1

INTRODUCTION

1

INTRODUCTION

The A Team has been approached by Deans, McEwan and MacConnell Consulting Engineers to submit a tender for the removal and disposal of drill cutting piles from the North Sea. In this document, we describe our proposed solution to this problem. The focus of our efforts is centred on providing a practicable solution to this environmental problem, based on a system that is highly reliable. Safety is an important factor that is constantly evaluated throughout our cost effective design.

Historically, the piles of drill cuttings at the base of North Sea platforms are a problem the severity of which are only now being fully realised. The issue was created during the initial years of the oil and gas industry when a holistic view was not taken of fossil fuel extraction. It is estimated that these piles release approximately 330 tonnes of oil per year. They also contain toxic heavy metals.

Current government legislation is non-specific about the removal of cuttings, and although there are some arguments for leaving the piles undisturbed it is looking increasingly likely that their removal will be necessary due to the environmental damage they are causing. The removal of platform structures is necessary upon their decommissioning (OSPAR convention '92) and this is not possible without disturbing the piles of cuttings at their base. In response to this social and environmental responsibility, operators are now looking at methods to prevent further pollution. The ideal solution to this problem minimises any future environmental damage, utilising a process which in itself is environmentally, economically and socially acceptable to all. An ongoing study by the UKOOA joint initiative is attempting to determine the best available techniques and environmental practices for dealing with this problem. It is expected that new guidelines and legislation will be based on its findings. In anticipation of this, our own designs have themselves been influenced by the current recommendations of the UKOOA investigation.

One of the most damaging aspects of the drill cuttings is the presence of drilling muds within them. These muds are required to facilitate the drilling process, both carrying the cuttings away from the drill face and providing the required hydrostatic pressure to work and maintain pressure control at such depths. In early operations, especially around the early to mid eighties, these muds were heavy oil-based substances having the potential to cause great environmental damage. More recently, following the complete ban of oil based muds in 1990, less toxic muds such as synthetic or water based substances have been used.

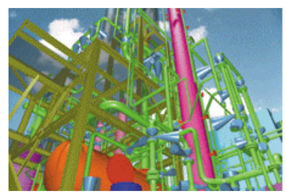
Despite this, the more toxic muds are still present in the bottom of many old cuttings piles. In addition, the significant presence of heavy metals in the cuttings has the potential for both environmental and human health damage, regardless what drilling muds are present. This risk is of grave concern as heavy metals are not easily broken down and tend to accumulate in the food chain, causing human health implications of eating seafood.

Although the removal of cuttings from the seabed is the primary concern, the issue of their handling and disposal is a much wider problem, especially with such harmful materials present. The aim of this document is to provide a complete disposal solution, which comprises the following areas:

- Collection from the sea bed
- Transportation to the surface
- Pre-treatment of the cuttings
- Transportation of the cuttings to a disposal site
- Final disposal of the cuttings.

In order to ensure a reliable process, the integration of these individual sub-systems is considered to form a cohesive process. This system provides all the qualities required for us, and our client, to become market leaders in this emerging field. The potential opportunities available to a successful partnership are evident to all involved.

2



CONCEPTUAL REVIEW

2

CONCEPTUAL REVIEW

The question of how best to treat the drill cuttings is a problem worthy of some discussion. This problem has been studied before but no satisfactory final design has previously been achieved. The UKOOA has conducted research and practical trials examining the issues, and a significant amount of knowledge has been gained from this analysis.

There are several factors which must be considered when developing a solution to the problem. Obviously the main stakeholders in this case are the oil companies and the government, but the environment and the general public must also be considered of equal importance. Government legislation states that installations must be removed and polluting substances cannot be left in place. It also influences wider issues such as the handling of toxic substances in order to protect the public and workforce. It must be noted that this is not only a British problem: the North Sea solution may also be used on other European installations and so should comply with their legislation. Other countries may also wish to utilise this design for similar removal of cuttings at other oil fields world-wide.

Another important influence is the cost. This may not be such a critical issue, as offshore operators will have to pay whatever is necessary to meet with legislative requirements. Even so the solution should be as cost effective as possible. Time is perhaps of more practical importance. The cuttings piles are relatively inert at North Sea temperatures, and in most cases have been there for many years. However, once the operation begins the chance of serious contamination to the water column and damaging faunal changes increases. The timescale is complicated by the unpredictable weather of the region, which will dramatically increase the possible downtime. To account for this, the system should be as reliable and maintainable as possible. Wherever possible it is better to use existing technology and processes as this not only removes the uncertainty of testing new designs but ensures ease of use within the existing offshore industry.

With these considerations in mind, there are several possibilities for dealing with the problem. An outline of the removal options is shown in figure 2.1. The chosen route can be seen in red.

