size. This criterion was evaluated subjectively by considering the levels of impacts.

B.2 Rig flexibility (10)

This criterion shows how flexible the management technology is to be installed and operated on different types of rigs or platforms (such as fixed GBS, semi-submersible, or FPSO). These platforms differ in many ways such as space availability and stability. Therefore, the options that can be used on more types of platforms are applicable to more drilling sites and are desirable. In case that previous offshore application is not available, susceptibility to vibration was used as an estimate to measure the options.

B.3 Size or space required (11)

The evaluation measure of this criterion was the dimensions of the complete system. This criterion is considered very important especially when the system will be installed on an offshore platform, which has limited space.

B.4 Weight (12)

As subsea platforms normally have weight constraints, the total weight of a management system is also important for the offshore application.

C. Environmental impacts and safety

The environmental impacts and safety category consists of four criteria regarding cuttings management systems' potential impacts on the environment and workers. This category includes treatment efficiency, associated wastes, energy and post-treatments, and safety criteria.

C.1 Treatment efficiency

Treatment efficiency was sub-divided into reduction of drilling fluids, and toxicity and volume of the effluent stream. These sub-criteria are described below.

C.1.1 Reduction of drilling fluids (13)

The efficiency of the system to reduce the amount of drilling fluids on cuttings is another important factor as this affects the final disposal options for cuttings. For example, the treated cuttings containing base fluid of less than the amount specified by the regulatory limit may be discharged offshore. Therefore, the percentage of drilling base-fluids retained on the cuttings after treatment was used as an evaluation measure under this criterion.

C.1.2 Toxicity and volume of effluent stream (14)

Under this criterion, not only the toxicity from drilling fluids was considered but also other compounds which cannot be treated by the treatment process. The toxicity of the residues is one of the important parameters contributing to the environmental impact of cuttings discharges. These residues are, for example, chemicals in drilling fluids, heavy metals, or formation oil. Volume of the treated cuttings, which affects the handling and storage of the treated waste, was also considered under this criterion.

C.2 Associated wastes

The associated wastes criterion consists of greenhouse gas emissions, non-greenhouse gas emissions, solid wastes, and liquid wastes.

C.2.1 Greenhouse gas emissions (15)

This criterion considers types and amounts of green house gases generated from the treatment or disposal process. The major greenhouse gases considered were carbon dioxide, methane, sulfur hexafluoride, dinitrogen oxides, and CFCs. The impacts from the release of these gases were evaluated based on the sources of emissions, such as burning fuel as an energy source, or greenhouse gases used or generated during the main treatment process.

C.2.2 Non-greenhouse gas emissions (16)

In addition to greenhouse gases, other gases are generated during the treatment process. These gases also cause environmental impacts, especially those generated in large amounts or those which might be toxic. Examples of non-greenhouse gas are dust and heavy metals in the released gas streams. These gas discharges were scored by a method based mainly on the toxicity of the gases. For example, a system associated with heavy metal releases was scored much lower than one associated with relatively benign dust.

C.2.3 Solid wastes (17)

In some treatment processes or other associated processes, solid wastes other than the treated cuttings are generated. These wastes are, for example, process sludge and filter media which require further treatment or appropriate disposal. The wastes were evaluated subjectively based on the type and the requirement of treatment and disposal. A system associated with some non-toxic solid wastes was scored lower than one without associated solid wastes but higher than one whose solid wastes are toxic and require transportation to shore for treatment and disposal.

C.2.4 Liquid wastes (18)

In some treatment processes or other associated processes, liquid wastes, such as washing liquid and solvent used to extract contaminants from cuttings or gas stream, may be generated. These liquid wastes may or may not require appropriate treatment or disposal. Under this criterion, these wastes were subjectively measured similarly to the solid wastes. The consideration was focused on the toxicity from the composition of the wastes and the requirement of further treatment and disposal.

C.3 Energy and post-treatments

The energy and post-treatments criterion includes two sub-criteria: energy consumption and transportation/disposal after treatment.

C.3.1 Energy consumption (19)

The energy consumption of each technology option was measured as the total energy used in the treatment process to treat a specific amount of cuttings. The evaluation measure was the energy used in Mega joule per tonne of cuttings waste handled.

C.3.2 Transportation/disposal after treatment (20)

Requirements for transportation or disposal of the treated cuttings were considered and rated based on the type of required post-treatment activities. The post-treatment activities included discharge overboard, ship-to-shore for further treatment, or ship-to-shore for disposal. Discharge overboard was scored higher as it is not associated with high energy consumption and accidental risks from transportation of cuttings to shore, as well as the fact that it is simple and preferred by operators. In addition, all the management options considered are able to treat cuttings to very low level of base-fluids. Therefore, environmental impacts from the discharge are expected to be low (due to reduced levels of contaminants and improved dispersion ability) compared with the risk of accidental spills of untreated waste during transportation to shore.

C.4 Safety

The safety criterion can be divided into human exposure and risk from accidents. These sub-criteria are described below.

C.4.1 Human exposure (21)

The evaluation measure for this criterion was human risks associated with handling and operating the treatment process. The number of exposure pathways (such as skin contact, inhalation, and noise level) of the process operations and the extent of the exposures were used to evaluate options. For example, the systems whose parts are covered and do not require close control by humans were assigned high scores as they prevent operators from direct contact with wastes or inhalation of volatile contaminants.

C.4.2 Risks of accident (22)

Under this criterion, accidents which are associated with the cuttings management process were considered. This included fire, explosion, and spills.

D. Costs

Under the costs category, capital and operational costs of the options were considered.

D.1 Capital costs (23)

The rental or purchase cost in using a technology was used as the evaluation measure.

D.2 Operational costs (24)

The operational cost of a technology was calculated based on the cost of handling a specific amount of drilling cuttings. This included costs such as personnel, maintenance, and consumables.

4.1.3 Evaluation Measures

The evaluation measures, which are used to measure alternatives' attainment under the corresponding criteria, were divided into two groups. The first group included those providing quantitative values while the other provided qualitative values. The interval scaled quantitative values were then normalized using single value functions, and the qualitative values were subjectively ranked and subjectively converted into numbers. The normalization and conversion of values is described in detail in the Scoring Section (Section 4.6). The evaluation measures of the 24 criteria are summarized in Table 4-1.

Table 4-1 Criteria and Evaluation Measures

No.	Criteria	Measures
Technical Feasibility		
1	Proven Technology and Availability	Subjective ranking: Previous application, types of wastes treated, status of the technology, success, and availability
2	Geologic Formation Requirement	Subjective ranking: Requirement of specific formation and its effects on the performance of a management system
Ease of Operation		
3	Pre-treatment Requirement	Subjective ranking: Requirement of pre-treatment or state of the feed (dewatered, initial %oil, slurry, etc.)
4	Operator Needed or Level of Control & Operator Training	Interval scale: Working hours per day of operators (assumed 24 hrs/day of operation), requirement of human control, operator's training and experience
5	Requirement of Chemicals	Subjective ranking: Amounts & types of chemicals
Installation and Maintenance		
6	Ease of Installation	Subjective ranking: Cost of installation, components
7	Repair Ease and Maintenance	Subjective ranking: Cost of maintenance, requirement of special equipment or personnel
8	Treatment Capacity	Interval scale: Tonne/day
Rig Compatibility		
9	Impacts on Other Operations	Subjective ranking: Severity of the impacts and cause of the impacts
10	Rig Flexibility	Subjective ranking: Types of rigs able to accommodate the system
11	Size or Space Required	Interval scale: Total area (m^2)
12	Weight	Interval scale: Total weight in tonne
Environmental & Safety		
Treatment Efficiency		
13	Removal of Drilling Fluids	Interval scale: Percentage of base fluid retained on cuttings
14	Toxicity & Volume of Effluents (WQ)	Subjective ranking: Amount and type of toxic residues (including drilling fluids, heavy metals, radioactive substances, etc.) and volume of wastes after treatment

No.	Criteria	Measures
Associated Wastes		
15	GHG emissions	Subjective ranking: GHG emitted based on sources of emissions
16	Non-GHG Emissions	Subjective ranking: Non-GHG emitted considered by types of released gases
17	Solid Wastes	Subjective ranking: Amount, composition, and management method of solid wastes other than the treated cuttings
18	Liquid Wastes	Subjective ranking: Volume, composition and management method of liquid waste generated from the treatment processes
Energy and Post-Treatments		
19	Energy Consumption	Interval scale: Total energy consumed per tonne of dry cuttings (kJ/tonne)
20	Transport/Disposal after Treatment	Subjective ranking: Post-treatment activities considering expected costs, associated risks, and environmental aspects
Safety		
21	Human Exposure	Subjective ranking: Types and level of exposures
22	Risk of Accident	Subjective ranking: Types of potential accidents and protections
Costs		
23	Capital Costs	Interval scale: Rental or purchase cost per day ($/day)
24	Operational Costs	Interval scale: Operational cost per day ($/day)

4.2 IDENTIFY ALTERNATIVES

Based on the threshold criteria, only treatment technologies with the capability of reducing the amount of retained base fluids on cuttings to lower than 6.9% (USEPA, 2001a; NEB et al., 2002) were selected.

The technologies in this study included existing offshore drilling cuttings treatment and disposal technologies and existing onshore technologies with potential for offshore application. The selected alternatives are outlined below:

1. Vertical Centrifuge
2. Horizontal Centrifuge
3. Thermal Desorption
4. Combustion
5. Grinding
6. Stabilization
7. Bioreactor
8. Re-injection

The preceding list consists of different treatment and disposal techniques including mechanical treatment, thermal treatment, chemical treatment, biological treatment, and re-injection, the only disposal method. Some of these technologies are currently in use offshore while the others have never been used offshore but have potential for offshore application in terms of performance, size, and so forth. As such, general information on each technology was known and most of the data required was expected to be available.

4.3 DATA GATHERING

In this step, the data needed to perform the evaluation were collected. Other than sources such as journal papers and company communications, two questionnaires were used to help in the data gathering process.

4.3.1 Questionnaires

To obtain data that are specifically for drilling cuttings and directly related to the criteria, two types of questionnaires were developed: one for suppliers and the other for the operators. Fourteen copies of the suppliers' questionnaires were distributed to companies supplying drilling cuttings treatment and disposal systems. Six of these were completed and returned. One copy of the industry's questionnaires was given out and was completed. These completed questionnaires were used as the main source of data for the evaluation. The questionnaires are shown in Appendix A and the data obtained is summarized in Appendix B.

4.3.2 Data Modifications

The data, which was collected from various sources, is based on different characteristics of wastes and different operating scenarios. Therefore, some modifications needed to be made in order to adjust the data to be most applicable to this study. Some assumptions were also made in order to score the options where data was missing. Some necessary assumptions and calculations of data for the evaluation are presented in detail in Chapter 5.

4.4 Screening

Generally, the selected alternatives are short-listed in this step in order to focus more on potential alternatives. However, as one of the purposes of this study was to provide a general idea of the technologies suitable to be used offshore, no alternatives mentioned in section 4.2 were discarded at this stage.

4.5 Assign Weights

Among many weighting methods presented in Chapter 2, a direct weighting method was selected to be used in this evaluation. In the direct weighting method, weights were directly assigned to the criteria according to their relative importance.

In Figure 4-1, weights are shown as bracketed numbers. As in Figure 4-1, weights of 20, 16, 32, and 32 were assigned to technical feasibility, rig compatibility, environmental & safety, and costs respectively. The weights of technical feasibility and rig compatibility add up to 36 which was almost equal to the weights assigned to the other two major groups of criteria. This means that approximately equal levels of importance were given to technical, environmental, and cost criteria.

Other sub-criteria were assigned weights based on the decision maker's consideration of their importance. The sub-criteria were grouped into higher levels of criteria for simplicity purposes in assigning weights. Appropriate weights were given to each group according to the relative importance and the sub-criteria in the same group were assigned equal weights. The weights of the sub-criteria in each group added up to the weight of the upper-level criteria and the weights of all the criteria in the same level added up to 100 percent. For example, as shown in Figure 4-1, three sub-criteria were grouped into the higher level criterion, namely, ease of operation. The ease of operation criterion was assigned a weight of six. Therefore, each of the three criteria under the ease of operation was assigned an equal weight of two.

4.6 Scoring

Scores are numbers assigned to represent the options' properties under each criterion. As previously indicated, the scoring schemes used in the evaluation were divided into two types according to the types of obtained data: qualitative and interval scale. The first type of data provided qualitative scores and the latter provided quantitative scores. The two types of scoring schemes are described below:

4.6.1 Qualitative scheme

Where quantitative data was not available, subjective rankings were used to measure or evaluate the option. In order to compare options, the subjective rankings were converted into numbers within the range of 0 - 10. As many levels of rankings are possible, conversion charts were used to keep the conversion of qualitative to quantitative consistent. The conversion charts were divided and marked with the numbers of 0-10. Characteristics of cuttings management systems were assigned to the chart in such a way that the most preferred characteristic corresponded to the number 10 and the least preferred was assigned zero. Scores were then directly obtained by comparing the characteristics of each option with the details on the chart. An example of the conversion charts that were used to change the subjective data to numbers is shown in Figure 4-2.

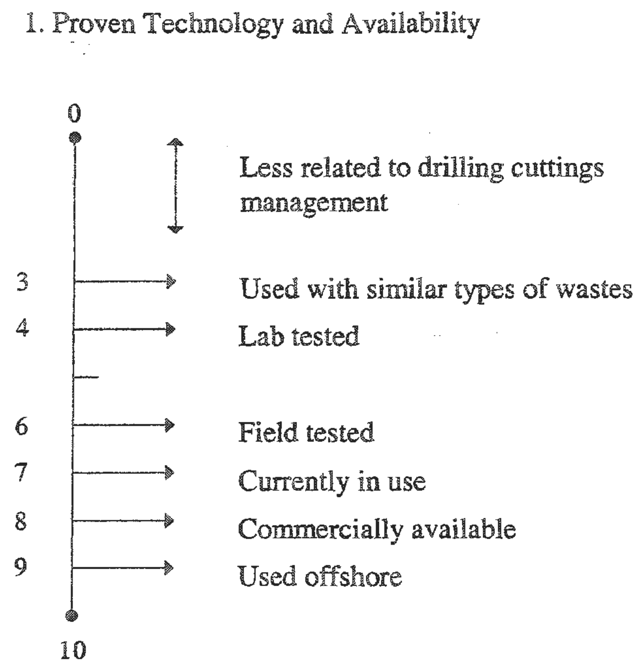

Figure 4-2 Conversion chart for the proven technology and availability criterion

4.6.2 Quantitative scheme

Quantitative data such as the weight and capacity of management systems were normalized to one-range interval scaled values before being used in the evaluation. The normalization was conducted using linear value functions.

As this type of data may have either increasing (higher value has positive effect on the overall value of the option) or decreasing (higher value has negative effect) value, two ranges of normalized scores were used. Positive scores with a range of 0 to 10 were given to those with increasing values and negative scores with a range of -10 to 0 were given to those with decreasing values as shown in Figure 4-3.

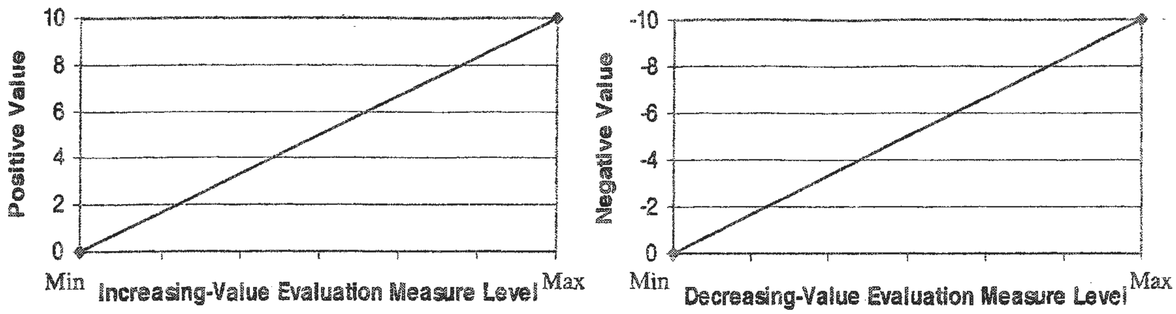

Figure 4-3 Single value functions used in normalizing quantitative scores

The general equation used to normalize quantitative values was:

$$Score\,(in\,0\text{ - }10\;range) = \frac{\pm\left(Quantitative\;data\;value\text{ - }Minimum\;Value\right)\times 10}{Maximum\;Value\text{ - }Minimum\;Value} \qquad (4.1)$$

An example of quantitative scheme scoring and its calculation are given here for the options' capacities which are considered a benefit (the more capacity, the more preferable an options is). In the evaluation, the capacities of the considered options varied from 0.11 to 40 tonnes/hour. It is then assumed that the capacity has a range of 0 to 40 tonnes/hour, and the capacities of 0 and 40 are used as the minimum and the maximum values respectively. Therefore, using equation 4.1, an option having a capacity of 20 tonnes/hour is assigned a score of +5 for the capacity criterion as calculated below.

$$Score\,(in\,0\text{ - }10\;range) = \frac{+20\times 10}{40}$$
$$= +5$$

Contrarily, under the size criterion, the larger space required for a management system is undesirable. Therefore, scores assigned are negative and vary from -10 to 0. As the size data varied from 23 to 98 m^2, the minimum and the maximum values of the options' sizes are assumed to be 0 and 100 m^2 respectively. If an option requires a space of 20 m^2 on an offshore platform, it is given a score of -2 according to the calculation below. Similarly, an option with a size of 80 m^2 is assigned a score of -8. This means that the options requiring larger space are assigned lower scores (more negative) which results in the options acquiring lower overall score.

$$\begin{aligned} Score\,(in\text{ - }10-0\ range) &= \frac{-20\times 10}{100} \\ &= -2 \end{aligned}$$

4.7 OVERALL VALUE MODEL

In this study, the widely used Additive Value Model was selected to be used as the overall value model because of its simplicity and robustness (Hobbs and Meier, 2000). This model provides a single index that can be used to compare alternatives.

The overall value for each cuttings management option can be calculated by using the equation (Modified from Parnell et al., 1999):

$$Overall\ Value,\ V(X) = \sum_{i=1}^{n} W_i X_i \tag{4.2}$$

where i is the criterion identification number,

X_i represents the score under the i^{th} criterion,

W_i is the corresponding weighting factor, and

n is the total number of criteria.

With the weights assigned and the ranges of the scores as mentioned in the preceding section, the overall values may range from -560 to 440. The minimum overall value of -560 is obtained by the worst option with the lowest scores (0 or -10) under all of the criteria while the maximum overall value (440) is the value of the ideal option obtaining the highest scores (0 or 10) for all criteria.

CHAPTER 5

DATA SCORING AND CALCULATIONS

In this chapter, scores and calculations are presented for each management option under each decision making criterion. The chapter is divided into four sections: technical feasibility, rig compatibility, environmental impacts and safety, and costs. The numbers in the brackets following the criteria represent the identification number of the corresponding criteria. The higher scores represent the more desirable quality of the options under corresponding criteria.

5.1 TECHNICAL FEASIBILITY

This criteria category includes five criteria: proven technology and availability, geologic formation requirement, ease of operation, installation and maintenance, and treatment capacity.

5.1.1 Proven technology and availability (1)

The options were scored under this criterion based on subjective judgment. A conversion chart (Figure 5-1) was used as a reference in scoring the options.

1. Proven Technology and Availability

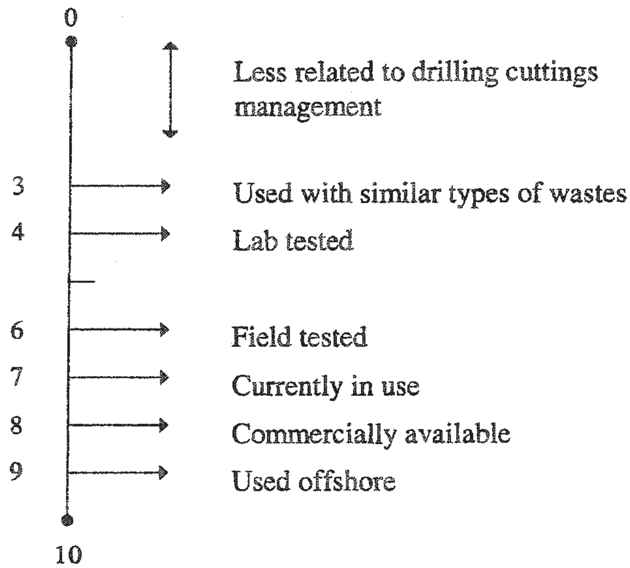

Figure 5-1 Conversion chart for proven technology and availability criterion

The options were assigned scores according to the conversion chart. As shown in Table 5-1, the assigned scores under proven technology and availability criterion vary from seven to nine as all of the considered options are existing technologies that are currently used either onshore or offshore.

Table 5-1 Scores assigned for proven technology and availability criterion

Technology	Score
Vertical Centrifuge	9
Horizontal Centrifuge	9
Thermal Desorption	8
Incineration	8
Grinding	7
Stabilization	8
Bioreactor	8
Re-injection	9

5.1.2 Geologic formation requirement (2)

The options were subjectively scored under this criterion according to a conversion chart as shown in Figure 5-2.

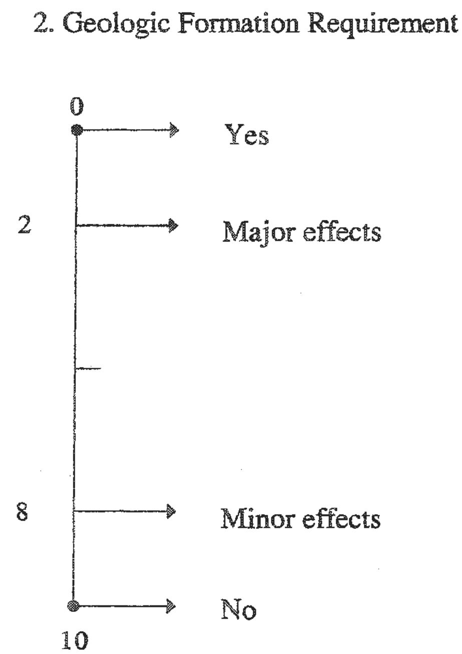

Figure 5-2 Conversion chart for geologic formation requirement criterion

According to Figure 5-2, the scores were assigned as shown in Table 5-2. There are only two scores in this case: zero and ten. A score of zero was assigned to re-injection as this technology requires a suitable formation for successful application of the technology. On the other hand, the other options were assigned a score of ten.

Table 5-2 Scores assigned for geologic formation requirement criterion

Technology	Score
Vertical Centrifuge	10
Horizontal Centrifuge	10
Thermal Desorption	10
Incineration	10
Grinding	10
Stabilization	10
Bioreactor	10
Re-injection	0

5.1.3 Ease of operation

This criterion was divided into three sub-criteria: pretreatment requirement, operator needed or level of control, and requirement of chemicals. The scoring process for these sub-criteria is explained below.

a) Pre-treatment requirement (3)

The options were again subjectively scored based on a conversion chart as shown in Figure 5-3.

As shown in Table 5-3, the assigned scores vary from four to nine based on the options' characteristics. For example, centrifuges were assigned a score of nine because of the ability to handle the cuttings wastes directly from the solids control equipment. Other options were assigned lower scores according to their relative level of pre-treatment requirement. Grinding was assigned a score of 5, which is the middle range value, due to insufficient information. An associated uncertainty value of ± 5 was also assigned to the grinding.

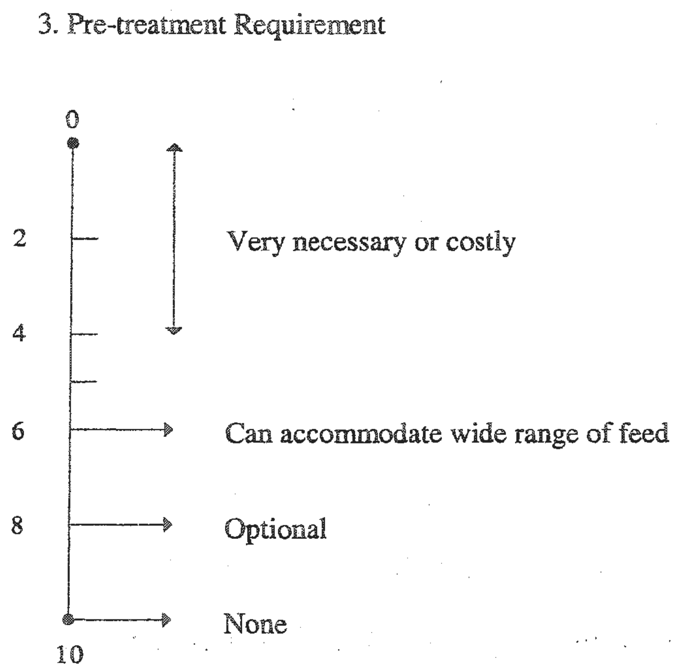

Figure 5-3 Conversion chart for pre-treatment requirement criterion

Table 5-3 Scores assigned for pre-treatment requirement criterion

Technology	Score
Vertical Centrifuge	9
Horizontal Centrifuge	9
Thermal Desorption	8
Incineration	7
Grinding	5
Stabilization	4
Bioreactor	4
Re-injection	9

b) **Operators needed or level of control (4)**

The scores under this criterion were quantitatively assigned to the options. The scores were calculated based on the assumption that the management systems were operated 24 hours per day. The scores were calculated using equation 4.1. As the maximum value of the obtained data for this criterion is 96, the range of the personnel-hour values was assumed to vary from the minimum value of 0 hours to the maximum value of 96 hours.

Table 5-4 shows the data and the assigned scores for this criterion. As the higher number of the operators needed to control the process operation implies higher cost, negative score values were assigned. Incineration was assigned the similar score to the one assigned for thermal desorption due to the fact that both systems employ thermal processes and, therefore, similar complexity of the systems was assumed. Stabilization and bioreactor were assigned a score of -5, which is the middle range value, due to insufficiency of information. An associated uncertainty value of ± 5 was also assigned to these options.

Table 5-4 Scores assigned for operators needed or level of control criterion

Technology	Values (Average value) (personnel-hours)	Score	Reference
Vertical Centrifuge	24	-2.5	Questionnaire
Horizontal Centrifuge	24	-2.5	Questionnaire
Thermal Desorption	96	-10	Questionnaire
Incineration	96	-10	-
Grinding	48	-5	UKOOA, 2000
Stabilization	48	-5	-
Bioreactor	48	-5	-
Re-injection	48-96 (72)	-7.5	Questionnaire reply

c) **Requirement of chemicals (5)**

The options were subjectively scored under requirement of chemicals criterion. The scores were assigned based on a conversion chart as shown in Figure 5-4.

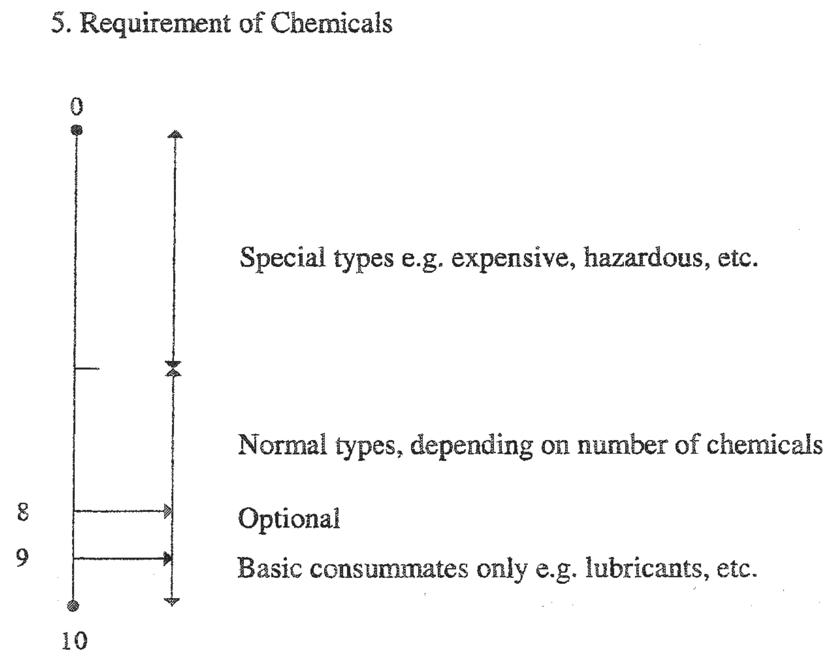

Figure 5-4 Conversion chart for requirement of chemicals criterion

As shown in Table 5-5, the assigned scores vary from five to nine based on the options' characteristics. Incineration and grinding were assigned the same scores as that of thermal desorption based on the fact that these systems are thermal treatment technologies and, therefore, similar level of chemical requirement was assumed. A score of 5, which is the middle range value, with an associated uncertainty of ± 5 was assigned to stabilization as the data on the technology is unavailable.

Table 5-5 Scores assigned for requirement of chemicals criterion

Technology	Score
Vertical Centrifuge	8
Horizontal Centrifuge	9
Thermal Desorption	6
Incineration	6
Grinding	6
Stabilization	5
Bioreactor	7
Re-injection	6

5.1.4 Installation and maintenance

This criterion was divided into two sub-criteria, ease of operation, and repair ease and maintenance. The scoring process for these sub-criteria is outlined below.

a) Ease of installation (6)

The options were subjectively scored under ease of installation based on a conversion chart shown in Figure 5-5.

As shown in Table 5-6, the assigned scores vary from four to nine based on the ease of installation for the options. The horizontal centrifuge was assigned the same score (nine) as the vertical centrifuge due to the fact that both systems employed centrifuge technology. Incineration was assigned a score of 5, which is the middle range value, with an associated uncertainty of ± 5 due to unavailability of data. The bioreactor was assigned the score of eight based on the nature of the process compared with those of other systems.

6. Ease of Installation

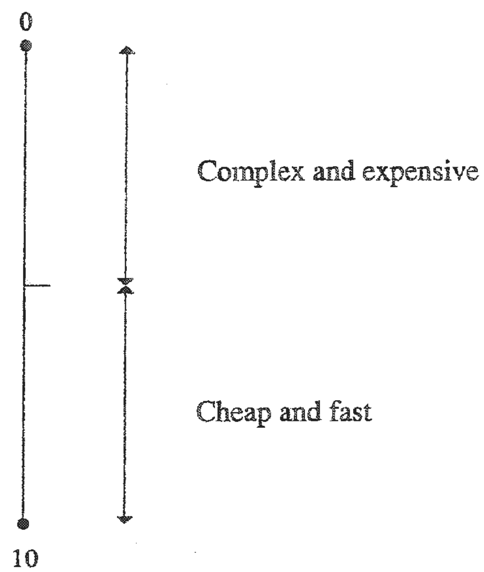

Figure 5-5 Conversion chart for ease of installation criterion

Table 5-6 Scores assigned for ease of installation criterion

Technology	Score
Vertical Centrifuge	9
Horizontal Centrifuge	9
Thermal Desorption	4
Incineration	5
Grinding	6
Stabilization	8
Bioreactor	8
Re-injection	8

b) **Repair ease and maintenance (7)**

The options were subjectively scored under repair ease and maintenance based on a conversion chart shown in Figure 5-6.

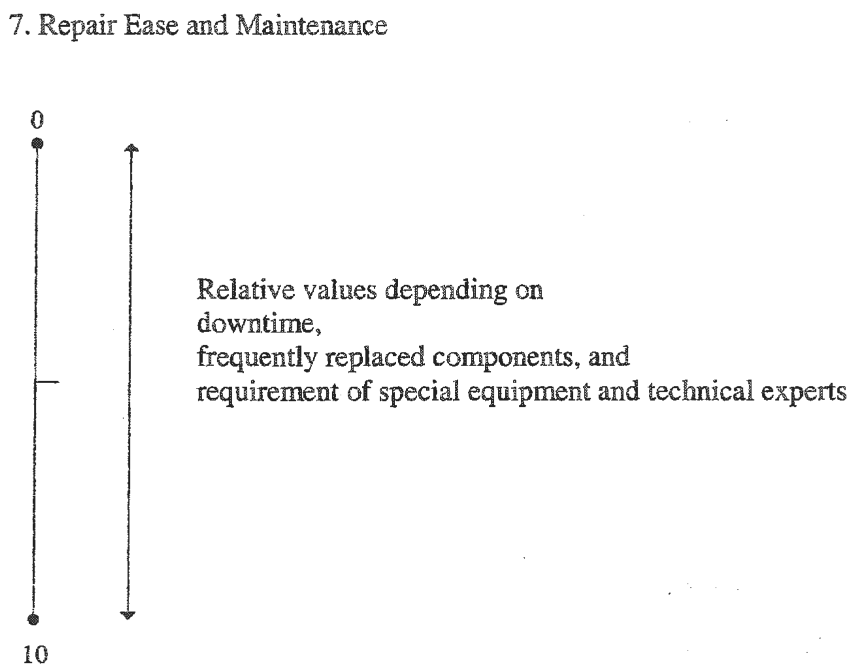

Figure 5-6 Conversion chart for repair ease and maintenance criterion

Table 5-7 Scores assigned for repair ease and maintenance criterion

Technology	Score
Vertical Centrifuge	6
Horizontal Centrifuge	6
Thermal Desorption	4
Incineration	5
Grinding	5
Stabilization	7
Bioreactor	7
Re-injection	5

As shown in Table 5-7, the assigned scores vary from four to seven. Incineration was assigned the middle range value (a score of 5) and an associated uncertainty of ± 5 due to insufficient data. Stabilization and bioreactor were assigned the score of seven based on their process' complexity compared with those of other systems.

5.1.5 Treatment capacity (8)

The scores for the options (Table 5-8) were calculated from the obtained data using equation 4.1. As the maximum treatment capacity of the considered options is 40, the range of the process capacity was assumed to vary from the minimum value of 0 tonne per hour to the maximum value of 40 tonnes per hour.

Table 5-8 Scores assigned for treatment capacity criterion

Technology	Data (Average value) (Tonnes/hour)	Score	Reference
Vertical Centrifuge	20-60 (40)	10	Questionnaire, Swaco, 2000, and Apollo, 2002
Horizontal Centrifuge	30	7.5	Swaco, 2002
Thermal Desorption	1.14-3.42 (2.28)	0.57	UKOOA, 2000
Incineration	5.87	1.47	Cripps et al., 1998
Grinding[2]	9	2.25	UKOOA, 2000
Stabilization	2-30 (16)	4	Cripps et al., 1998
Bioreactor[1]	0.011	0.00	Cripps et al., 1998
Re-injection[2]	20	5	UKOOA, 2000

[1] Calculated from the treatment rate in tonnes per year

[2] Calculated from the treatment rate with the unit in m^3/hour, converting based on dry cuttings' density of 2.57 tonnes/m^3 (Sadiq, 2001)

5.2 RIG COMPATIBILITY

This section includes criteria related to rig compatibility of the options. The criteria in this category include impacts on other operations, rig flexibility, size, and weight. The criteria and the option scores are presented below.

5.2.1 Impacts on other operations (9)

The options were subjectively scored under impacts on other operations criterion based on a conversion chart shown in Figure 5-7.

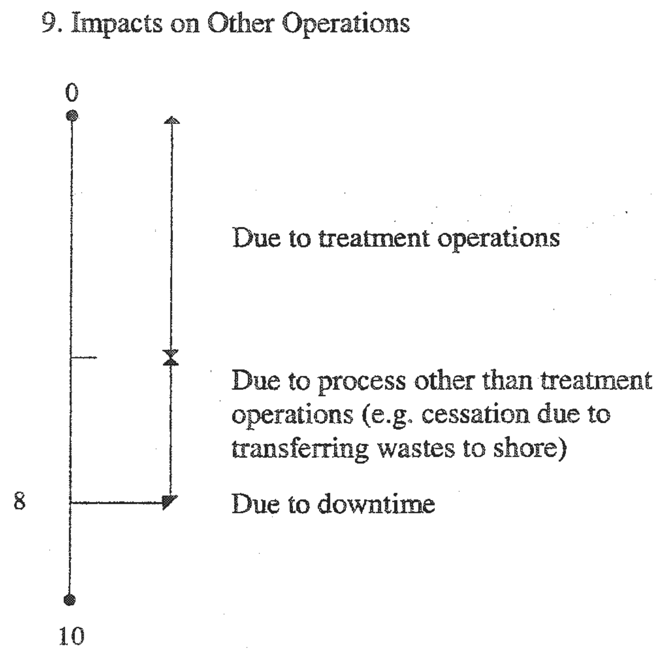

Figure 5-7 Conversion chart for impacts on other operations criterion

According to the conversion chart and the characteristics of the options, the assigned scores (Table 5-9) vary from five to eight. The options from which fewer impacts on other operations (only from downtime) are expected were assigned the highest score of eight. The other options were assigned lower scores due to other impacts, such as from transferring treated solids to shore, or from very low cuttings treatment rate. Incineration was assigned the middle range value (a score of 5) and an associated uncertainty of ± 5 due to unavailability of data.

Table 5-9 Scores assigned for impacts on other operations criterion

Technology	Score
Vertical Centrifuge	8
Horizontal Centrifuge	8
Thermal Desorption	6
Incineration	5
Grinding	6
Stabilization	7
Bioreactor	6
Re-injection	8

5.2.2 Rig Flexibility (10)

According to the conversion chart shown in Figure 5-8, the options were subjectively scored under rig flexibility criterion.

The options were assigned scores varying from five to eight (Table 5-10). The options that can be installed and operated on all types of offshore rigs or platforms were assigned a score of eight. Incineration, stabilization, and bioreactor were assigned the middle range value (a score of 5) and an associated uncertainty of ± 5 due to unavailability of data.

10. Rig Flexibility

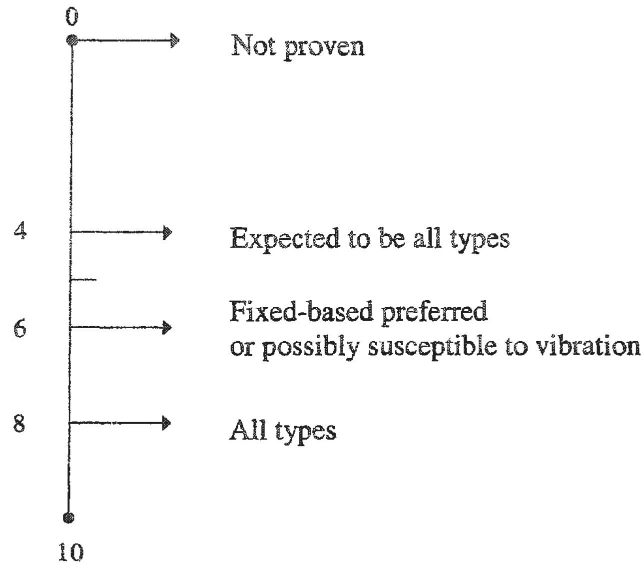

Figure 5-8 Conversion chart for rig flexibility criterion

Table 5-10 Scores assigned for rig flexibility criterion

Technology	Score
Vertical Centrifuge	8
Horizontal Centrifuge	8
Thermal Desorption	8
Incineration	5
Grinding	8
Stabilization	5
Bioreactor	5
Re-injection	8

5.2.3 Size or space required (11)

Under this criterion, the scores were calculated from the obtained data by using equation 4.1. As the maximum area required for the considered options is 98, the range of the system size values was assumed to vary from the minimum value of 0 m^3 to the maximum value of 100 m^3. The assigned scores for the options are shown in Table 5-11.

As larger space required on an offshore platform is undesirable, negative score values were assigned. Incineration, stabilization, and bioreactor were assigned a score of -5, which is the middle range value, due to lack of information on the size of the systems. An associated uncertainty value of ± 5 was also assigned to each of these options.

Table 5-11 Scores assigned for size or space required criterion

Technology	Data (Average value) (m^3)	Score	Reference
Vertical Centrifuge	24.7	-2.5	UKOOA, 2000
Horizontal Centrifuge	22.6	-2.3	Swaco, 2002
Thermal Desorption	98	-9.8	UKOOA, 2000
Incineration	-	-5	-
Grinding	70	-7	UKOOA, 2000
Stabilization	-	-5	-
Bioreactor	-	-5	-
Re-injection	70	-7	UKOOA, 2000

5.2.4 Weight (12)

The weight scores (Table 5-12) were also calculated by using equation 4.1. The range of the system weight values was assumed to vary from the minimum value of 0 tonnes to the maximum value of 40 tonnes as the highest value of weight for the options is 35.

Similar to the size of the systems, the high weight of a treatment system is undesirable. Therefore, negative values were used for the assigned scores. Incineration, stabilization, and bioreactor were assigned a score of -5, which is the middle range value, due to insufficient information. An associated uncertainty value of ± 5 was also assigned to each of these options.

Table 5-12 Scores assigned for weight criterion

Technology	Data (Average value) (Tonnes)	Score	Reference
Vertical Centrifuge	16.5	-4.1	Swaco, 2000
Horizontal Centrifuge	12.4	-3.1	Swaco, 2002
Thermal Desorption	30-40 (35)	-8.8	Questionnaire and UKOOA, 2000
Incineration	-	-5	-
Grinding	30	-7.5	UKOOA, 2000
Stabilization	-	-5	-
Bioreactor	-	-5	-
Re-injection	30	-7.5	UKOOA, 2000

5.3 Environmental Impacts and Safety

The environmental impacts and safety category was sub-divided into four groups of sub-criteria: treatment efficiency, associated wastes, energy and post-treatments, and safety. The decision making criteria under this category and the scores assigned are described below.

5.3.1 Treatment efficiency

This criterion was divided into two sub-criteria, reduction of drilling fluids, and toxicity and volume of effluent streams.

a) Reduction of drilling fluids (13)

The scores under this criterion were calculated from the percentage of the base fluid retained on the treated cuttings that the options can achieve. The values of 0.5 percent were assigned to the options with the data value of less than 1 percent but not as low as zero. The scores were then calculated using equation 4.1. The range of the percentage of drilling fluids retained on the treated cuttings was assumed to vary from the minimum value of 0 percent to the maximum value of 6.9 percent which is the value used as the threshold criterion for selecting options and the USEPA's discharge limit for SBF cuttings (USEPA, 2000a; NEB et al., 2002).

The assigned scores are shown in Table 5-13. Negative scores were used in this criterion as the higher percentage of base fluid retention on cuttings after treatment is undesirable. The numbers of percentage of fluid retention assigned to stabilization and bioreactor were based the nature of the process. Re-injection was assigned 0% fluid retention as it does not involve treatment of drilling cuttings.

Table 5-13 Scores assigned for reduction of drilling fluids criterion

Technology	Data (Average value) (% fluid retention)	Score	Reference
Vertical Centrifuge	1.8-4.3 (3)	-4.3	Swaco, 2000, Apollo, 2002, and Oiltools, 2002b
Horizontal Centrifuge	3-5 (4)	-5.8	Swaco, 2002
Thermal Desorption	<1 (0.5)	-0.7	Oiltools, 2002a
Incineration	<1 (0.5)	-0.7	Cripps et al., 1998
Grinding	<1 (0.5)	-0.7	UKOOA, 2000
Stabilization	0	0	-
Bioreactor	<1 (0.5)	-0.7	-
Re-injection	0	0	-

b) Toxicity and volume of effluent streams (14)

According to the conversion chart shown in Figure 5-9, the options were subjectively scored under this criterion.

The options were assigned scores varying from four to nine (Table 5-14) based on the contaminants remained after treatment and volume of the treated cuttings. The options using thermal process are not able to treat heavy metals and were assigned the scores of four. The options were assigned scores subjectively according to the characteristics of the treated wastes.

14. Toxicity and Volume

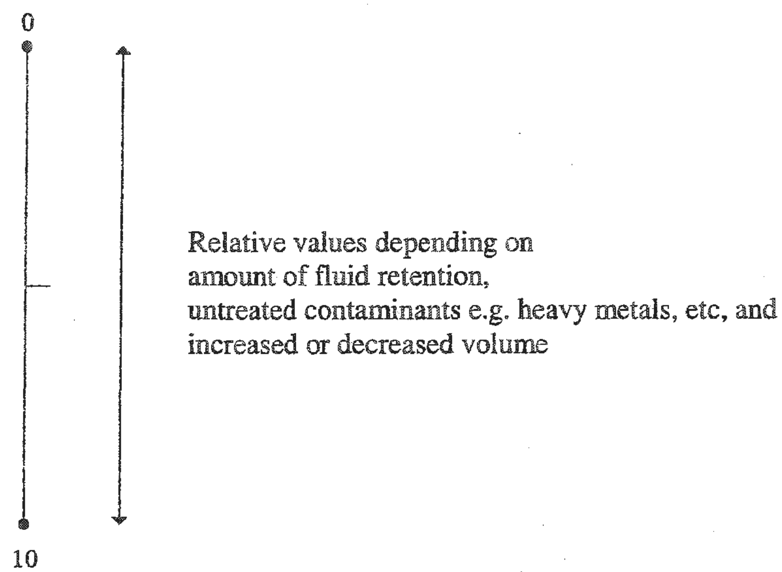

Figure 5-9 Conversion chart for toxicity and volume of effluent streams criterion

Table 5-14 Scores assigned for toxicity and volume of effluent streams criterion

Technology	Score
Vertical Centrifuge	7
Horizontal Centrifuge	7
Thermal Desorption	4
Incineration	4
Grinding	4
Stabilization	6
Bioreactor	8
Re-injection	9

5.3.2 Associated wastes

Associated wastes which are concerns in management of drilling cuttings include greenhouse gas emissions, non-greenhouse gas emissions, solid wastes, and liquid wastes.

a) Greenhouse gas emissions (15)

According to the conversion chart (Figure 5-10), the options were subjectively scored under greenhouse gas emissions criterion.

The options were assigned scores varying from four to nine (Table 5-15) based on the potential greenhouse gas emissions from the systems.

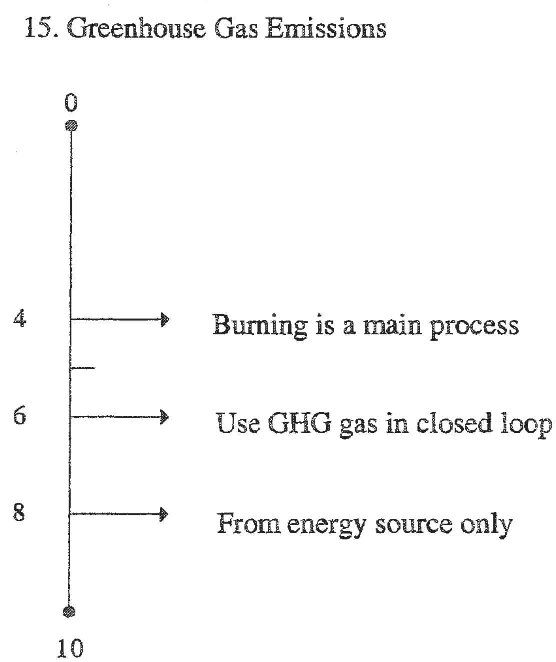

Figure 5-10 Conversion chart for greenhouse gas emissions criterion

Table 5-15 Scores assigned for greenhouse gas criterion

Technology	Score
Vertical Centrifuge	8
Horizontal Centrifuge	8
Thermal Desorption	4
Incineration	4
Grinding	6
Stabilization	8
Bioreactor	9
Re-injection	8

b) Non-greenhouse gas emissions (16)

The options were subjectively scored under non-greenhouse gas emissions criterion according to the conversion chart (Figure 5-11).

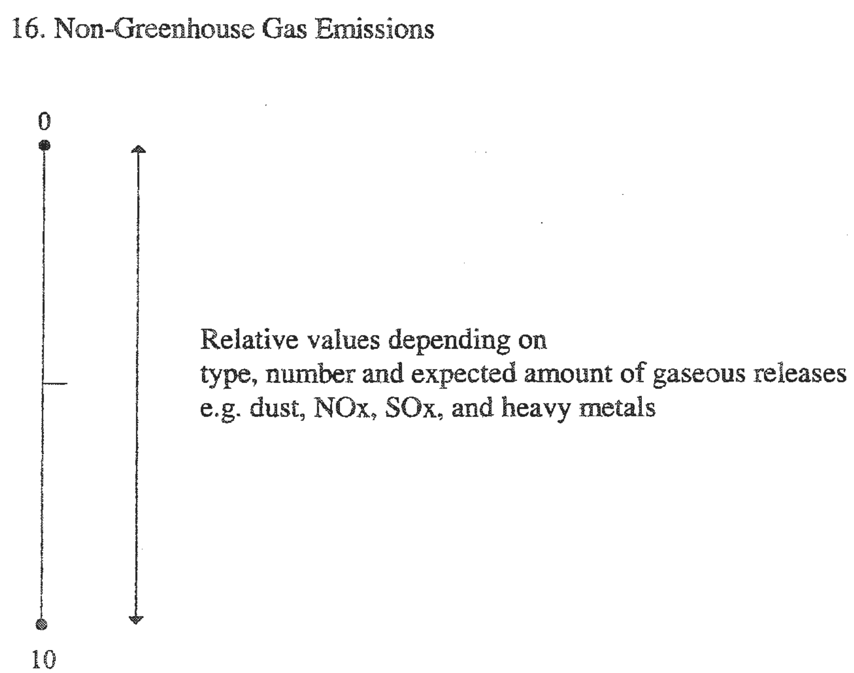

Figure 5-11 Conversion chart for non-greenhouse gas emissions criterion

As shown in Table 5-16, the scores vary from four to nine depending on the emission potential of non-greenhouse gas.

Table 5-16 Scores assigned for non-greenhouse gas criterion

Technology	Score
Vertical Centrifuge	8
Horizontal Centrifuge	8
Thermal Desorption	6
Incineration	4
Grinding	6
Stabilization	8
Bioreactor	9
Re-injection	8

c) Solid wastes (17)

The options were subjectively scored under solid wastes criterion according to the conversion chart (Figure 5-12).

The options were assigned scores varying from nine to ten (Table 5-17) based on solid wastes generated during the process. Under this criterion, only the solids wastes other than the treated drilling cuttings are considered. The options using thermal processes were assigned the lower score of nine due to the expectation of some solid wastes generated from gas treatment equipment such as gas filters.

17. Solid Wastes

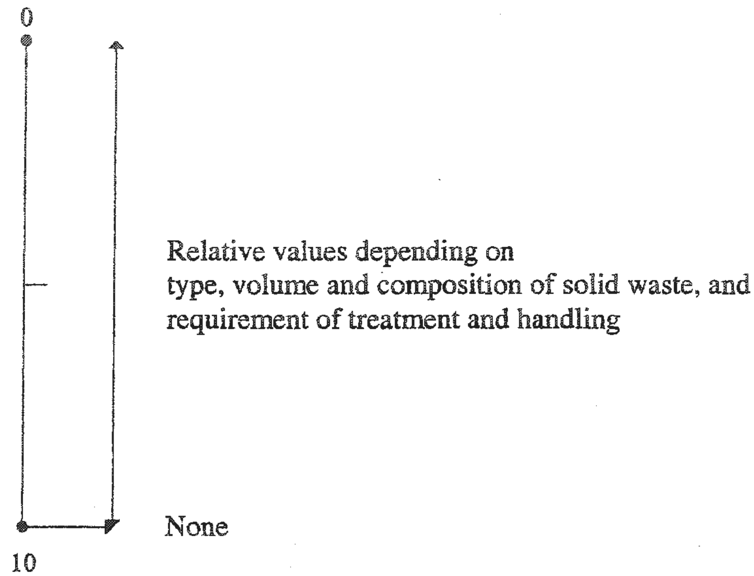

Figure 5-12 Conversion chart for solid wastes criterion

Table 5-17 Scores assigned for solid wastes criterion

Technology	Score
Vertical Centrifuge	10
Horizontal Centrifuge	10
Thermal Desorption	9
Incineration	9
Grinding	9
Stabilization	10
Bioreactor	10
Re-injection	10

d) Liquid wastes (18)

The options were subjectively scored under this criterion according to the conversion chart (Figure 5-13).

The options were assigned scores varying from four to ten (Table 5-18) based on volume and type of liquid wastes generated during the process. Requirement of treatment and handling also affects the scoring consideration. The options using thermal processes were assigned a score of nine as there might be some liquid wastes generated from gas treatment equipment such as wet scrubber. On the other hand, bioreactor was assigned a score of four due to the liquid waste separated from the solid phase after treatment. The liquid may be reused or require treatment before disposal.

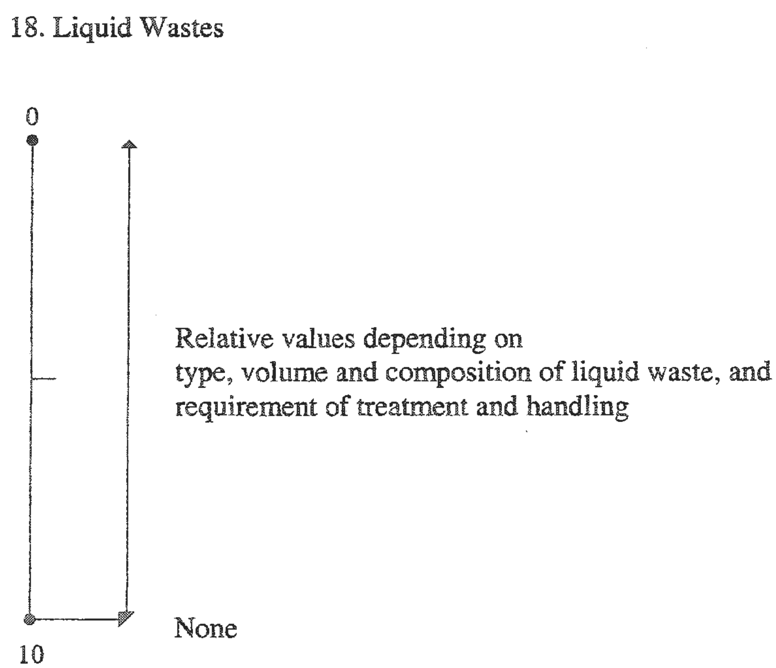

Figure 5-13 Conversion chart for liquid wastes criterion

Table 5-18 Scores assigned for liquid wastes criterion

Technology	Score
Vertical Centrifuge	10
Horizontal Centrifuge	10
Thermal Desorption	9
Incineration	9
Grinding	9
Stabilization	10
Bioreactor	4
Re-injection	10

5.3.3 Energy and post-treatments

This criteria group was sub-divided into two criteria: energy consumption, and transportation and disposal after treatment.

a) Energy consumption (19)

The scores (Table 5-19) were calculated from the energy used per tonne of cuttings using equation 4.1. The range of the energy consumption values was assumed to vary from the minimum value of 0 MJ/tonne to the maximum value of 1100 MJ/tonne, which is the maximum value of the obtained data. The calculations are as shown below.

Table 5-19 Scores assigned for energy consumption criterion

Technology	Data (Average value) (MJ/tonne)	Score	Reference
Vertical Centrifuge	5.1-5.8 (5.5)	-0.1	-
Horizontal Centrifuge	7.2	-0.1	-
Thermal Desorption	740	-6.7	-
Incineration	1100	-10	-
Grinding	290	-2.6	-
Stabilization	-	-5	-
Bioreactor	-	-5	-
Re-injection	17.8-40 (28.9)	-0.3	UKOOA, 2000

Calculations

Vertical Centrifuge

Energy required to operate a vertical centrifuge system is approximately 75.5 – 86.25 HP (Apollo, 2002; Oiltools, 2002b) with the capacity of treating 40 tonnes of cuttings per hour.

Therefore, the energy consumption

$$= \frac{75.5HP \times 745.7J/sec \cdot HP \times 3600sec/hr}{40tonne/hr} - \frac{86.25HP \times 745.7J/sec \cdot HP \times 3600sec/hr}{40tonne/hr}$$

= 5.1 – 5.8 MJ/tonne

Horizontal Centrifuge

Energy required to operate a horizontal centrifuge system is approximately 80 HP (Swaco, 2002) with the capacity of treating 30 tonnes of cuttings per hour.

Therefore, the energy consumption

$$= \frac{80HP \times 745.7J/sec \cdot HP \times 3600sec/hr}{30tonne/hr}$$

= 7.2 MJ/tonne

Thermal Desorption

The energy of 2,960 GJ is required to treat 4,000 tonnes of oil-based drilling cuttings using indirect thermal desorption system (UKOOA, 2000). The cuttings contain approximately 50% water content (5,000 tonnes) and 150 tonnes of oil (20% maximum oil content by weight of dry cuttings).

Therefore, the energy consumption

$$= \frac{2960GJ}{4000tonnes}$$

= 740 MJ/tonne

The differences in energy consumption in treating SBF-cuttings and OBF-cuttings are due to higher solid throughput and higher operating temperature when treating OBF-cuttings (UKOOA, 2000). Therefore, this value was used for SBF cuttings as a conservative value.

Incineration

The energy of 4,165 GJ is required to treat 3,780 tonnes of drilling cuttings using an incineration system (Cripps et al., 1998). The cuttings contain approximately 40% water content (2,850 tonnes) and 143 tonnes of oil. The figure of the energy consumption was estimated based on the energy generated in treating the specified amount of the oil-based cuttings with the assumption that no external fuel was required.

Therefore, the energy consumption

$$= \frac{4165GJ}{3780tonnes}$$

= 1.1 GJ/tonne

Grinding

The energy of 1,160 GJ is required to treat 4,000 tonnes of drilling cuttings using an indirect thermal desorption system (UKOOA, 2000). The cuttings contain approximately 50% water content (5,000 tonnes) and 150 tonnes of oil (20% maximum oil content by weight of dry cuttings).

Therefore, the energy consumption

$$= \frac{1160GJ}{4000tonnes}$$

= 290 MJ/tonne

b) Transportation/disposal after treatment (20)

The options were subjectively scored under this criterion according to the conversion chart shown in Figure 5-14.

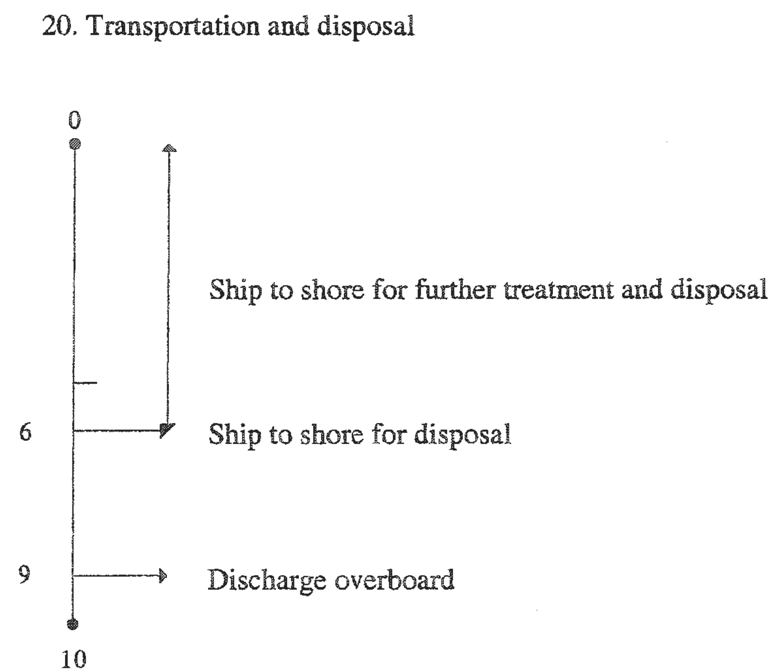

Figure 5-14 Conversion chart for transportation/disposal after treatment criterion

Table 5-20 Scores assigned for transportation/disposal after treatment criterion

Technology	Score
Vertical Centrifuge	9
Horizontal Centrifuge	9
Thermal Desorption	6
Incineration	6
Grinding	9
Stabilization	6
Bioreactor	9
Re-injection	10

The options were assigned scores varying from six to ten (Table 5-20). Re-injection was assigned a score of ten as it provides final disposal of drilling cuttings. The options which do not require transporting the treated solids to shore were assigned a score of nine. On the other hand, other options which may require further treatment of the treated cuttings or require appropriate onshore disposal method were assigned a lower score.

5.3.4 Safety

Under this criterion, there were two sub-criteria: human exposure and risk of accident. The options were scored under these two sub-criteria and the scores are presented below.

a) Human exposure (21)

Subjective consideration was used to score the options under this criterion. The conversion chart used in for scoring the options is shown in Figure 5-15.

21. Human Exposure

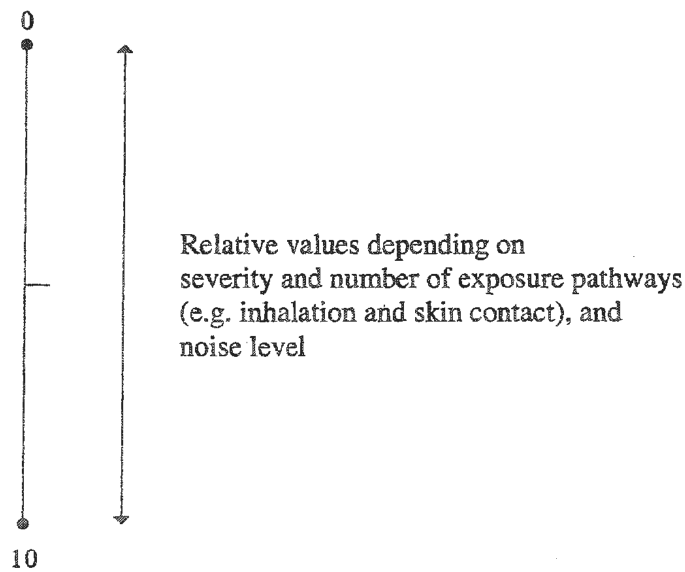

Figure 5-15 Conversion chart for human exposure criterion

The options were assigned scores varying from four to eight (Table 5-21). The thermal treatment options were assigned lower scores due to the potential of untreated heavy metals retained in dust. The other options were assigned higher scores according to potential human exposure during the process operations.

Table 5-21 Scores assigned for human exposure criterion

Technology	Score
Vertical Centrifuge	6
Horizontal Centrifuge	8
Thermal Desorption	4
Incineration	4
Grinding	4
Stabilization	8
Bioreactor	8
Re-injection	6

b) **Risks of accident (22)**

Under this criterion, the options were subjectively scored according to the conversion chart shown in Figure 5-16.

The options were assigned scores varying from four to eight (Table 5-22). The thermal treatment options were assigned relatively low scores due to their risks associated with high temperature processes.

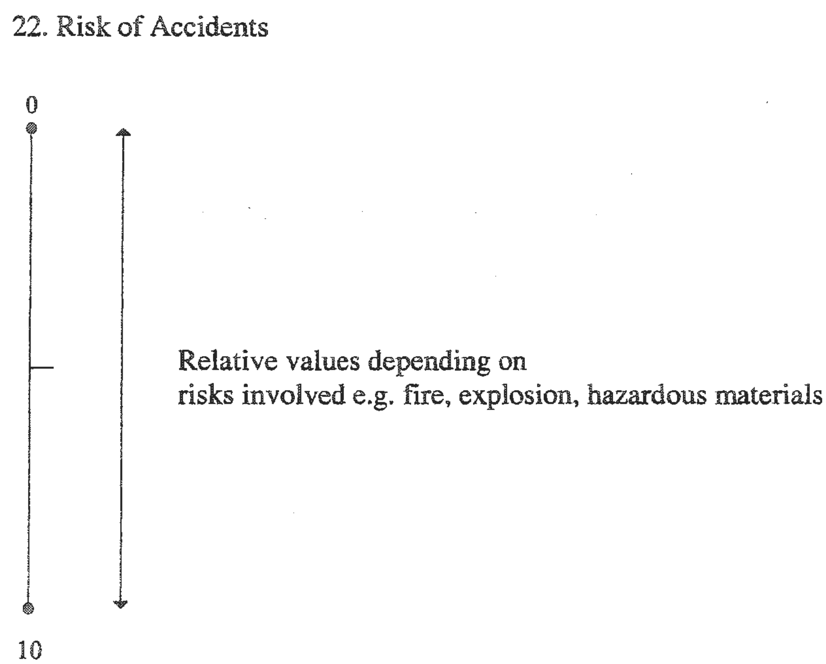

Figure 5-16 Conversion chart for risks of accident criterion

Table 5-22 Scores assigned for risks of accident criterion

Technology	Score
Vertical Centrifuge	8
Horizontal Centrifuge	8
Thermal Desorption	4
Incineration	4
Grinding	4
Stabilization	8
Bioreactor	8
Re-injection	6

5.4 COSTS (23 and 24)

This criterion includes two sub-criteria: capital cost and operational cost. The scores were calculated by using equation 4.1. As separated costs of capital and operational costs were in some cases not available, costs were considered in the evaluation as total costs with rental costs used to represent capital costs. The weight used in the evaluation was 32 which was the total weight of this criteria category. The range of the total cost values was assumed to vary from the minimum value of 0 USD/day to the maximum value of 317,000 USD/day (the maximum total cost for the considered options). The estimated cost values are shown in Table 5-23, and calculations as well as assumptions used are presented below.

Table 5-23 Scores assigned for cost criteria

Technology	Capital cost (Average value) (USD)	Operational cost (Average value) (USD)	Total cost (Average value) (USD)	Score
Vertical Cent.	756-1200 (978)	346.5-670 (508)	1100-1870 (1485)	-0.05
Horizontal Cent.	2080	890	2973	-0.09
Thermal Desorp.	-	-	96K-192K (101K)	-3.2
Incineration	-	-	106K-528K (317K)	-10
Grinding[1]	-	165K	-	-5
Stabilization	-	-	245K	-7.7
Bioreactor	-	-	45K	-1.4
Re-injection	-	14K-26K (20)	24K-72K (48)	-1.5

[1] Middle ranged value was assigned due to lack of information. Associated uncertainty value of ± 5 was also assigned.

Calculations

For comparison purposes, costs associated with applying each management option were estimated and modified so that every option's costs have the same basis of treating a specific amount of wastes. Some modification of data values and assumptions were made as follows:

- All the cost values were converted into the costs incurred per day of operation.
- It is assumed that all the options had to process the same amount of cuttings per hour. Therefore, in one day of operation, 40 tonnes of cuttings were assumed to be processed per hour.
- It was assumed that each system was operated 12 hours per day.
- From the previous basis of treating 40 tonnes/hour for 12 hours, 480 tonnes of cuttings are treated per day.

- All the costs which were in US Dollars were adjusted to the values in the year 2002 using equation 5.1 (Rinard, 1999) and the interest rate of 7%.

$$FV = PV(1+i)^N \tag{5.1}$$

where *FV* represents value in the future year.

PV represents present value,

i is interest rate,

and *N* is the number of years.

Vertical Centrifuge

Rental cost: 756-1200 USD/day (Questionnaire)

Operational cost: 346.5-670 USD/day (Questionnaire)

Capacity: 40 tonnes/hour

Therefore, no modification was needed for vertical centrifuge.

Horizontal Centrifuge

Rental cost: 1560 USD/day (Questionnaire)

Operational cost: 670 USD/day (This value was assumed to be similar to the upper value of vertical centrifuge's operational cost. This assumption was based on the similar treatment process and the estimated personnel cost value of 450 USD/day obtained from the technology's supplier questionnaire.)

Capacity: 30 tonnes/hour

Based on the ratio of 40 tonnes/hr of drilling cuttings to be treated to the 30 tonnes/hr capacity of the centrifuge, the following modifications to costs were performed:

Modified rental cost = $\frac{40}{30} \times 1560$

= 2,080 USD/day

Modified operational cost = $\frac{40}{30} \times 670$

= 890 USD/day

Thermal Desorption

Total cost: 200-400 USD/tonne (Questionnaire reply)

The total cost to treat 480 tonnes of cuttings was as follows:

Total cost = 96,000 – 192,000 USD/day

Incineration

Total cost: 220-1100 USD/tonne (Cripps et al., 1998)

The total cost to treat 480 tonnes of cuttings was as follows:

Total cost = 105.6K – 528K USD/day

Grinding

Operational cost: 300 USD/tonne (value in year 2000) (UKOOA, 2000)

The total cost to treat 480 tonnes of cuttings was as follows:

Operational cost = 144K USD/day

The year 2002 value is:

Operational cost = $144K \times (1 + 0.07)^{(2002-2000)}$

= 165K USD/day

Stabilization

Total cost: 390 USD/tonne (value in year 1998) (Cripps et al., 1998)

The total cost to treat 480 tonnes of cuttings was as follows:

Total cost = 187K USD/day

The year 2002 value is:

$$\text{Total cost} = 187K \times (1+0.07)^{(2002-1998)}$$

$$= 245\text{K USD/day}$$

Bioreactor

Total cost: 70 USD/tonne (value in year 1998) (Cripps et al., 1998)

The total cost to treat 480 tonnes of cuttings was as follows:

Total cost = 34K USD/day

The year 2002 value is:

$$\text{Capital cost} = 34K \times (1+0.07)^{(2002-1998)}$$

$$= 45\text{K USD/day}$$

Re-injection

Total cost: 50-150 USD/tonne (Questionnaire reply)

Operational cost: 25-47 USD/tonne (value in year 2000) (Questionnaire)

The costs to treat 480 tonnes of cuttings were as follows:

Total cost = 24K – 72K USD/day

Operational cost = 12K – 22.6K USD/day

or the year 2002 values are:

$$\text{Operational cost} = 12 \times (1+0.07)^{(2002-2000)} - 22.6 \times (1+0.07)^{(2002-2000)}$$

$$= 14\text{K} - 26\text{K USD/day}$$

Table 5-24 Summary of the scores obtained

No	Criteria (Unit) (min-max)	Weight	Scores							
			Vertical Centrifuge	Horizontal Centrifuge	Thermal Desorption	Incineration	Grinding	Stabilization	Bioreactor	Re-injection
	Technical	20								
1	Proven Technology	4	9	9	8	8	7	8	8	9
2	Geologic Formation Req.	2	10	10	10	10	10	10	10	0
	Ease of Operation	*6*								
3	Pre-treatment Req.	2	9	9	8	7	5	4	4	9
4	Operator Needed or Level of Control (0-96)	2	-2.5	-2.5	-10	-10	-5	-5	-5	-7.5
5	Req. of Chemicals	2	8	9	6	6	6	5	7	6
	Installation and Maintenance	*4*	0	0	0	0	0	0	0	0
6	Ease of Installation	2	9	9	4	4	6	8	8	8
7	Repair Ease and Maintenance	2	6	6	4	5	5	7	7	5
8	Treatment Capacity (Tonnes/hr)(0-40)	4	10	7.5	0.57	1.47	2.25	4	0.003	5
	Rig Compatibility	*16*								
9	Impacts on Other Operations	2	8	8	6	5	6	7	6	8
10	Rig Flexibility	2	8	8	8	5	8	5	5	8
11	Size or Space Req. (m^2)(0-100)	6	-2.5	-2.3	-9.8	-5	-7	-5	-5	-7
12	Weight (Tonnes)(0-40)	6	-4.1	-3.1	-8.8	-5	-7.5	-5	-5	-7.5
	Environmental	32								
	Treatment Efficiency	*14*								
13	Removal of Drilling Fluids (%ROC)(0-6.9)	7	-4.3	-5.8	-0.7	-0.7	-0.7	0	-0.7	0
14	Toxicity and Volume of the Effluent (WQ)	7	7	7	4	4	4	6	8	9
	Associated Wastes	*8*								
15	GHG	2	8	8	4	4	6	8	9	8
16	Non-GHG	2	8	8	6	4	6	8	9	8
17	Solid Wastes	2	10	10	9	9	9	10	10	10
18	Liquid Wastes	2	10	10	9	9	9	10	4	10

No	Criteria (Unit) (min-max)		Weight	Scores							
				Vertical Centrifuge	Horizontal Centrifuge	Thermal Desorption	Incineration	Grinding	Stabilization	Bioreactor	Re-Injection
	Energy and Post-treatments		***6***								
19	Energy Consumption (MJ/Tonne)(0-1100)		3	-0.1	-0.1	-6.7	-10	-2.6	-5	-5	-0.3
20	Transport/Disposal after Treatment		3	9	9	6	6	9	6	9	10
	Safty		***4***								
21	Human Exposure		2	6	8	4	4	4	8	8	6
22	Risk of Accident		2	8	8	4	4	6	8	8	6
	Costs		***32***								
23	Capital Costs	Total cost (USD) (0-317000)	32	-0.05	-0.09	-3.2	-10	-5	-7.7	-1.4	-1.5
24	Operational Costs										
			100								

CHAPTER 6

RESULTS AND ANALYSES OF THE EVALUATION

From the evaluation method and data in the previous chapters, overall values of all the evaluation options were determined. The overall values were used as indices to compare and rank the options. In order to determine the best drilling cuttings management option, uncertainty analysis and sensitivity analysis were also conducted. The results of the evaluation are outlined in the following sections.

6.1 RESULTS OF THE EVALUATION FOR EXISTING TECHNOLOGIES

According to the calculated overall values for each cuttings management option presented in Figure 6-1, the three best alternatives were vertical centrifuge, horizontal centrifuge and re-injection. The technologies attained the overall values of 291, 285, and 182 respectively. Therefore, based on the overall values alone, these three options were considered the optimum alternatives for drilling cuttings management under the established set of criteria. The bioreactor, which ranks fourth in this evaluation, obtained a slightly lower overall value than re-injection. Therefore, even though this option has never been used offshore, it is one of the most promising options for offshore applications.

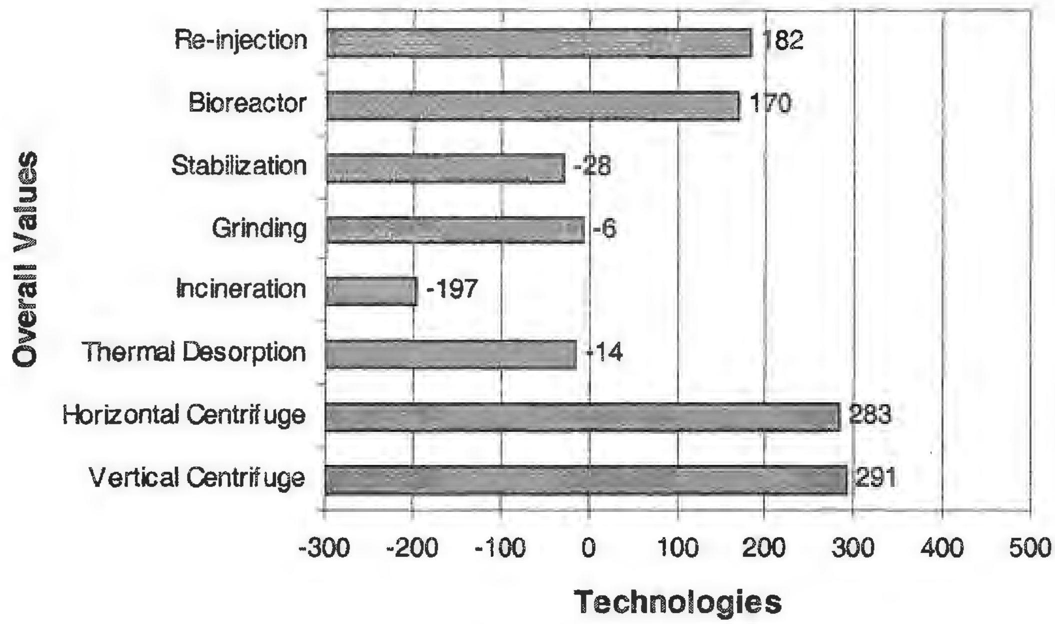

Figure 6-1 Overall values of the alternatives

Figure 6-2 presents a comparison of the total scores of each major category. Centrifuges scored the best under technical feasibility. This is partly due to their high capacity to process the waste and their ease to operate and maintain. Under rig compatibility, centrifuges (vertical and horizontal) also attained the highest scores, mainly because of compact size and weight. Previous offshore application also demonstrated the high rig compatibility. Re-injection was assigned the highest score under the environmental and safety category because of the reduction of toxic substances and future liability. Under cost criteria, centrifuges scored the highest.

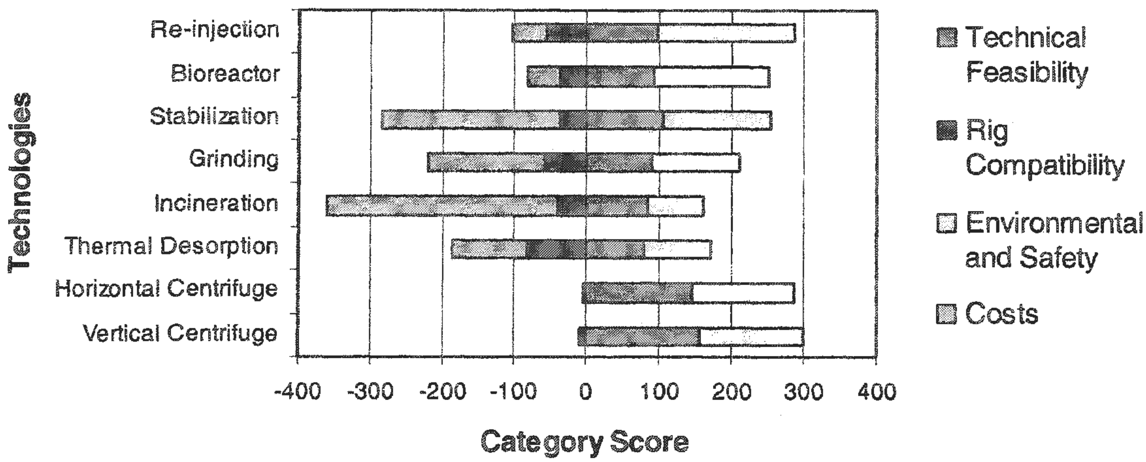

Figure 6-2 Category scores of each technology option

To compare cost-effectiveness of each option, the relationship between offshore applicability and costs was considered. The offshore applicability, in this case, was defined as the applicability of a treatment option to be used offshore with regard to offshore technical feasibility, rig compatibility, and environmental and safety issues. As such, the offshore applicability of an option was represented by the sum of the three category scores under technical feasibility, rig compatibility, and environmental impacts and safety categories (or it could be calculated using the overall value of an option minus its cost category score). The numbers representing offshore applicability were then plotted against cost category scores of the evaluated options as shown in Figure 6-3. The figure outlines the performance of each management option compared with its costs. From the plot, the two types of centrifuges (vertical and horizontal) provided high values of offshore applicability with the lowest costs (least negative) and are considered the most cost-effective. Re-injection, in spite of its slightly higher costs than a bioreactor's, showed significantly better offshore applicability. Therefore, re-injection was the third most cost-effective option in this case.

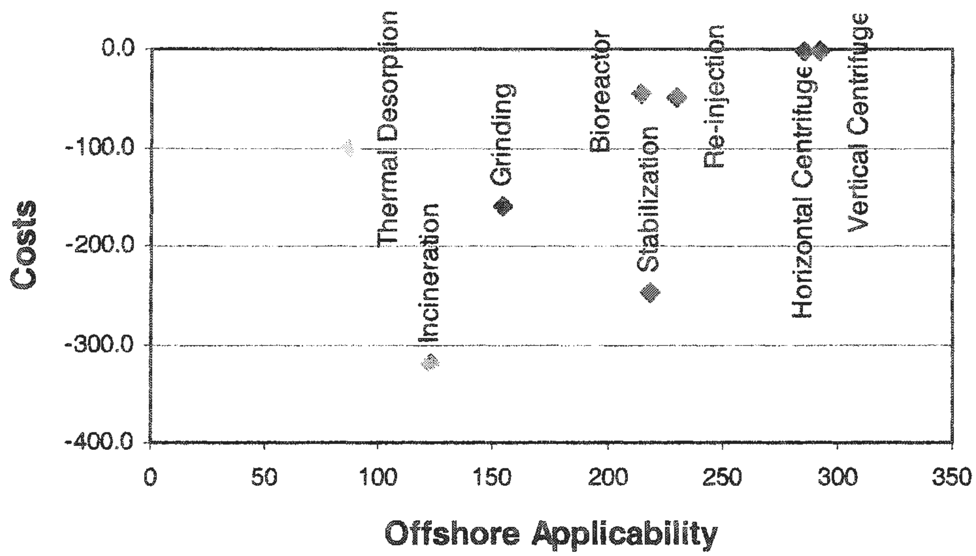

Figure 6-3 Costs vs. offshore applicability (overall value – cost value)

6.2 UNCERTAINTY ANALYSIS

Uncertainty analysis was conducted in order to identify the reliability of the final results. For values of data that were not available, a mid-range value was assigned (for example, a value of 5 in the range from 0 to 10) with associated uncertainty which would reflect the reliability of the final results. The uncertainty of ±5 was assigned to indicate that each of the assumed mid-range values could actually vary from zero to ten. The total uncertainty was then calculated using the following equations.

The general equation for uncertainty analysis is (Coleman and Steele, 1989):

$$U_r = \left[\left(\frac{\partial r}{\partial x_1} U_{x_1} \right)^2 + \left(\frac{\partial r}{\partial x_2} U_{x_2} \right)^2 + \ldots + \left(\frac{\partial r}{\partial x_j} U_{x_j} \right)^2 \right]^{1/2} \tag{6.1}$$

where U_j represents the uncertainty value of the data under criterion j^{th}, and

r is data reduction equation.

In this case, r is the overall value model as shown in equation 4.2. Thus

$$r = \sum_{i=1}^{n} W_i X_i \tag{6.2}$$

Therefore, the uncertainty values of the final overall values were calculated by using the equation:

$$Uncertainty\left(U\right) = \left[\sum_{i=1}^{24} \left(W_i U_i\right)^2\right]^{1/2} \tag{6.3}$$

where U_i represents the uncertainty value of the data under the i^{th} criterion, and W_i represents the weight assigned to the criterion.

The estimated uncertainty values used are listed in Table 6-1. These values are considered relative uncertainties. This is because the value of zero does not mean that the data for the option has no uncertainty associated with it, but rather that all the data for that option was available and no figures were assumed. There may still be uncertainty associated even if data is adopted from literature since specific origin of the data is relatively unknown.

The uncertainty value ($\pm U$) of each management option was added to and subtracted from the option's overall value. Consequently, a range of overall values was obtained as shown in Figure 6-4.

Table 6-1 Associated uncertainties of evaluation options

Cuttings management options	Uncertainty value
Vertical Centrifuge	0.0
Horizontal Centrifuge	0.0
Thermal Desorption	0.0
Incineration	46.9
Grinding	160.3
Stabilization	48.2
Bioreactor	47.2
Re-injection	0.0

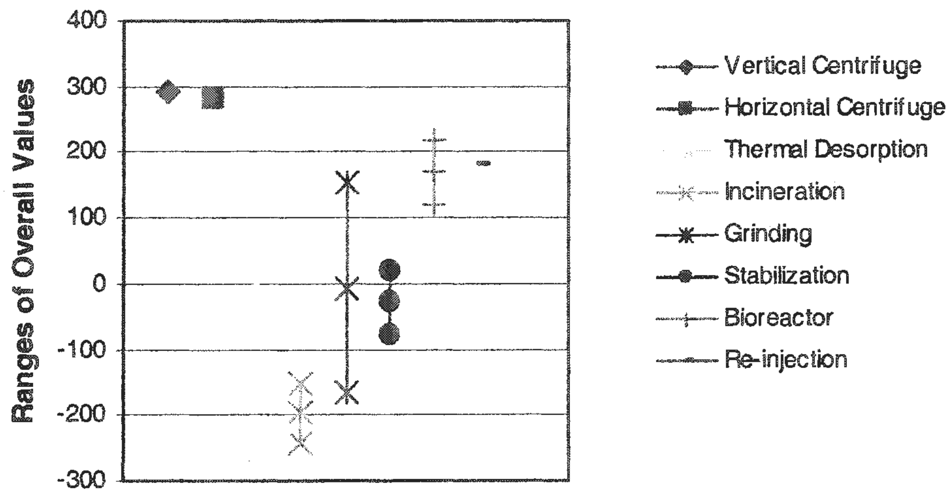

Figure 6-4 Ranges of overall values

According to Figure 6-4, the centrifuges (vertical and horizontal) provide the highest overall values with the lowest uncertainty. While either re-injection or bioreactor might be considered the third best choice, the bioreactor has a higher uncertainty. Therefore, re-injection was chosen as the third best option.

6.3 SENSITIVITY ANALYSIS

In this part of the study, criteria weights were varied and new overall values and alternative ranks were determined. The extent and the patterns of changes reflect the evaluation results' sensitivity to the assigned criteria weights. In addition, this analysis assures that the weights used in the evaluation were well defined to ensure the various distributions of the weights among the criteria reflect differences in the results.

Seven sets of analyses were conducted by specifying a weight for one criterion or weights for a group of criteria and adjusting the weights of the other criteria proportionally. In all cases, the total weight remained constant. Therefore, once a weight was increased, the others decreased, resulting in different tradeoffs among the criteria in each set of the analyses. In the following section, a criterion or a group of criteria was assigned weight(s) which were decreased by up to 75% and/or increased by up to 150% in order to determine changes in alternative ranks. The sensitivity of each evaluation option was also compared by using the range of the varying overall values.

6.3.1 Adjusting the weights of the cost criteria

The total weight of the cost criteria category was varied from a 75% decrease (0.25 times as much as the original weight) to 150% increase (2.50 times as much as the original weight). Therefore, the original total weight of 32 was varied between 8 and 80. The weights of the other criteria were adjusted accordingly. The overall values are shown in Table 6-2. Figure 6-5 and Figure 6-6 show the ranks and the sensitivity to costs of the evaluation options under the various cost weights.

Table 6-2 Overall scores with adjusted weights based on modified weight of the cost criteria

Weight	Vertical Centrifuge	Horizontal Centrifuge	Thermal Desorption	Incineration	Grinding	Stabilization	Bioreactor	Re-injection
Increased by 150%	**86**	**80**	-218	-758	-346	-548	**-44**	-45
Increased by 100%	**159**	**151**	-138	-564	-223	-368	34	**40**
Increased by 50%	**232**	**222**	-57	-371	-100	-188	112	**126**
Original weight	**291**	**283**	-14	-197	-6	-28	170	**182**
Decreased by 50%	**377**	**365**	103	16	146	172	268	**296**
Decreased by 75%	**414**	**401**	143	113	208	262	307	**339**

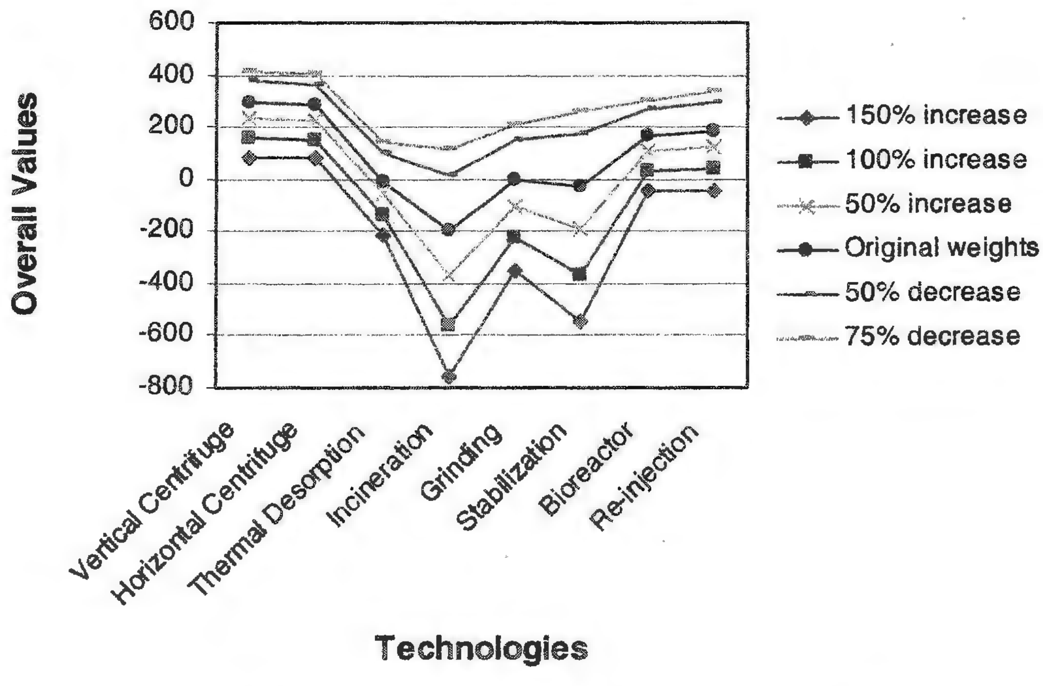

Figure 6-5 Alternative ranks for varied cost weights

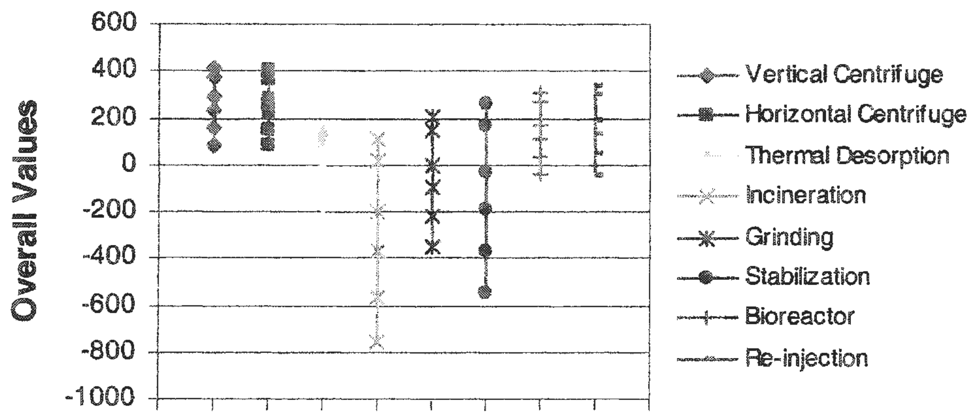

Figure 6-6 Variation of overall values for adjusted cost weights

From the analysis, an increase in cost weight lowered the overall values of evaluation options. From Figure 6-5, in most cases, the ranks of the options were unchanged, that is, the best options were the two types of centrifuges and re-injection respectively. The bioreactor became slightly more preferred than re-injection when the total weight of the cost criteria was increased by 150% due to its lower cost. Figure 6-6 showed that the most sensitive options to adjusted weights were incineration, stabilization, and grinding. As these options were those with the highest costs, the overall values became closer to the best options when the weight of cost criteria was considerably reduced.

6.3.2 Adjusting the weights of the environmental and safety criteria

The total weight of the environmental and safety category, which was 32 in the evaluation, was varied from 75% decrease (0.25 times as much as the original weight) to 150% increase (2.50 times as much as the original weight). The weights under this category and the weights of the other criteria were adjusted proportionally. The result of this analysis is shown in Table 6-3 and Figure 6-7.

Table 6-3 Overall scores with adjusted weights based on modified weight of the environmental and safety criteria

Weight	Vertical Centrifuge	Horizontal Centrifuge	Thermal Desorption	Incineration	Grinding	Stabilization	Bioreactor	Re-injection
Increased by 150%	410	394	211	122	276	326	406	477
Increased by 100%	375	360	148	22	192	215	334	388
Increased by 50%	340	327	86	-77	107	103	262	300
Original weight	291	283	-14	-197	-6	-28	170	182
Decreased by 50%	269	261	-40	-277	-61	-120	117	122
Decreased by 75%	252	244	-71	-327	-103	-176	81	78

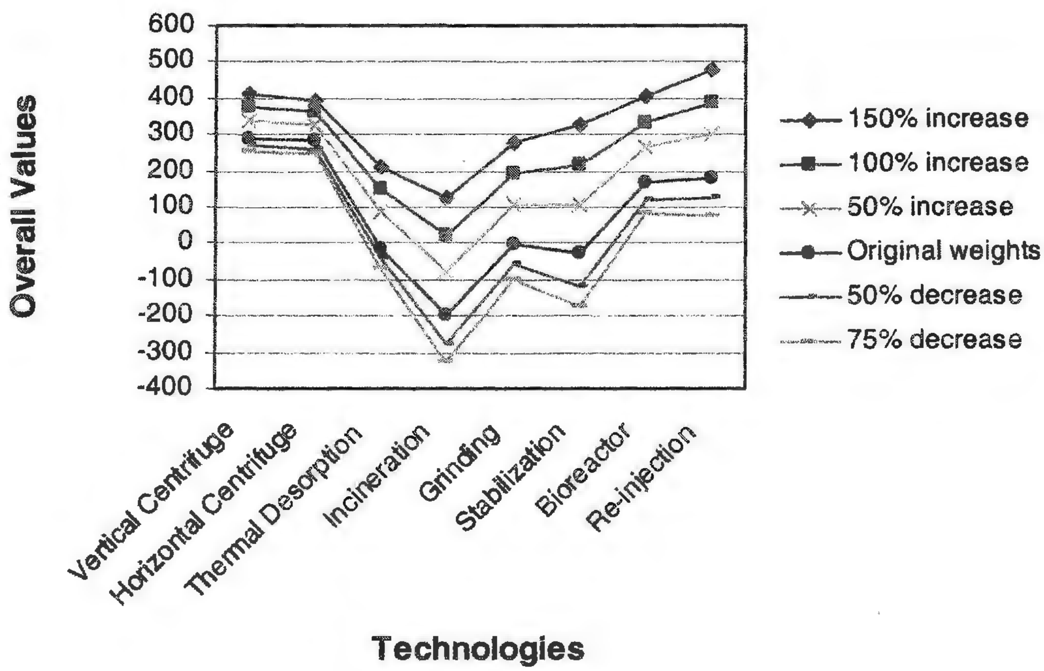

Figure 6-7 Alternative ranks for varied environmental and safety weights

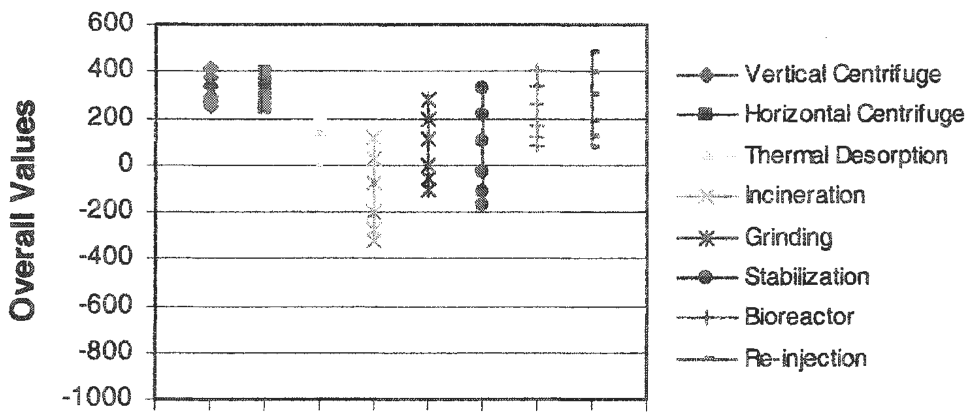

Figure 6-8 Variation of overall values for adjusted environmental and safety weights

The results show that the overall values increase with the increase in environmental and safety weights. This is because most of the scores under environmental and safety were positive values. In most cases, the best three options were the two types of centrifuges and re-injection. The re-injection became superior when the weights in this category were increased as shown in the highlighted cells of Table 6-3. When the weights were increased by 100% and higher, the re-injection option ranked the best among all the options. This is because the re-injection does not involve offshore discharge and, thus, attained the highest score under environmental and safety category. The bioreactor became the third ranked option when the weights were increased or decreased sufficiently. It became better than the horizontal centrifuge when the weights were increased by 150% and better than re-injection when the weights were decreased by 75%. This is due to the bioreactor's environmental and safety score, which was higher than that of the horizontal centrifuge but less than that of the re-injection. Nevertheless, assigning the total weight of more than 64 out of 100 (100% increase of the original weight) and less than 8 (75% decrease of the original weight) of the environmental and safety issues is impractical. Figure 6-8 shows that centrifuges are the least sensitive to the changes in the weights.

6.3.3 Adjusting the weights of the technical feasibility criteria

The total weight of this technical feasibility criteria category was varied from a 75% decrease to a 150% increase. In other words, the original total weight of 20 was varied between 5 and 50. The weights of the other criteria were adjusted accordingly.

Table 6-4 Overall scores with adjusted weights based on modified weight of the technical feasibility criteria

Weight	Vertical Centrifuge	Horizontal Centrifuge	Thermal Desorption	Incineration	Grinding	Stabilization	Bioreactor	Re-injection
Increased by 150%	**481**	**459**	161	47	185	194	295	**314**
Increased by 100%	**422**	**404**	115	-28	131	126	260	**279**
Increased by 50%	**363**	**349**	69	-103	77	59	225	**245**
Original weight	**291**	**283**	-14	-197	-6	-28	170	**182**
Decreased by 50%	**246**	**239**	-23	-252	-31	-76	154	**176**
Decreased by 75%	**216**	**211**	-46	-289	-58	-109	137	**159**

The results show that the overall values increase with the increase in technical feasibility weights as the scores are mostly positive. From Figure 6-9 and Figure 6-10, the two types of centrifuges and re-injection are still the best three options regardless of the changes in the criteria weights. None of the options was very sensitive in this case compared with the first two cases.

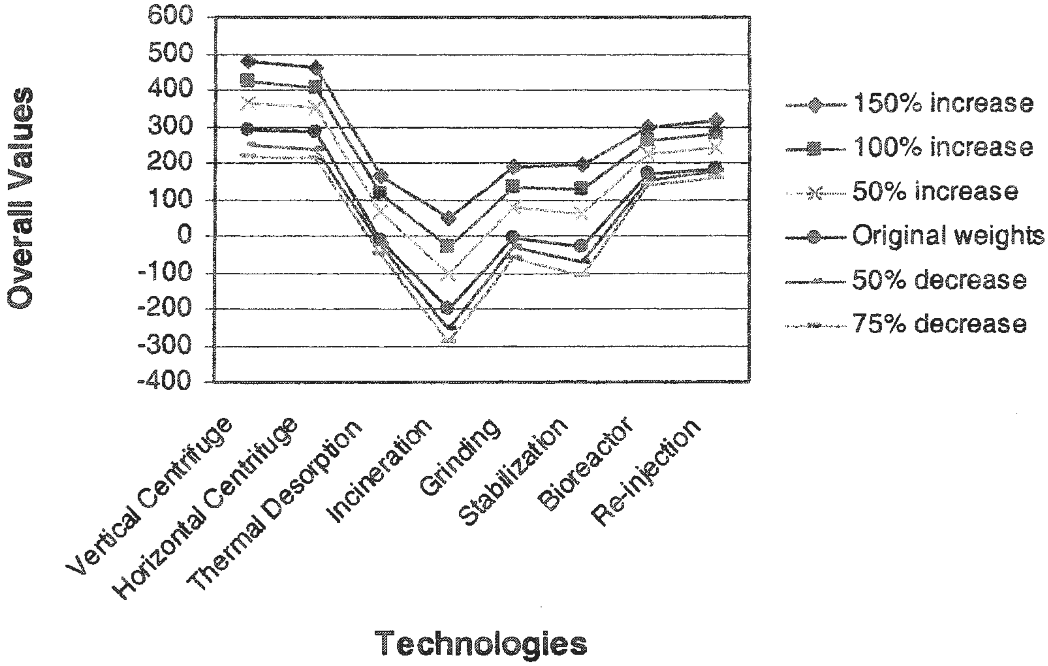

Figure 6-9 Alternative ranks for varied technical feasibility weights

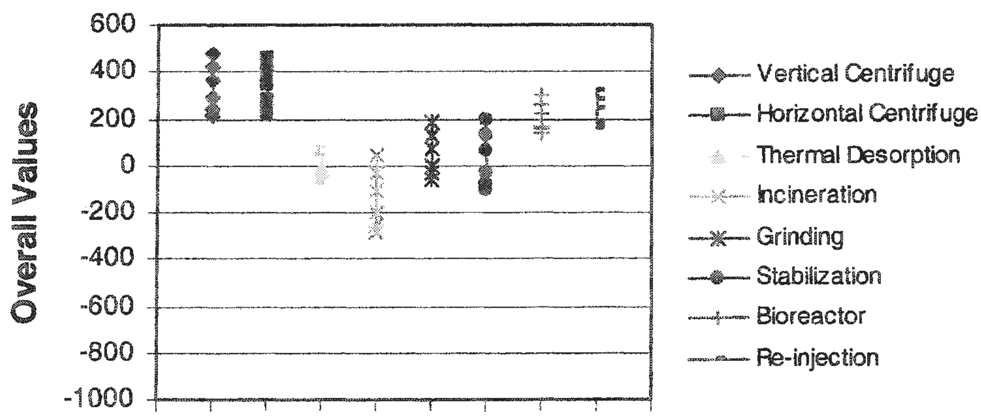

Figure 6-10 Variation of overall values for adjusted technical feasibility weights

6.3.4 Adjusting the weights of the rig compatibility criteria

The total weight of 16 of this cost criteria category was varied from a 75% decrease to a 150% increase, or from 4 and 40. The weights of the other criteria were adjusted accordingly.

Table 6-5 Overall scores with adjusted weights based on modified weight of the rig compatibility criteria

Weight	Vertical Centrifuge	Horizontal Centrifuge	Thermal Desorption	Incineration	Grinding	Stabilization	Bioreactor	Re-injection
Increased by 150%	**228**	**229**	-66	-162	-37	-35	103	**104**
Increased by 100%	**253**	**250**	-36	-167	-17	-26	132	**140**
Increased by 50%	**279**	**272**	-7	-172	3	-17	161	**175**
Original weight	**291**	**283**	-14	-197	-6	-28	170	**182**
Decreased by 50%	**330**	**315**	53	-182	43	0	218	**246**
Decreased by 75%	**343**	**326**	67	-185	53	5	233	**264**

The results show that the overall values decrease when the rig compatibility weights increase, because the highest weighted criteria in this group, weight and size criteria, were assigned negative scores. Even though the best three options are still the centrifuges and re-injection, the horizontal centrifuge attained the highest overall value when the rig compatibility weights increased by 150% as shown in Table 6-5. All of the options were relatively insensitive to the weight change in this case. Figure 6-11 and 6-12 show the ranks of the options and their sensitivity.

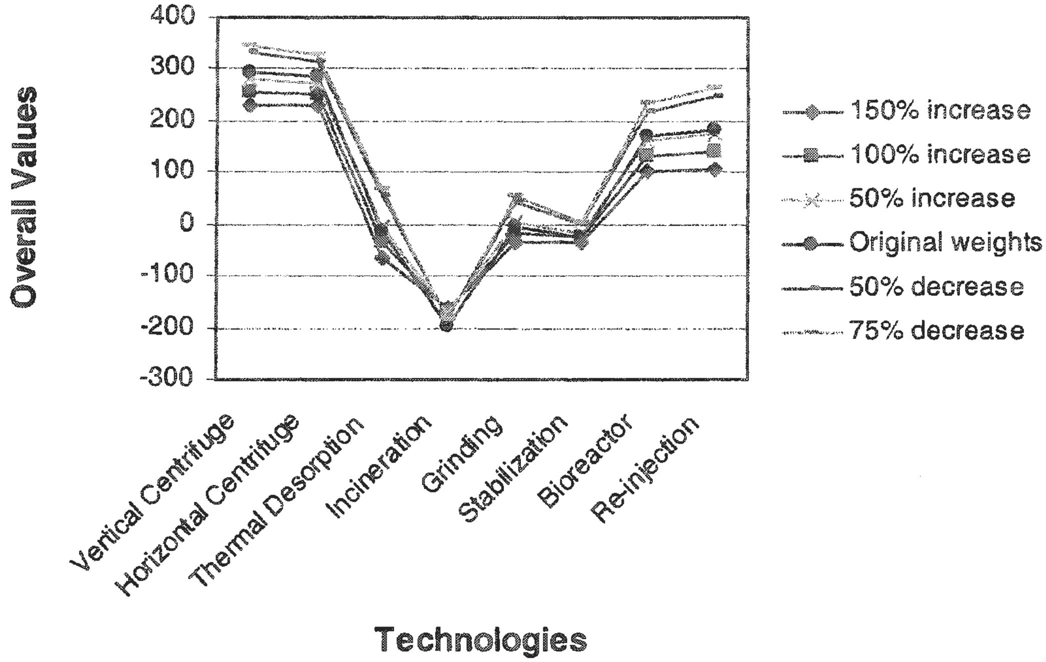

Figure 6-11 Alternative ranks for varied rig compatibility weights

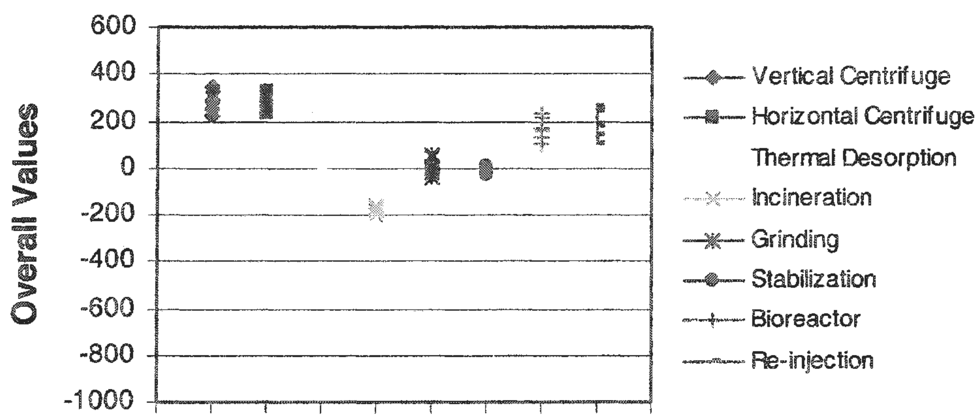

Figure 6-12 Variation of overall values for adjusted rig compatibility weights

6.3.5 Adjusting the weights of the treatment capacity criterion

According to the questionnaire reply by an operator, capacity was one of the most important factors in selecting a management system for drilling cuttings. Therefore, the weight of treatment capacity criterion with the original weight of 4 was varied from a 50% decrease to a 250% increase. This resulted in the treatment capacity weight ranging from 2 to 14. The weights of the other criteria were adjusted proportionally.

Table 6-6 Overall scores with adjusted weights based on modified weight of the treatment capacity

Weight	Vertical Centrifuge	Horizontal Centrifuge	Thermal Desorption	Incineration	Grinding	Stabilization	Bioreactor	Re-injection
Increased by 250%	**377**	**341**	26	-143	44	34	170	**241**
Increased by 100%	**334**	**313**	24	-164	31	9	182	**223**
Increased by 50%	**319**	**303**	24	-170	27	0	186	**217**
Original weight	**291**	**283**	-14	-197	-6	-28	170	**182**
Decreased by 50%	**290**	**284**	22	-184	19	-17	193	**205**

The overall values increased with the increased treatment capacity weight due to this criterion's positive effect on the options' feasibility. The ranks of the evaluation options remained unchanged as shown in Figure 6-13. The best three options were the two types of centrifuges and the re-injection. From Figure 6-14, the overall values of all the options did not change much compared with the previous cases. This is because the weights were not varied significantly in this case, resulting in the overall values for the options (Table 6-6) being altered to a lesser degree.

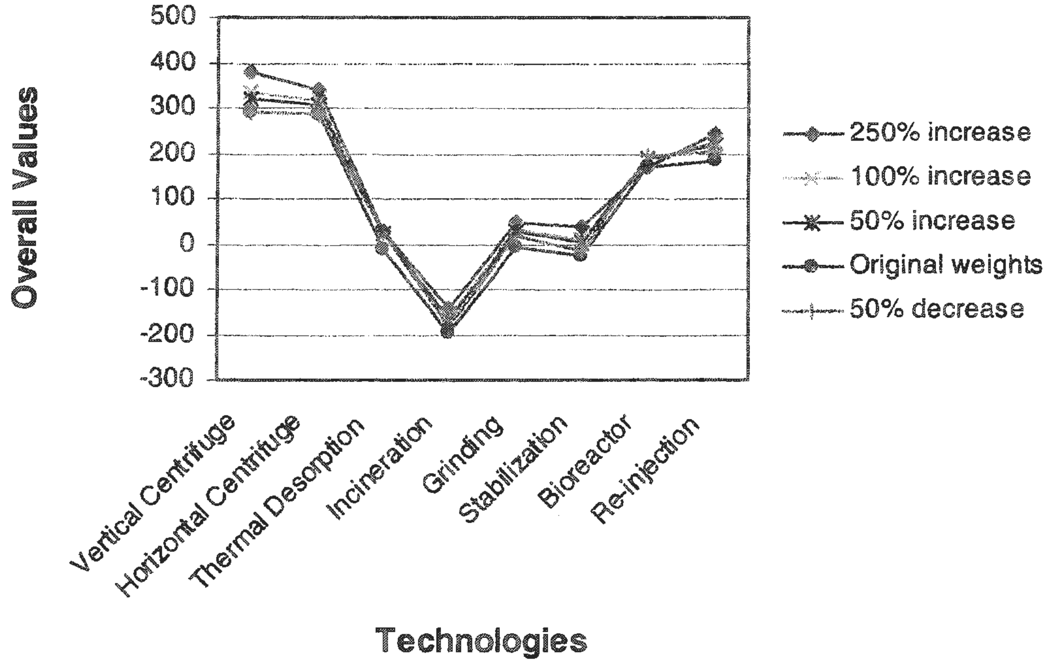

Figure 6-13 Alternative ranks for varied treatment capacity weight

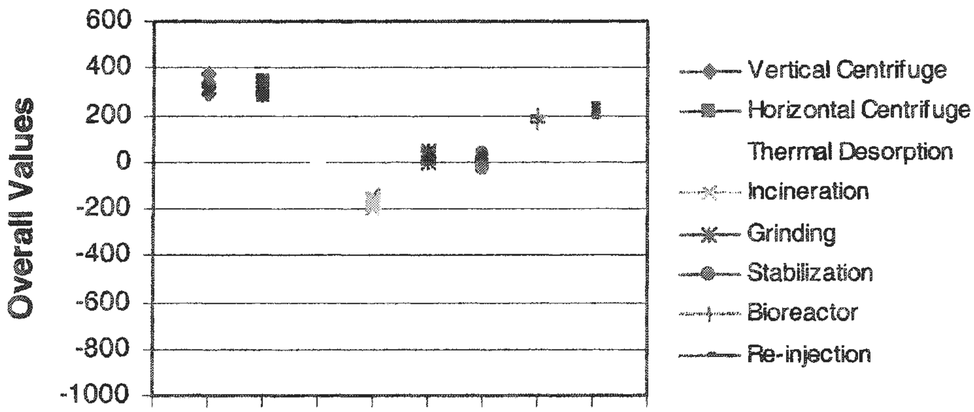

Figure 6-14 Variation of overall values for adjusted treatment capacity weight

6.3.6 Adjusting the weights of the treatment efficiency criterion

In this analysis, the weights of the criteria under treatment efficiency were varied from a 75% decrease to a 150% increase. The original total weight of this group was 14, which was varied in this case from 3.5 to 35. The weights of the other criteria were adjusted proportionally.

Table 6-7 Overall scores with adjusted weights based on modified weight of the treatment efficiency

Weight	Vertical Centrifuge	Horizontal Centrifuge	Thermal Desorption	Incineration	Grinding	Stabilization	Bioreactor	Re-injection
Increased by 150%	263	237	57	-94	57	67	232	269
Increased by 100%	277	256	46	-122	46	42	218	250
Increased by 50%	291	275	34	-149	34	17	204	230
Original weight	291	283	-14	-197	-6	-28	170	182
Decreased by 50%	319	313	11	-205	12	-33	175	191
Decreased by 75%	326	322	6	-219	6	-46	168	182

The overall values decreased with the increased treatment efficiency weight. The best three options were the two types of centrifuges and the re-injection, as in the previous cases. However, as shown in Table 6-7, when the treatment efficiency weight was increased by 150% or assigned the weight of 35, re-injection became the first ranked option. This is because the percentage of fluid retention after treatment is the main consideration under the treatment efficiency criterion. Therefore, re-injection, which provides 0% fluid retention, is better when compared with centrifuges, which have the lowest fluid reduction efficiency among this group of the options. The overall values of all the options were not very sensitive to the weight changes.

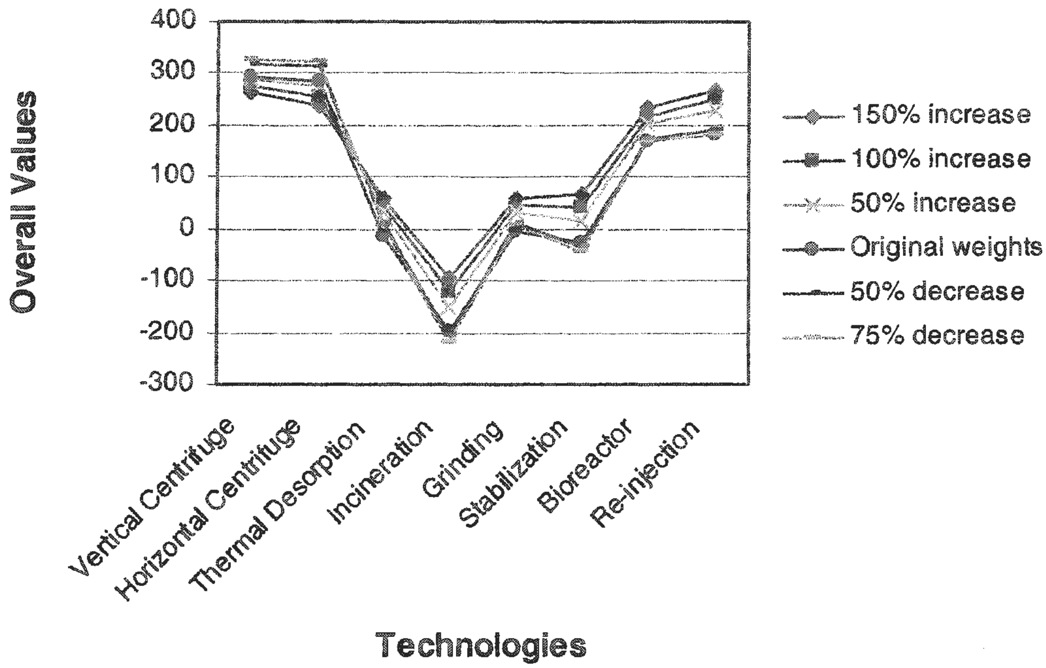

Figure 6-15 Alternative ranks for varied treatment efficiency weight

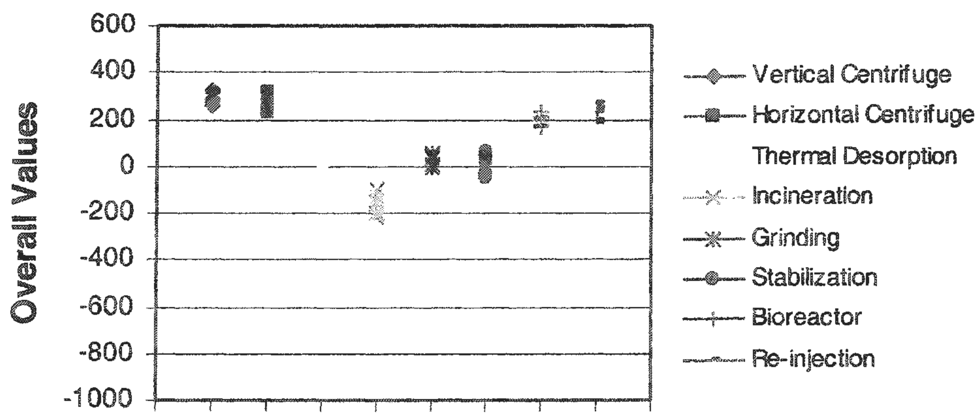

Figure 6-16 Variation of overall values for adjusted treatment efficiency weight

6.3.7 Adjusting the weights of the technical feasibility and rig compatibility criteria

The technical feasibility and the rig compatibility categories were considered the group of criteria reflecting the offshore technical applicability of the cuttings management options. The sum of weights under these two criteria categories was originally 36 or around 1/3 of the total criteria weight. The original weights under these groups were varied from a 75% decrease to a 150% increase, or from 9 to 90. The weights of the other criteria were adjusted accordingly.

Table 6-8 Overall scores with adjusted weights based on modified weight of the technical feasibility and rig compatibility

Weight	Vertical Centrifuge	Horizontal Centrifuge	Thermal Desorption	Incineration	Grinding	Stabilization	Bioreactor	Re-injection
Increased by 150%	**424**	**415**	79	122	147	**210**	208	199
Increased by 100%	**384**	**375**	60	22	105	137	202	**203**
Increased by 50%	**344**	**334**	42	-77	64	64	196	**207**
Original weight	**291**	**283**	-14	-197	-6	-28	170	**182**
Decreased by 50%	**265**	**253**	4	-277	-18	-81	183	**215**
Decreased by 75%	**245**	**233**	-5	-327	-39	-117	180	**216**

The overall values increased with the increased technical applicability weight. In most conditions, the best three options were the two types of centrifuges and the re-injection. When the treatment efficiency weight was increased by 150% or assigned the total weight of 90, stabilization became the third ranked option. The bioreactor also scored better than re-injection, ranking fourth. However, assigning the weight of 90% to the offshore technical applicability was not really realistic. Therefore, the re-injection was still considered one of the three best options. Incineration and stabilization were the most sensitive options to the weight changes.

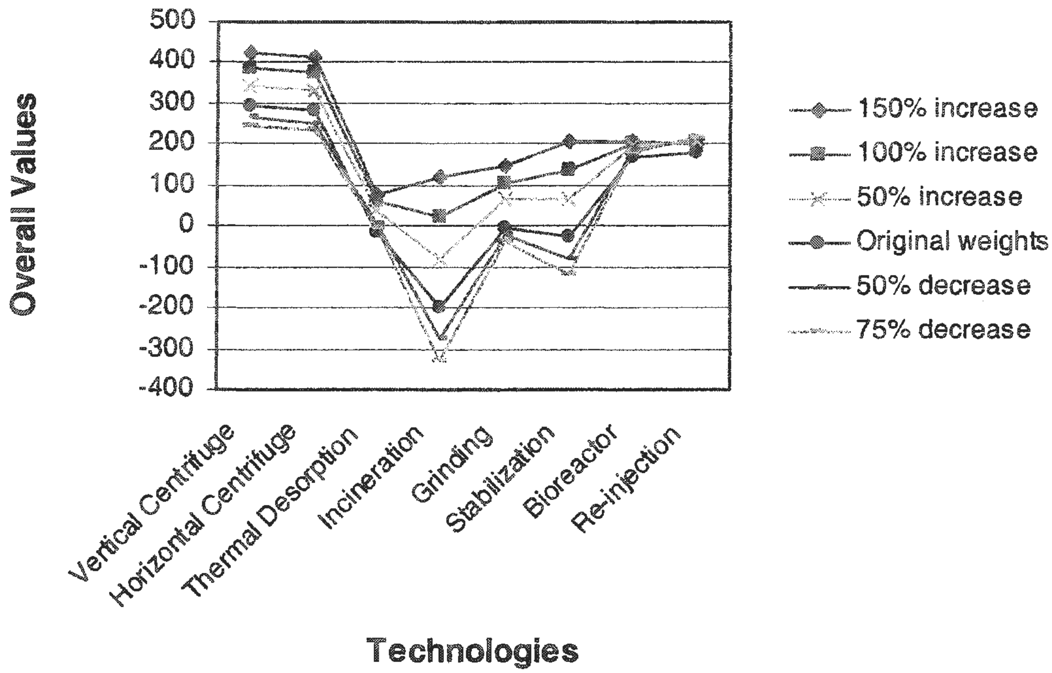

Figure 6-17 Alternative ranks for varied technical feasibility and rig compatibility weights

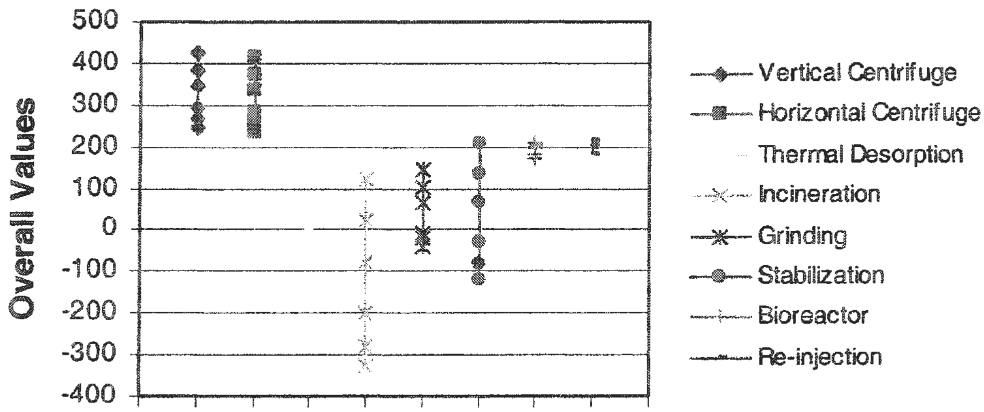

Figure 6-18 Variation of overall values for adjusted technical feasibility and rig compatibility weights

6.4 DOMINATING CRITERIA

This study provides a broad evaluation of offshore technology for drilling cuttings management. Therefore, all of the factors which were expected to affect the suitability of the cuttings management were included. However, not all criteria contribute significantly to the final results and evaluating the options was also limited by a large number of criteria. Another disadvantage of having too many criteria is that weights, which were distributed among many criteria, may not be able to properly represent the difference in the importance of the criteria. As such, it was important to identify the dominating criteria, the most influential criteria on the final results, and to perform detailed evaluations focusing on these criteria.

There are two factors determining the contribution of a criterion to the overall values: the assigned criteria weights and the score variation.

6.4.1 The assigned weights of the criteria

The assigned weights represent the relative importance of the criteria compared with the other criteria used in the evaluation. As each of the scores has to be multiplied by the corresponding criteria weights in order to calculate the overall values, the criteria that are assigned higher weights play a more important role in the options' overall values.

6.4.2 The range of variation of the scores under each criterion

The range of variation of the scores reflects whether the options are significantly different under a considered criterion. In other words, the criterion under which the options possess similar properties is considered insignificant and unnecessary in comparing the evaluation. For example, in the case that all the options have the same size, these options are then assigned an equal score under the size criterion. This means that all the options have the same property in terms of size and this criterion is not necessary in comparing the options.

To assess the range of variation of each criterion, the standard deviation of the options' scores under the criteria were used. The higher values of standard deviations reflect significant differences in the options' properties. From the scores shown in Table 5-24 in the previous chapter, the standard deviations of the scores with the range of ten were calculated using equation 6.4 (Swinscow, 1997) and are outlined in Table 6-9.

$$SD = \sqrt{\frac{\sum\left(x - \bar{x}\right)^2}{n-1}} \tag{6.4}$$

In order to determine the dominating criteria in the evaluation, the scores' standard deviations were considered along with the assigned weights of the criteria. From Table 6-9, five each of the highest and the lowest values of standard deviations were observed. As shown in the lightly shaded cells of the Table 6-9, the five criteria with the lowest score standard deviations includes associated solid wastes, proven technology, ease of repair and maintenance, impacts on other operations, and requirement of chemicals. These criteria have the standard deviations which range from 0.52 to 1.30. The proven technology was assigned the weight of four while the others were assigned a weight of two, the lowest weight assigned in the evaluation.

Table 6-9 Standard deviations of scores for each criterion

No.	Criteria		Weight	Standard Deviation
	Technical		20	
1	Proven Technology		4	0.71
2	Geologic Formation Requirement		2	3.54
	Ease of Operation		6	
3	Pre-treatment Requirement		2	2.25
4	Operator Needed or Level of Control		2	2.97
5	Requirement of Chemicals		2	1.30
	Installation and Maintenance		4	
6	Ease of Installation		2	1.89
7	Repair Ease and Maintenance		2	1.06
8	Treatment Capacity (Tonnes/hr)		4	3.51
	Rig Compatibility		16	
9	Impacts on Other Operations		2	1.16
10	Rig Flexibility		2	1.81
11	Size or Space Requirement (m^2)		6	2.49
12	Weight (Tonnes)(0-40)		6	1.94
	Environmental		32	
	Treatment Efficiency		14	
13	Removal of Drilling Fluids (%ROC)		7	2.18
14	Toxicity and Volume of the Effluent (WQ)		7	1.96
	Associated Wastes		8	
15	Greenhouse Gas		2	1.96
16	Non-Greenhouse Gas		2	1.64
17	Solid Wastes		2	0.52
18	Liquid Wastes		2	2.03
	Energy and Post-treatments		6	
19	Energy Consumption (MJ/Tonne)		3	3.62
20	Transport/Disposal after Treatment		3	1.69
	Safety		4	
21	Human Exposure		2	1.85
22	Risk of Accident		2	1.77
	Costs		32	
23	Capital Costs	Total cost (USD)	32	3.67
24	Operational Costs			
			100	

On the other hand, the five criteria with the highest ranges of variations in the scores are cost, energy consumption, geological formation requirement, treatment capacity, and operator needed/level of control. The standard deviations ranged from 2.97 to 3.67 (as shown in the heavily shaded cells of Table 6-9). Cost is the criterion in this group that was assigned a relatively very high weight of 32. The energy consumption and treatment capacity were assigned lower weights of 3 and 4 respectively. The geological formation requirement and the operator needed/level of control were assigned weights of 2.

In addition, there are also groups of criteria under which scores have a relatively high range of variation. These groups include the treatment efficiency, and the size and weight criteria. The first group consists of two criteria which have standard deviations of 2.18 and 1.96 and was assigned the total weight of fourteen. The latter group is comprised of the size and weight criteria, which have standard deviations of 2.49 and 1.94. The total weight for these criteria is twelve.

Therefore, according to the analysis, the dominant criteria include cost, treatment efficiency criteria, and size and weight of the technologies. In addition, energy consumption and treatment capacity are considered important in comparing options if higher weights are assigned. In contrast, the least significant criteria include solid wastes associated, repair ease and maintenance, impacts on other operations, and requirement of chemicals, as they were assigned low weights and have low ranges of variation in scores.

This conclusion on dominating criteria is only applicable to a specific evaluation problem and depends on the evaluation options involved. The importance of criteria may be changed when different groups of options are considered. For instance, the requirement of chemicals (which is not important in this case) could be very important in comparing the options when more intensive chemical treatments are included.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 DISCUSSION AND CONCLUSIONS

This thesis presents an evaluation of management technologies for drilling cuttings that are generated from ongoing offshore drilling operations. A multicriteria decision making technique was used to evaluate eight cuttings management options. Technical feasibility, rig compatibility, environmental impact and safety, and cost aspects were considered in the evaluation as the decision making criteria. The options were compared using a weighted deterministic model where the individual criteria were weighted according to their importance. However, the main aspects including the technical, environmental, and financial issues were considered to be equally important.

Based on the results of the evaluation, the most suitable drilling cuttings management options for offshore use are the vertical centrifuge, horizontal centrifuge, and re-injection. The offshore feasibility and low cost were the dominant factors in these options emerging as the most favorable. In addition, the three selected options are the only technologies currently used offshore to handle drilling cuttings wastes.

Uncertainty and sensitivity analyses were conducted to verify the accuracy of the results. Uncertainty reflects the reliability of the options' overall scores due to the limited availability of data. The reliability is most affected by the data available for the various options. The centrifuges and re-injection scored the best when uncertainty values were considered along with the overall scores. They also have relatively low uncertainty as the data for these options are readily available for offshore application, as opposed to the data from onshore options. In addition to the best three options, the forth-ranked bioreactor is considered the most promising technology for offshore applications, but with larger associated uncertainties. The size, weight, and energy consumption of the bioreactor are the most important uncertainties that are needed if it is to be selected as a possible offshore management technology.

The effects of changes to the criteria weights on the ranks of the options were observed through a sensitivity analysis. It was shown that the three highest ranked technologies from the previous analysis also ranked the highest in most cases with some changes in their ranking order. Changes in the top three rankings occurred only under conditions of unrealistic criteria weights. It can therefore be concluded that the three best options do not change significantly with assignment of different weights. This is largely due to the fact that the top three options are markedly superior in important criteria, which results in the options scoring higher regardless of the weight alterations. Another possible reason is that there are many criteria used in the evaluation and the total weight was distributed among a larger number of criteria. This makes the weights for individual criteria small and therefore rankings are less sensitive to changes in any one criterion.

The dominating criteria for this evaluation include costs, energy consumption, treatment capacity, treatment efficiency, size, and weight. This is because these criteria contribute relatively more to the difference among the overall scores of the options compared with the other criteria. As an extension to this research, these criteria, along with some other significant criteria such as the requirement of geologic formation and operator needed/level of control, should be chosen for detailed reassessment of the options to verify the results. This detailed reassessment will allow more detailed investigation of the considered options and can lead to better evaluation results.

The reliability and validity of the evaluation results are influenced by many factors. The validity of the results depends considerably on the discharge regulations that were used as the threshold criterion in this evaluation. As regulations for SBF drilling cuttings discharge vary from place to place and are moving toward zero discharge in some jurisdictions, the results of this evaluation are only valid for some locations. Re-injection also has a major limitation in that it requires a suitable formation, which means that this technique is not technically feasible in all locations. Therefore, the results of this evaluation are valid only for an offshore site where there is a suitable receiving formation available for re-injection. In case there is no suitable formation in vicinity of the drilling site, the re-injection cannot be included as an evaluation option or the evaluation may consider remote re-injection instead.

The reliability of the results is also limited by the availability and the quality of the data. As some options have never been used offshore, some data used in the evaluation are not specifically for offshore operations and therefore the application might be very different when they are used offshore. For example, the costs of using a technology will be more expensive offshore than onshore due to factors such as the reduced capacity, the ease of installation, and smaller tonnage of waste to be treated (such as when the treatment is performed by suppliers and it is charged per tonnes of wastes). As a consequence, the ranks of the technologies may change when data from offshore applications are available and are used instead of onshore data.

Another factor affecting the reliability of the evaluation results is the subjective consideration used in the evaluation, for example to assign weights and to subjectively score the options. These processes might contain biased values, which in turn affect the final results. The bias from weight assignment was minimized by carefully assigning weights based on the relative importance of the criteria. Further, the errors due to the subjectively assigned weights were tested through the sensitivity analyses, which showed that the best three options were unchanged with the altered weight distributions. On the other hand, the subjective rankings that were performed in the process of scoring option properties may have larger effects on the results. This is because the ranges of the qualitative characteristics are large so it is possible that the score assigned to an option based on a qualitative value does not provide an appropriate value for comparison. An example is the case that all of the three optimum options are the options which have been used offshore. These options might have been scored high due to the bias towards the offshore applications. However, these options score considerably better than the others in many quantitative aspects, such as size, weight, and costs, which are more important (relatively higher weighted) in offshore application. Therefore, the bias initiated from the subjective scoring is considered less significant compared with the superiority in overall quantitative scores of the options and does not affect the rankings of the technologies to a large extent.

Innovative technologies, including microemulsion, supercritical extraction, and silica microencapsulation, were not included as evaluation options in this study as they are in the development stage and data are rarely available. However, the technologies were reviewed on their status, general process, and potential for offshore applications. From the technology reviews, the important factors in development of new technologies include compact size and very high treatment efficiency (to be installed offshore and to meet progressively more stringent discharge regulations). All of the reviewed innovative technologies involve use of chemicals to provide advanced levels of drilling fluid separation from the cuttings. In addition, some of these technologies also allow recovery of drilling fluids after separation. As they involve chemical treatment processes, the issues in applying these innovative technologies are mostly related to the different chemicals used and the safety of the process to be used offshore (such as use of high pressure gas). From the reviews, the major limitation on most of the reviewed innovative technologies is cost, which is relatively high compared with conventional cuttings treatment. However, costs of treatment are expected to be reduced when technologies become more widely used.

This evaluation was designed to provide a simple but comprehensive methodology to initially assess drilling cuttings management technologies. As selecting the most suitable management technology depends on many site specific parameters, the appropriate evaluation should be conducted on a case-by-case basis. Decision-making should be performed with care and a good understanding of the evaluated technologies. Modifications of some details of the methodology, such as the evaluation criteria, may also be required. Use of more accurate or more specific data will also provide better evaluation results.

7.2 RECOMMENDATIONS FOR FUTURE WORK

1. This study is to be used as a basis in the evaluation of drilling cuttings management using multicriteria decision making. Therefore, this method may be used as an initial screening process to be followed by more detailed evaluation for specific conditions. The results of the study and the reviews of technologies can also be used to facilitate different cuttings management decision making problems.

2. In the detailed evaluation, uncertainty of data may be considered if the data distributions can be determined. More appropriate value functions may be used if better data is available, instead of those used here, which were assumed to be linear.

3. The evaluation may be modified to include the possibility of recovering the separated base fluid and reusing the treated cuttings as evaluation criteria.

4. As the data for the evaluating options significantly affect the reliability of the evaluation results, improving data quality is critical to enhance performance of the evaluation. More reliable data, especially those specifically for offshore drilling cuttings management, should be used if they are available. Updates of the existing data and collection of newly available data should be done in the future. These data additions can easily be incorporated into this method.

5. The weights and scores assigned in the evaluation may be verified or re-assigned by the people with expertise in drilling cuttings management in order to obtain better results.

6. The studies and the results of the evaluation may be used to determine the direction in development of drilling cuttings management technologies (e.g. which type of cuttings management is more feasible and should be further developed). Detailed

studies on potential technologies or management mechanisms may be conducted in order to further develop or reduce limitations of the technologies to suit offshore applications.

7. The reviews of innovative technologies can be used to determine interesting new technologies that may be useful in offshore applications in the future. The technologies may be studied further to determine alternative chemicals or processes. These new technologies may also be included later as one of the options once sufficient data are available.

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APPENDIX A

QUESTIONNAIRES

A.1 QUESTIONNAIRE FOR SUPPLIERS

Please choose the best answer or answer the following questions as detailed as possible.

General information

1. What is the name and type of your technology?

 ____

If the technology is re-injection, please go to question 5.

2. What is the current stage of development of the technology? (More than 1 choice may be chosen.)
 - ☐ Research and development stage
 - ☐ Laboratory tested
 - ☐ Field tested
 - ☐ Commercially available
 - ☐ Currently in use
 - ☐ Others____

3. Is the technology proven to be able to treat drilling cuttings?
 - ☐ Yes, it has been previously used for drilling cuttings treatment
 - ☐ Maybe, it has been used for similar types of wastes. Please specify the wastes similar to drilling cuttings and have been successfully treated by the technology

 ____

 - ☐ No, the technology cannot be used for drilling cuttings and it has no potential of treating drilling cuttings at all

4. Has the technology been used offshore? (More than 1 choice may be chosen.)
 - ☐ Never been used offshore (Please answer question 4.1)
 - ☐ Commonly used offshore
 - ☐ Not commonly used offshore but there are some offshore applications
 - ☐ Used onshore

Description of the technology

5. Please list the major components of the treatment system in order from the beginning of the process? (such as conveyor, combustor, baghouse, etc.)

 ____

 ____

6. What types of contaminants was the technology designed to treat?

____

7. Does the technology require specific type of geologic formation?
   - ☐ The treatment process cannot be successful without suitable formation
   - ☐ Suitable formation can improve the performance of the treatment process
   - ☐ No, the formation does not affect the treatment process
   - ☐ Others______________________________

8. Please answer the following questions:
   In what state must the feed into the unit be in (i.e. slurry, dewatered, etc.)?

   ____

   Are there limits on fraction of contaminant in feed (i.e. 2% of oil)?

   ____

9. Please specify the number of operators required in operating the system and the personnel-hours required per day

   Number of operators: ____________________________

   Personnel hours (per day): ____________________________

10. What training level or skill level is required of the system's operators?
    - ☐ No special training required
    - ☐ Specially trained operators are required
    - ☐ Experienced operators are required
    - ☐ Other______________________________

11. Are there any chemicals required in the treatment processes or other consumables (such as lubricants, fresh water, etc)?
    - ☐ Yes. Please specify types and amount

      ____

      ____

    - ☐ No.

12. What is the expected life of the equipment?

    ____

13. What is the typical maintenance required for the system and what is the approximate downtime per day?

    ____

14. What components most often need replacement and how often per month, or year?

    ____

15. Does the technology require technical experts or special equipment for repairs? (More than 1 choice may be chosen.)
   - ▢ Require technical experts
   - ▢ Can be done by operators
   - ▢ Require special equipment
   - ▢ Simple equipment available offshore
   - ▢ Others____

16. What is the treatment capacity of the technology (measured in tonnes of waste per day)?

   ____

17. Does the technology create any impacts on other platform operations, either during treatment operation or downtime periods?
   - ▢ Impacts on drilling operation due to treatment system operations such as______ ____
   - ▢ Impacts on drilling operation due to the downtime period of the treatment system such as____
   - ▢ Others____

18. Please specify types of drilling rigs that could accommodate for the treatment system and rank based on preference?
   - ▢ Floating vessel
   - ▢ Fixed platform
   - ▢ Semi-submersible
   - ▢ Others____

19. Is the treatment system susceptible to vibration or does it require housing? (More than 1 choice may be chosen.)
   - ▢ Vibration can cease or considerably decrease the performance of the treatment process
   - ▢ Vibration has minor impacts on the treatment process such as reducing the treatment efficiency
   - ▢ The unit must be covered
   - ▢ The unit should be covered
   - ▢ No, the treatment technology is not susceptible to vibration or weather conditions

20. What are the dimensions (i.e. height, length and width) of the complete treatment system?

   ____

21. What is the approximate weight of the complete treatment system?

   ____

Environmental and safety information

For re-injection, please go to question 24 and go to question 27

22. What is the percentage of drilling fluids retained on cuttings after treatment or what is the %removal of pollutant from wastes (Please specify the type of the waste if the technology is not drilling cuttings)

____

If the treatment technology is not for drilling cuttings, please go to question 24.

23. Are there any contaminants on drilling cuttings which cannot be treated by the technology? If yes, please answer this question as well as question 23.1. (More than 1 choice may be chosen.)
    - ☐ No, the treatment will treat the fluid on cuttings as a whole
    - ☐ Heavy metals
    - ☐ Radioactive materials
    - ☐ Salt
    - ☐ Others

    23.1 What forms of the residual contaminants after treatment? (More than 1 choice may be chosen.)
    - ☐ Retained on treated cuttings and require further treatment
    - ☐ Retained on treated cuttings but do not require further treatment
    - ☐ Gaseous form
    - ☐ Liquid effluent stream

24. What are the factors affecting the efficiency of the technology?
    - ☐ Cuttings size or particle size. Please specify the optimum size to be treated

      ____

    - ☐ Initial amount of drilling fluid on cuttings or contaminants on wastes

      ____

    - ☐ Water content. Please specify the optimum water content in wastes to be treated

      ____

    - ☐ Others____

25. Does the treatment result in change of the total volume of the waste?
    - ☐ Increased total volume
    - ☐ Decreased total volume
    - ☐ Unchanged total volume
    - ☐ Others____

      ____

26. What kinds of disposals are applicable for the treated waste and please rank the preferred disposal method?
- ☐ Discharge overboard
- ☐ Landfill
- ☐ Others___

27. What is the total energy expected to be used in operating the treatment process?

___

28. What kinds of atmospheric emissions are expected from the treatment process? Please specify the sources of the emissions in the system at the end of the chosen answers? (More than 1 choice may be chosen.)
- ☐ Dust___
- ☐ CO_2___
- ☐ Methane ___
- ☐ VOCs ___
- ☐ NOx___
- ☐ SOx___
- ☐ Heavy metals ___
- ☐ Others (specify)___

___

29. Following question 28, please approximately quantify each of the gaseous release?

___

___

30. Are there any solid wastes, other than the treated cuttings, generated from the treatment processes? If yes, please specify the wastes and answer question 30.1 and 30.2.
- ☐ Yes___

___

- ☐ No.

30.1 What are the amounts of the wastes in question 30?

___

30.2 What kind of treatment and/or disposal required for the wastes in question 30?
- ☐ Treat and dispose of (please also specify the treatment and disposal method)___
- ☐ Landfill without treatment
- ☐ Others___

31. Are there any liquid wastes generated from the treatment processes? If yes, please specify the wastes and answer question 31.1 and 31.2.
   - ☐ Yes____

     ____
   - ☐ No

   31.1 What are the amounts of the wastes in question 31?

   ____

   31.2 What kind of treatment and/or disposal required for the wastes in question 31?
   - ☐ Treat and dispose of. (please also specify the treatment and disposal method)______________________
   - ☐ Dispose of without treatment (please specify the disposal method)

     ____
   - ☐ Others____

32. What kinds of human health risks are created from the treatment process? (More than 1 choice may be chosen.)
   - ☐ Inhalation of volatile contaminants on the cuttings during handling or treatment process. Please also answer question 32.1.
   - ☐ Inhalation of air emissions from the system's exhausts or stacks.
   - ☐ Skin exposure during handling or treatment process.
   - ☐ Consumption
   - ☐ Others____

   32.1 To what extent are the workers exposed to the contaminants during the handling or treatment process? (More than 1 choice may be chosen.)
   - ☐ All the processes are operated in covered units
   - ☐ All the processes are operated in exposed units
   - ☐ Most of the processes are operated in covered units
   - ☐ Most or the processes are operated in exposed units
   - ☐ All the units must be closely controlled by humans
   - ☐ All the units require some human control
   - ☐ Most of the units must be closely controlled by humans
   - ☐ Most of the units require some human control
   - ☐ All the units do not require human's control
   - ☐ Others____

33. Does the technique involve handling of hazardous substances and/or chemicals? (More than 1 choice may be chosen.)
- ▢ Yes, handling of hazardous substances such as________________________

  ____
- ▢ Yes, handling of hazardous chemicals such as________________________

  ____
- ▢ No, there is no hazardous substance involved in the treatment process.

34. Does the treatment process involve use of flammable and/or explosive substances or units?
- ▢ Yes, it involves flammable substance(s) such as________________________

  ____
- ▢ Yes, it involves explosive substance(s) such as________________________

  ____
- ▢ Yes, it involves flammable unit(s) such as________________________

  ____
- ▢ Yes, it involves explosive unit(s) such as________________________

  ____
- ▢ No, there is no flammable/explosive unit or substance involved in the technology.

35. What are the noise levels of the treatment process? Are there any protection measures? (More than 1 choice may be chosen.)
- ▢ Higher than standard limit but with protection for operators' ears
- ▢ Higher than standard limit but with equipment cover or closed room
- ▢ Not exceed the standard limit but quite loud
- ▢ The system is very quiet
- ▢ Others____

36. Are there any accidental risks associated with the treatment processes or handling process? Please specify the sources of the accidents or the units which might cause the corresponding accidents. (More than 1 choice may be chosen.)
- ▢ No, there are no accidental risks associated.
- ▢ Fire____
- ▢ Explosion ____________________________________
- ▢ Uncovered moving parts__________________________
- ▢ Chemicals____________________________________
- ▢ High voltage units______________________________
- ▢ Spills during the treatment or handling process________________

  ____
- ▢ Others____

37. Are there any permits required for the use of the technology? Please provide some brief details of the permissions required.
   - ☐ Yes, for transportation of the treatment system________________________
     ____
   - ☐ Yes, for transportation of the wastes________________________
     ____
   - ☐ Yes, for treatment or technical processes________________________
     ____
   - ☐ Yes, ____
   - ☐ No, there is no permission required for the use of the technology.

Cost information

38. What are the estimated capital costs per tonne of waste to be treated? If separate costs are not available, please provide total cost.

    Purchase: ____

    Rent: ____

    Installation: ____

    Total: ____

39. What are the estimated annually or monthly operational costs per tonne of waste? If separate costs are not available, please provide total cost.

    Personnel: ____

    Energy: ____

    Maintenance: ____

    Total: ____

A.2 QUESTIONNAIRE FOR OPERATORS

Please choose the best answer or answer the following questions as detailed as possible.

General information

1. What types of drilling fluids are you using now? (More than 1 choice may be chosen.)
   - ☐ Synthetic-based fluid. Please specify the "base fluid"______________________
   - ☐ Oil-based fluid. Please specify the "base fluid"_________________________
   - ☐ Water-based fluid.

2. What are the major components of the drilling fluids?

   ____

3. What standard requirements for drilling fluids and waste cuttings management are you following?
   - ☐ USEPA
   - ☐ OSPAR
   - ☐ Canadian
   - ☐ Others (please also answer question 3.1)______________________________

   3.1 What are the major requirements of the standard according to the answer for question 3? (More than 1 choice may be chosen)
   - ☐ Discharge overboard with %drilling fluid on cutting of________________
   - ☐ Zero discharge
   - ☐ No discharge of neat drilling fluids
   - ☐ Others____

4. What are the cuttings treatment and disposal methods currently in use?
   - ☐ Treat offshore and discharge overboard. Please answer question 4.1
   - ☐ Treat offshore and ship to shore for disposal. Please answer question 4.1
   - ☐ Ship to shore for treatment and disposal. Please answer question 4.1
   - ☐ Re-inject offshore. Please specify name of the technology

     ____
   - ☐ Others____

   4.1 What kind of cuttings treatment are you using now?

   Name of the technology:____

   Type of the technology:____

5. Other than the solid separation equipment, are you using any cuttings treatment technology (also known as cutting dryer) on the platform?

 ▢ Yes. Please specify____________________________________
 ▢ Cutting dryer will be used in the future. Please specify________________
 ▢ No, only solid separation equipment is used.

6. Please list the major components of your solids separation and treatment system on the platform.

 ____

 ____

7. Why was the current technology chosen? (More than 1 choice may be chosen)
 ▢ Low costs associated
 ▢ Low energy consumption
 ▢ Simple operation
 ▢ Fewer safety concerns
 ▢ Low environmental impact (air, sea, land)
 ▢ Reliable
 ▢ Commonly used
 ▢ Commercially available
 ▢ Has been previously used for the similar applications
 ▢ Others____

8. How long have you been using the technology?

 ____

9. Have you ever had any major problems in using the treatment technology?

 ____

<u>Description of the technology</u>

10. Does the technology require specific type of geologic formation?
 ▢ The treatment process cannot be successful without suitable formation
 ▢ Suitable formation can improve the performance of the treatment process
 ▢ No, the formation does not affect the treatment process
 ▢ Others____

11. Please answer the following questions:

Does the technology require any pre-treatment prior to the main process?

☐ Yes, pre-treatment(s) is required. Please specify the pre-treatment(s) below.

____

☐ No, there is no pre-treatment required.

Does it require other additional units to make the treatment process complete?

☐ Yes, additional unit(s) is required. Please specify the additional unit(s) below.

____

☐ No, there is no additional unit required

12. How complex is the installation of the treatment system in terms of cost and/or technical aspects?

☐ Very expensive or very complex
☐ Easily installed
☐ The system is portable
☐ Other____

13. Please specify the number of operators required in operating the system and the personnel-hours required per day

Number of operators: ____

Personnel hours (per day): ____

14. What training level or skill level is required of the system's operators?

☐ Specially trained operators are required
☐ No special training required
☐ Experienced operators are required
☐ Others____

15. Are there any chemical required in the treatment processes or other consumables (such as lubricants, fresh water, etc)?

☐ Yes. Please specify types and amount

____

____

☐ No.

16. What is the expected life of the equipment?

____

17. What is the typical maintenance required for the system and what is the approximate downtime per day?

____

18. What components most often need replacement and how often per month, or year?

____

19. Does the technology require technical experts or special equipment for repairs? (More than 1 choice may be chosen.)
   - ☐ Require technical experts
   - ☐ Can be done by operators
   - ☐ Require special equipment
   - ☐ Simple equipment available offshore
   - ☐ Others____

20. What is the treatment capacity of the technology?

____

21. Does the technology create any impacts on other platform operations, either during treatment operation or downtime periods?
   - ☐ Impacts on drilling operation due to treatment system operations such as______

     ____
   - ☐ Impacts on drilling operation due to the downtime period of the treatment system

     such as____
   - ☐ Others____

22. Please specify types of drilling rigs that could accommodate the treatment system and rank based on preference?
   - ☐ Floating vessel
   - ☐ Fixed platform
   - ☐ Semi-submersible
   - ☐ Others____

23. Is the treatment system susceptible to vibration or does it require housing? (More than 1 choice may be chosen.)
   - ☐ Vibration can cease or considerably decrease the performance of the treatment process
   - ☐ Vibration has minor impacts on the treatment process such as reducing the treatment efficiency
   - ☐ The unit must be covered
   - ☐ The unit should be covered
   - ☐ No, the treatment technology is not susceptible to vibration or weather conditions

24. What are the dimensions of the complete treatment system?

____

25. What is the approximate weight of the complete treatment system?

____

Environmental and safety information

26. What is the average % drilling fluid retention on the cuttings feed?

____

For re-injection, please answer question 29 and go to question 33

27. What is the percentage of drilling fluids retained on cuttings after treatment?

____

28. Is the treatment efficiency of the system according the answer to question 27 different from the supplier's claim?

____

29. What are the factors affecting the efficiency of the technology?
    - ☐ Cuttings size. Please specify the optimum size of the cuttings to be treated_____
      ____
    - ☐ Initial amount of drilling fluid on cuttings
      ____
    - ☐ Water content. Please specify the optimum water content of the cuttings to be treated____
    - ☐ Others____

30. Does the treatment result in change of the total volume of the waste cuttings?
    - ☐ Increased total volume
    - ☐ Decreased total volume
    - ☐ Unchanged total volume
    - ☐ Others____

31. What kind of disposal is used for the treated cuttings?
    - ☐ Discharge overboard
    - ☐ Landfill
    - ☐ Others____

32. Are there any contaminants on drilling cuttings which cannot be treated by the technology? If yes, please answer this question as well as question 32.1. (More than 1 choice may be chosen.)
- ☐ No, the treatment will treat the fluid on cuttings as a whole
- ☐ Heavy metals
- ☐ Radioactive materials
- ☐ Salt
- ☐ Others____

32.1 What forms of the residual contaminants after treatment? (More than 1 choice may be chosen.)
- ☐ Retained on treated cuttings and require further treatment
- ☐ Retained on treated cuttings but do not require further treatment
- ☐ Gaseous released into the atmosphere
- ☐ Gaseous form requiring gas treatment process
- ☐ Others____

33. What is the total energy expected to be used in operating the treatment process?

____

34. What kinds of atmospheric emissions are expected from the treatment process? Please specify the sources of the emissions in the system at the end of the chosen answers? (More than 1 choice may be chosen.)
- ☐ Dust____
- ☐ CO_2____
- ☐ Methane ____
- ☐ VOCs ____
- ☐ NOx____
- ☐ SOx____
- ☐ Heavy metals ____
- ☐ Others (specify)____

____

35. Following question 34, please approximately quantify each of the gaseous release?

____

____

36. Are there any solid wastes, other than the treated cuttings, generated from the treatment processes? If yes, please specify the wastes and answer question 36.1 and 36.2.
- ☐ Yes____

____

- ☐ No.

36.1 What are the amounts of the wastes in question 36?

____

36.2 What kind of treatment and/or disposal required for the wastes in question 36?

- ▢ Treat and discharge overboard. (please also specify the treatment method)____________________
- ▢ Treat offshore and ship to shore for disposal. (please specify the treatment and disposal method)____________________
- ▢ Ship to shore for treatment and disposal. (please specify the treatment and disposal method)____________________
- ▢ Others____________________

37. Are there any liquid wastes generated from the treatment processes? If yes, please specify the wastes and answer question 37.1 and 37.2.

- ▢ Yes____________________
- ▢ No

37.1 What are the amounts of the wastes in question 37?

____

37.2 What kind of treatment and/or disposal required for the wastes in question 37?

- ▢ Treat and discharge overboard. (please also specify the treatment method)____________________
- ▢ Treat offshore and ship to shore for disposal. (please specify the treatment and disposal method)____________________
- ▢ Ship to shore for treatment and disposal. (please specify the treatment and disposal method)____________________
- ▢ Others____________________

38. What kinds of human health risks are created from the treatment process? (More than 1 choice may be chosen.)

- ▢ Inhalation of volatile contaminants on the cuttings during handling or treatment process. Please also answer question 39.1.
- ▢ Inhalation of air emissions from the system's exhausts or stacks.
- ▢ Skin exposure during handling or treatment process.
- ▢ Consumption
- ▢ Others____________________

38.1 To what extent are the workers exposed to the contaminants during the handling or treatment process? (More than 1 choice may be chosen.)
- ▢ All the processes are operated in covered units
- ▢ All the processes are operated in exposed units
- ▢ Most of the processes are operated in covered units
- ▢ Most or the processes are operated in exposed units
- ▢ All the units must be closely controlled by humans
- ▢ All the units require some human control
- ▢ Most of the units must be closely controlled by humans
- ▢ Most of the units require some human control
- ▢ All the units do not require human's control
- ▢ Others______________________________

39. Does the technique involve handling of hazardous substances and/or chemicals? (More than 1 choice may be chosen.)
- ▢ Yes, handling of hazardous substances such as______________________________
____
- ▢ Yes, handling of hazardous chemicals such as______________________________
____
- ▢ No, there is no hazardous substance involved in the treatment process.

40. Does the treatment process involve use of flammable and/or explosive substances or units?
- ▢ Yes, it involves flammable substance(s) such as______________________________
____
- ▢ Yes, it involves explosive substance(s) such as______________________________
____
- ▢ Yes, it involves flammable unit(s) such as______________________________
____
- ▢ Yes, it involves explosive unit(s) such as______________________________
____
- ▢ No, there is no flammable/explosive unit or substance involved in the technology.

41. What are the noise levels of the treatment process? Are there any protection measures? (More than 1 choice may be chosen.)
- ▢ Higher than standard limit but with protection for operators' ears
- ▢ Higher than standard limit but with equipment cover or closed room
- ▢ Not exceed the standard limit but quite loud
- ▢ The system is very quiet
- ▢ Others______________________________

42. Are there any accidental risks associated with the treatment processes or handling process? Please specify the sources of the accidents or the units which might cause the corresponding accidents. (More than 1 choice may be chosen.)
- ☐ No, there are no accidental risks associated.
- ☐ Fire______________________________
- ☐ Explosion ______________________________
- ☐ Uncovered moving parts______________________________
- ☐ Chemicals______________________________
- ☐ High voltage units______________________________
- ☐ Spills during the treatment or handling process______________________________

  ____
- ☐ Others______________________________

43. Are there any permits required for the use of the technology? Please provide some brief details of the permissions required.
- ☐ Yes, for transportation of the treatment system______________________________

  ____
- ☐ Yes, for transportation of the wastes______________________________

  ____
- ☐ Yes, for treatment or technical processes______________________________

  ____
- ☐ Yes, ______________________________
- ☐ No, there is no permission required for the use of the technology.

Cost information

44. What are the estimated capital costs per tonne of cuttings to be treated? If separate costs are not available, please provide total cost.

Purchase: ______________________________

Rent: ______________________________

Installation: ______________________________

Total: ______________________________

45. What are the estimated annually or monthly operational costs per tonne of cuttings? If separate costs are not available, please provide total cost.

Personnel: ______________________________

Energy: ______________________________

Maintenance: ______________________________

Total: ______________________________

Preference information

46. What type of technology do you prefer? Please also give specific type of the technology if applicable (e.g. thermal desorption, centrifuge, etc)

- ☐ Thermal treatment________________________________
- ☐ Mechanical treatment________________________________
- ☐ Chemical treatment________________________________
- ☐ Others________________________________

47. What are the characteristics of cuttings treatment technology do you expect? (More than 1 choice may be chosen)

- ☐ Low costs associated
- ☐ Low energy consumption
- ☐ Simple operation
- ☐ Fewer safety concerns
- ☐ Less pollution produced
- ☐ Fewer environmental threats
- ☐ Reliable
- ☐ Commonly used
- ☐ Commercially available
- ☐ Have been previously used for the similar applications
- ☐ Others________________________________

48. Please choose the drilling cuttings management, which you prefer. Also, please give a brief comment on each of the following option.

- ☐ Onshore treatment________________________________
- ☐ Offshore treatment________________________________
- ☐ Re-injection________________________________
- ☐ Others________________________________

49. Please give comments on the cutting treatment technology listed below according to your understanding. What are the major advantages or concerns on application of those technologies?

High G Shale shaker:________________________________

High G Centrifuge:________________________________

Press:________________________________

Thermal desorption:________________________________

Combustion:________________________________

Grinding:________________________________

Microemulsion:____

Supercritical extraction:____________________________________

50. From the list of the technologies in question 49, which innovative technologies or onshore treatments have the most potential of offshore application?

____

51. Do the current regulations meet your economic and environmental issues?
    - ☐ Yes.
    - ☐ No. (Please give reasons)________________________________

APPENDIX B

SUMMARY OF DATA OBTAINED THROUGH QUESTIONNAIRES

A.1 DATA ON VERTICAL CENTRIFUGE

No.	Question	Oiltools	Brandt
	General Information		
1	Name of the technology	Oilfree Plus	Vortex Dryer/ Tornado Dryer
	Type of the technology	Vertical centrifuge	Vertical centrifuge
2	Current stage	Commercially available, currently in use	Commercially available, currently in use
3	Proven technology	Previously used for cuttings	Previously used for cuttings
4	Offshore use	Commonly used offshore	Not commonly used offshore but some offshore applications, used onshore
	Description of the Technology		
5	Components	-	Shale Shaker, conveyer or vacuum transfer system, vortex dryer, collection/storage tank, centrifuge
6	Contaminants type	Oil on cuttings	Oil based or synthetic based cuttings
7	Formation req.	No	suitable formation can improve the performance of the treatment process
8	Feed state	Slurry	Very heavy solid slurry state, usually the vortex dryer is fed with either a worm/nemo style pump or an auger of some sort
	Limits on fraction of contaminant	No	not to my knowledge
9	No. of operators	2	2 in a 24 hour operating period
	Personal hours (per day)	24 hours	12 hours per day
10	Training level	Specially trained operators, experienced operators	Operators that understand the drilling process and realization of how solids control equipment work

No.	Question	Oiltools	Brandt
11	Chemical req.	No	Yes, At times, dilution of the feed stock maybe necessary to increase oil separation, depending upon formation and type of cuttings produced. i.e. sand/silt/clay/chert. Etc. As well, we are working with a group from Nova Scotia that is introducing a chemicall to increase oil separation from the solids.
12	Expected life	15 years+	Unknown at this time, generally when equipment is taken care of, especially centrifuges i.e. the vortex is a vertical screen centrifuge, they can last up to 25 years
13	Maintenance req.	1 day/mo	basic service checks per day can take up to an hour per day and should occur once per tour (every 12 hours especially if the machine is working consistently), which includes checking fights, and screens, if a change out is required, down time would be 2-3 hours for change out.
14	Replacement of components	Screen basket	The scraping fights and the vertical screen
15	Repair ease	Can be done by operators	Can be done by operators, require special equipment
16	Treatment capacity	up to 32 tonnes/hr	20 tonnes per hour - manufacture specs
17	Impacts on platform act.	Impacts due to the downtime period	Impacts on drilling operation due to treatment system operations such as taking up space in the drilling ship where a small footprint size is important, Impacts due to the downtime period of the treatment system such as removal of cuttings conventionally by means of ship to shore
18	Rig types	Floating vessel, fixed platform, semi-submersible	Floating vessel, fixed platform, semi-submersible, it all depends if they can accommodate the footprint of the treatment system
19	Vibration and housing	No impacts	Vibration can cease or considerably decrease the performance of the treatment process
20	Dimensions	-	Overall dimension are as follows: H 1813mm (nominal), LL 1810 mm, W 2946 mm (Vortex dryer only!!)
21	Weight	-	5430 kg.

No.	Question	Oiltools	Brandt
	<u>**Environmental and Safety Information**</u>		
22	%removal	~2 %, 30-40 gsm/kg wet (brochures)	Depends on the formation, anywhere from 1-2 to 9-10%
23	Residues	No, treat fluid as a whole	Heavy metals, radioactive materials, Salt
	Form of residues	Retained on treated cuttings and do not require further treatment	Retained on treated cuttings and require further treatment
24	Factors on efficiency	Water content, doesn't like water-wet cuttings as they blind the basket	cuttings size or particle size. Depends on the type of screen is contained in the dryer, will give different results on the dryness of the cuttings due to various sizes of feed stock
			Initial amount f drilling fluid, may have to introduce dilution feed to maximize performance of dryness
25	Volume change	Decreased total volume	Unchanged total volume, The total volume never changes but the size of the particles changes when the cuttings are processed through the vortex dryer
26	Disposal of treated cuttings	Discharge overboard*, Landfill	Discharge overboard*, Landfill
27	Energy consumption	75.5 Hp electric from rig's power source	Unknown
28	Atmospheric emissions	No	dust coming from the bottom of the dryer, VOCs coming from the effluent discharge line, Sox possible sour gas from both solids discharge and effluent discharge
29	Quantity of emissions	-	Unknown
30	Solid wastes	No.	No
31	Liquid wastes	Liquid mud - goes to active mud system	Yes not really a waste, for we recycle the fluid back to the active drill system, so not only does it treat the cuttings, but we reclaim fluid that would have usually been lost in conventional methods of cuttings treatment.
		Send back to shore or recycle (to the mud system)	Amount varies, depends on the % of oil on the surface area of the cuttings

No.	Question	Oiltools	Brandt
32	Human health risks	Skin exposure	Treat and dispose of. Centrifuge with high "g" forces to remove ultra fine particulate, then the fluid is introduce back in the active drill system, solids removed must be disposed of by conventional methods i.e. landfill, composing, bioremediation, etc.
		All the processes are operated in covered units	Inhalation of voatie contaminants, skin exposure
		Most of the units must be closely controlled by human - control feed, monitor discharge	Most of the processes are operated in covered units
		Most of the units require some human control	All units must be closely controlled by humans
33	Hazardous substances	No	Yes, handling of hazardous substances such as the drilled cuttings is considered to be a hazardous substance, of course it all is dependent on what type of oil is used in the drilling process
34	Flammable/explosive	No	No
35	Noise level	Not exceed the standard limit but quite loud	Higher than standard limit but with protection for operators' ears
36	Accidental risks	Fire (electrical), Spills during the treatment or handling process breakdown, wet cuttings go through	Uncovered moving parts, high voltage units, others removal of parts- all wear parts are quite heavy and difficult
37	Permits requirement	No	No, there I no permission required for the use of the technology
	Cost Information		
38	Capital	Purchase - 200,000$	Purchase - 95,000USD
		Rent - 1,200$/d	Rent - 1200CAD per day, plus a man
		Installation - 15,000$	Installation - unknown at this time
39	Operational	Personnel 20,000$/mo	Personnel 550 CAD per day per man for operation
		Maintenance 3,000$/mo	Energy - unknown at this time - 100 amp 3 wire 4 pole plug in
			Maintenance 4000CAD per month

A.2 Data on Horizontal Centrifuge

No	Question	Hutchison-Hayes Int, Inc.
	General Information	
1	Name of the technology	Duster
	Type of the technology	Horizontal centrifuge with a cylindrical screen
2	Current stage	Commercially available, currently in use
3	Proven technology	Previously used for cuttings
4	Offshore use	Used offshore
	Description of the Technology	
5	Components	Mechanical dryer, uses screen and conveyor
6	Contaminants type	Drilling fluids from cuttings
7	Formation req.	No
8	Feed state	Doesn't require special slurry
9	No. of operators	1 per tower
	Personal hours (per day)	
10	Training level	Specially trained operators are required
11	Chemical req.	No
12	Expected life	10 years
13	Maintenance req.	15 mins downtime
14	Replacement of components	No history as of yet
15	Repair ease	Require technical experts
16	Treatment capacity	30-90 tonnes/hour
17	Impacts on platform act.	If equipment is not operated correctly there's no downtime caused by the process
18	Rig types	All types
19	Vibration and housing	Vibration has minor impacts
20	Dimensions	-
21	Weight	8,600 Lbs.
	Environmental and Safety Information	
22	%removal	3-5% ROC (brochure), 1.5-3.5% wt.
23	Residues	Treat fluid as a whole
24	Factors on efficiency	Works under all conditions
25	Volume change	Decreased total volume
26	Disposal of treated cuttings	Discharge overboard
27	Energy consumption	Works on 100 Amp power source (electric, from rig's power generator)

No	Question	Hutchison-Hayes Int, Inc.
28	Atmospheric emissions	No
29	Quantity of emissions	-
30	Solid wastes	No.
31	Liquid wastes	The remaining oil on cuttings
	Amount	3% of cuttings processed
	Treatment/Disposal	Dispose of without treatment
32	Human health risks	Skin exposure All the processes are operated in covered units All the units require some human control
33	Harzardous substances	No
34	Flammable/explosive	No
35	Noise level	Very quiet
36	Accidental risks	No.
37	Permits req	No.
	Cost Information	
38	Capital	Rent, depends on length of project (1,560$/day)
39	Operational	Personnel, 450$/day

A.3 Data on Thermal Desorption

No	Question	Hutchison-Hayes Int, Inc.
	General Information	
1	Name of the technology	Thermal-D
	Type of the technology	Low temp indirect thermal desorption
2	Current stage	Commercially available, currently in use
3	Proven technology	Previously used for cuttings
4	Offshore use	Used onshore only
	Description of the Technology	
5	Components	
6	Contaminants type	Drilling fluids from cuttings
7	Formation req.	No
8	Feed state	Can handle any proportion
	Limits on fraction of contaminant	No limit
9	No. of operators	4 men per shift (12 hours)
	Personal hours (per day)	12
10	Training level	Specially trained operators are required Project manager requires understanding of basic physics
11	Chemical req.	Yes, some surfactants minor quantity of oil absorbing filter media (organophilic)
12	Expected life	30 years
13	Maintenance req.	Minimal, >90% on-line time
14	Replacement of components	Boiler tubes - temperature & time dependent 6 months - 2 years
15	Repair ease	Require technical experts for control system Done by operators Require special equipment
16	Treatment capacity	10,000, 20,000, 30,000 MT/yr and other sizes on request
17	Impacts on platform act.	Inappropriate for drilling operations due to size, power, weight, ability to handle surges in cuttings from drilling operations (need storage boxes and use batch process)
18	Rig types	All types, space and weight loading are main constraints
19	Vibration and housing	No impacts
20	Dimensions	Capacity dependent - approx 4 tractor trailer loads 10x40
21	Weight	40 tons

No	Question	Hutchison-Hayes Int, Inc.
	Environmental and Safety Information	
22	%removal	< 1%TPH
23	Residues	Salt - removes liquids only, can process all contaminants
	Form of residues	Retained on treated cuttings, do not require further treatment (landfill)
24	Factors on efficiency	Cuttings size, large particles with minimal surface area
		Water content, zero is optimal - more water requires more energy and time
25	Volume change	Unchanged
26	Disposal of treated cuttings	Discharge overboard - water
		Landfill - solids
		Reuse - oil
27	Energy consumption	Water content, tons/hour
		+,- 5 mm BTU Boiler
28	Atmospheric emissions	Dust - minor
		CO_2 from boiler
		VOCs < 10 ppm avg.
		NO_2 142 mg/m3
		SO_2 None detected
		Heavy metals - None
29	Quantity of emissions	Must quantify the amount of gas or diesel required to fire the boiler
30	Solid wastes	No.
31	Liquid wastes	Water (clean) and oil (uncracked) from cuttings
32	Human health risks	Skin exposure, handling risks
		All the processes are operated in covered units
		All the units require some human control
33	Hazardous substances	No
34	Flammable/explosive	Fuel source (Boiler)
35	Noise level	Very quiet (only boiler)
36	Accidental risks	Assumes fixed site, land-based
		Spills - transportation risk
		Handling of cuttings boxes/truck accidents
37	Permits requirement	Normal permitting requirements as for any industrial process
		Disposal permit for cuttings

No	Question	Hutchison-Hayes Int, Inc.
	Cost Information	
38	Capital	Not for sale Rent 200-400$/tonne - depending upon country Installation 100,000-200,000$ - site dependent
39	Operational	Total 200-400$/tonne

A.4 DATA ON RE-INJECTION

No	Question	Oiltools
	General Information	
1	Name of the technology	-
	Type of the technology	Waste Injection
2	Current stage	Field tested, commercially available, currently in use
3	Proven technology	Previously used for cuttings
4	Offshore use	Used onshore
	Description of the Technology	
5	Components	Collection - sorting - slurrification - pumping - injection
6	Contaminants type	Drilling cuttings and muds
7	Formation req.	Requires suitable formation
8	Feed state	Slurry or liquid
	Limits on fraction of contaminant	No limit
9	No. of operators	3-4 men/24 hours
	Personal hours (per day)	24 hours
10	Training level	Specially trained operators are required
11	Chemical req.	Requires dilution as surface area of solids increases through grinding (slurrification) process
12	Expected life	20 years
13	Maintenance req.	1 hour/day
14	Replacement of components	The grinding equipment - monthly check
15	Repair ease	Require technical experts, Require special equipment
16	Treatment capacity	120 tonne/hour
17	Impacts on platform act.	Takes up space on rig
18	Rig types	Floating vessel, fixed platform, semi-submersible, jack-up
19	Vibration and housing	No impacts
20	Dimensions	20'x40'
21	Weight	10 tonnes
	Environmental and Safety Information	
22	%removal	Does not remove
23	Residues	-
	Form of residues	-
24	Factors on efficiency	Cuttings size, smaller is better, abrasive formation are more difficult
		Water content, optimum 80% (pumpable and re-inject)

No	Question	Oiltools
25	Volume change	Increased total volume by adding seawater
26	Disposal of treated cuttings	-
27	Energy consumption	Electrical usually 4x100 hp + 600 hp main pump (from rig power generator, size dependent)
28	Atmospheric emissions	CO_2 from electricity generation
29	Quantity of emissions	-
30	Solid wastes	No.
31	Liquid wastes	No.
32	Human health risks	It may come to surface through a "fault"
		All the processes are operated in covered units
		Most of the processes are operated in covered units
		All the units require some human control
33	Hazardous substances	No
34	Flammable/explosive	No
35	Noise level	Not exceed the standard limit but quite loud
36	Accidental risks	Uncovered moving parts, chain guards
37	Permits requirement	Yes, in some countries must have permit to inject
	Cost Information	
38	Capital	Not for sale
		Rent- 750$/day, day rate dependent upon complexity of the installation or 50-150$/tonne of solids
39	Operational	Man 400$/day

A.5 DATA ON SUPERCRITICAL EXTRACTION USING NATURAL GAS

No	Question	
	General Information	
1	Name of the technology	-
	Type of the technology	Drill cutting clean-up by supercritical extraction
2	Current stage	Research and development stage, Laboratory tested
3	Proven technology	Yes, it has been previously used for drilling cuttings treatment
4	Offshore use	Never been used offshore
	Description of the Technology	
5	Components	Shale shaker – lock hopper – supercritical pressure vessel – cuttings transport system. High pressure pump, valves, piping
6	Contaminants type	Oil based muds
7	Formation req.	No, the formation does not affect the treatment process
8	Feed state	Bulk oil must be removed from the cutting surface
	Limits on fraction of contaminant	Probably, but currently unknown
9	No. of operators	One per shift
	Personal hours (per day)	24 hours per day
10	Training level	Experienced operators are required
11	Chemical req.	Yes. Solvent – probably propane – loss rates are unknown but will not be zero
12	Expected life	10 years
13	Maintenance req.	330 days per year of stream time
14	Replacement of components	Cuttings contacting components due to erosion
15	Repair ease	Simple equipment available offshore
16	Treatment capacity	Not sure – should be able to handle cuttings load for a normal drilling program
17	Impacts on platform act.	Impacts on drilling operation due to the downtime period of the treatment system
18	Rig types	Floating vessel, fixed platform, semi-submersible
19	Vibration and housing	No impacts
20	Dimensions	Not known - but should be the size of a typical module
21	Weight	Unknown
	Environmental and Safety Information	
22	%removal	Lab test on actual cuttings yielded 100% removal of oil contamination
23	Residues	Heavy metals, Radioactive materials, Salt
	Form of residues	Liquid effluent stream

No	Question	
24	Factors on efficiency	Optimum (particle) size is unknown – smaller particles will be better but will have a higher pressure drop thorough the contactor
		Typical shale shaker effluent loadings
		(Optimum water content) Was not quantified during pilot tests
25	Volume change	Decreased total volume
26	Disposal of treated cuttings	Discharge overboard, Landfill
27	Energy consumption	Unknown
28	Atmospheric emissions	Dust
29	Quantity of emissions	Unknown
30	Solid wastes	No.
31	Liquid wastes	No., recombine with drilling mud
32	Human health risks	Inhalation or air emissions from the system's exhausts or stacks
		All the processes are operated in covered units
		All the units must be closely controlled by humans
33	Hazardous substances	No
34	Flammable/explosive	Yes, Propane
35	Noise level	Not exceed the standard limit but quite loud
36	Accidental risks	Fire, Explosion, High voltage units, Spills during the treatment or handling process
37	Permits requirement	Transportation, Offshore cuttings disposal permit
	Cost Information	
38	Capital	Unknown
39	Operational	Unknown

A.6 Data From Hibernia's Operator

No.	Question	Hibernia development
	General Information	
1	Types of drilling fluids	Synthetic-based - PureDrill IA-35
		Water-based fluid
2	Drilling fluid components	Novamul L, MI-157, Lime, CaCl2, Truvis, Verstrol or Soltex, Barite, CaCO3, Water and Based fluid
3	Standard requirements	OSPAR, Canadian
3.1	Major requirements	Discharge overboard with 15% ROC (dry weight)
		No discharge of neat drilling fluids
		Components on DSL, not on toxic list
		New regulations as of 21-Aug-02 require an additional toxicity test on Generic fluid and target 6.9% (wet weight) on discharged material
4	Type of the management technology	Treat offshore and discharge overboard - high G shakers, centrifuges
		Re-inject offshore
5	Cutting dryer	No, only solid separation equipment is used
6	Solid separation	High G shakers, centrifuges
7	Why the current treatment technology?	Simple operation, reliable, commonly used, commercially available, has been previously used for the similar applications
8	Has been used for	Entire project
9	Major problems	Keeping SOC within limits
	Description of the technology	
10	Formation requirement	No, has no effect on the treatment process
		Soft, reactive shales can sometimes block the grinder on the cuttings re-injection unit
11	Pre-treatment and additional unit	None
12	Ease of installation	Very expensive and very complex
13	No. of operators	4
	Personal hours (per day)	48
14	Training level	Specially trained and experienced operators are required
15	Chemical req.	None
16	Expected life	5-8 yrs
17	Maintenance req.	Greasing & servicing - no downtime
18	Replacement of components	Screens
19	Repair ease	Can be done by operators

No.	Question	Hibernia development
20	Treatment capacity	Shaker - 2000-4000 litres per min
		Centrifuges - 50-200 litres per min
		CRI unit - 100 meters per hour or 445 mm hole
21	Impacts on platform act.	Impacts due to the downtime period of the treatment system such as reduced rates or complete cessation of drilling, higher dilution rates
22	Rig types	Fixed platform, all rigs can use the separation equipment. CRI units have been installed on most types of rigs, but are most suitable for fixed platform
23	Vibration and housing	Not susceptible to vibration or weather conditions
24	Dimensions	Unique to each rig - do not know the exact figures
25	Weight	Unique to each rig - do not know the exact figures
	Environmental and Safety Information	
26	% ROC prior to treatment	
27	%removal	Typical SOCs of : from shakers 10-20%
		Centrifuge : 15-25%
		CRI : everything is re-injected
28	Manufactures claims	Most manufactures claims are for much higher efficiencies, but these are based on "standard muds" with much different properties
29	Factors on efficiency	Cutting size, Initial amount of drilling fluid on cuttings
		The quick answer to all this is the size of the cutting and the viscosity of the mud will be the amount of drilling fluid attached and the easier it will be to remove it mechanically. Best results will be obtained when cuttings arriving at the shakers is greater than 1-1.5 cm., which will generally indicate a low proportion of "fines"
30	Volume change	Increased total volume: The CRI unit grinds the cuttings into a slurry using water that will also require disposal. Centrifuges eject weighting material - Barite, as well as cuttings
31	Disposal of treated cuttings	Discharge overboard, currently at Hibernia – reinjection of the cuttings from the shakers and discharge of the centrifuge underflow
32	Residues	No, will treat the fluid on cuttings as a whole
	Form of residues	Retained on treated cuttings but do not require further treatment
33	Energy consumption	-
34	Atmospheric emissions	-
35	Quantity of emissions	-

No.	Question	Hibernia development
36	Solid wastes	Water from the CRI unit and Barite from the centrifuges
		Water : unknown, Barite : makes up 5% to 50% of the centrifuge underflow depending on the mud weight and drilling rate
		They are disposed of with the treated material
37	Liquid wastes	Water with CRI unit : unknown amount
		Disposed of with the treated material
38	Human health risks	Inhalation of volatile contaminants on the cuttings during handling or treatment process
		Skin exposure during handling or treatment
		Most of the processes are operated in exposed units
		All the units must be closely controlled by humans
39	Harzardous substances	None
40	Flammable/explosive	None
41	Noise level	Higher than std limit but with protection for operators' ears
		Higher than std limit but with equipment cover or closed room
		Not exceed the std limit but quite loud
42	Accidental risks	In general, the occurrence accidents is restricted to installation and repair processes and are very rare during operation
43	Permits requirement	-
	Cost Information	
44	Capital	-
45	Operational	-
	Preference information	
46	Preferred technologies (in order of preference)	1. Chemical treatment : while this can be extremely efficient, the toxicity of the chemicals many cases often compromise the ability to dispose of the treated materials and effluent
		2. Mechanical treatment : where accepted this is the best method with its drawback being the low efficiency gives rise to higher dilution rates
		3. thermal treatment : provides a better processing result, but operates only after the mechanical process
47	Expected treatment characteristics	Effectiveness, efficiency and capacity and then all of the above (see questionnaire)

No.	Question	Hibernia development
48	Preferred management option	Offshore treatment: where acceptable this is the most cost effective method. It reduces the risk of spilling untreated material
		Re-injection: probably the best solution, where applicable. Puts everything back where it came from and keeps it isolated from the environment
49	Comments on treatment tech	
	High G shale shaker	High processing rate, effective, creates hard to process "fines" good for offshore purposes
	High G Centrifuge	Discharge contains mud solids, notably Barite with cuttings. Good for offshore purposes.
	Press	Moderately efficient, more than shakers and centrifuges, but slow.
		Removes "fines". More suited to shore based processing
	Thermal desorption	Very efficient and effective. Very complex, costly and bulky. More suited to a land operation.
		Requires heat energy input for operation.
		Outputs vapours and combustion gasses.
	Combustion	Very Efficient and Effective. Processing rates can be high, but "drop-out" is a concern for offshore. Difficult to ensure combustion is complete and requires an input of flammable oil to support the operation and of course creates combustion gasses.
	Grinding	I only recognize this as a precursor to the cuttings re-injection method
50	Most offshore application potential	Cuttings Reinjection, Improvements to the mechanical separation process, with or without chemical enhancement that still permits offshore discharge of treated cuttings and solids.
51	Current regulations	Meet economic and environmental issues
	Note	The Tera Nova project: this is being developed using a semi-submersible rig. With the exception of the CRI unit, it utilizes the same drilling fluids and mechanical processing equipment, as does the Hibernia project. The above responses also apply to this project