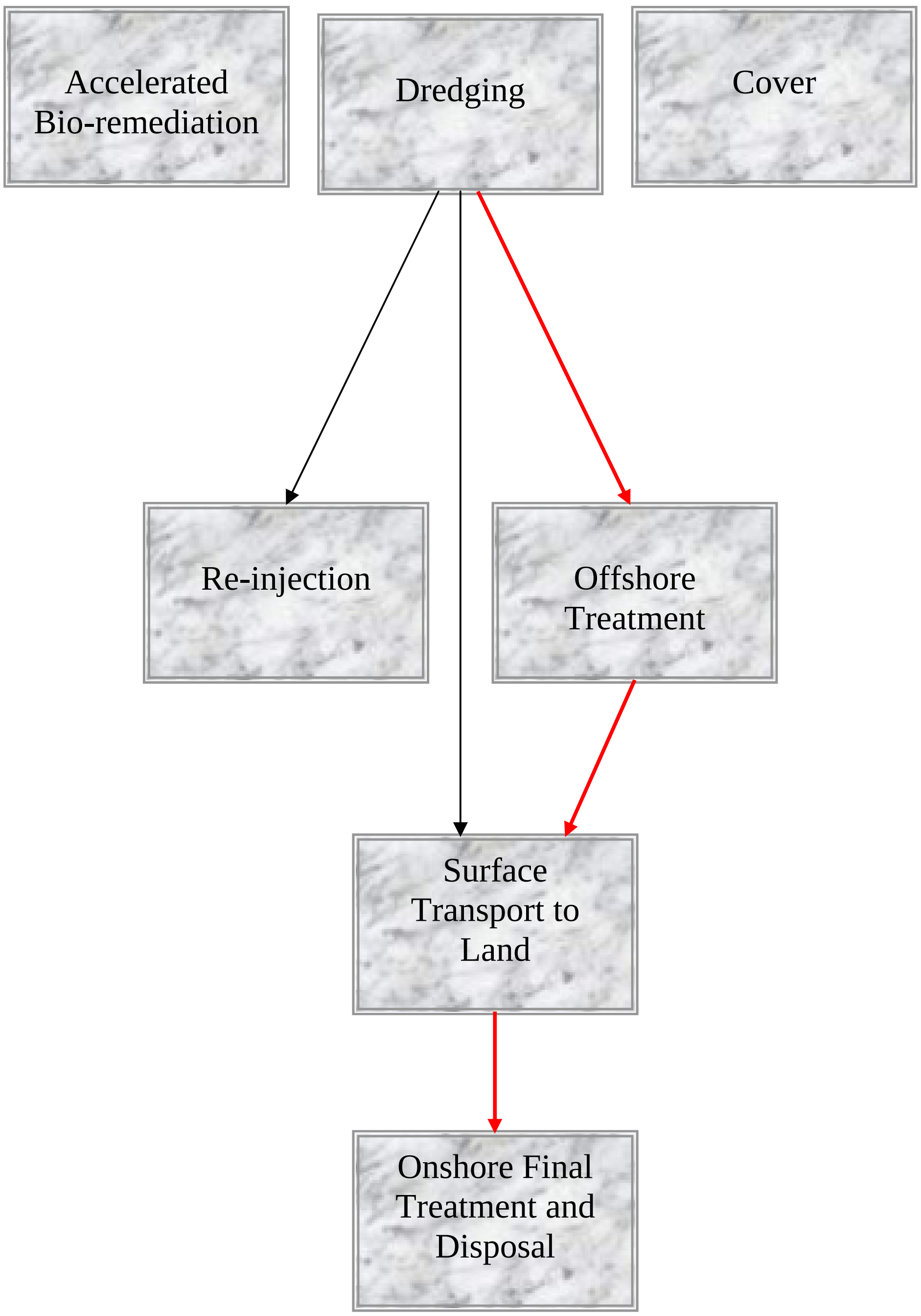

Accelerated Bio-remediation
Dredging
Cover
Re-injection
Offshore Treatment
Surface Transport to Land
Onshore Final Treatment and Disposal

figure 2.1

There is a persuasive argument for leaving the piles as they are. Arguably the large amounts of energy and money spent in dealing with the cuttings could be spent on more beneficial environmental schemes. Unfortunately this preposition is weakened when the long term environmental effects of the toxic metals and hydrocarbons are considered. Based on previous high profile cases it is unlikely that the oil companies will be allowed to ignore their environmental responsibilities. The piles themselves do naturally bio-remediate over time. This is a term which describes the chemical breakdown down of hydrocarbons. This process, however, occurs only on the outer layers in any reasonable time scale. There are methods to accelerate this process but these are unproven and would not deal with the physical debris of the piles that legally have to be removed. These involve, amongst others, raising the temperature locally or drawing water through the cuttings to ensure flow of oxygen.

If the technical difficulties associated with accelerated bio-remediation are considered to be too great, another minimally intrusive method is that of covering the drill cuttings in situ. This involves laying concrete slabs over the entire surface of the piles. This limits leaking of hydrocarbons into the water column and effectively hides the pollution and debris from the North Sea. The advantages are the low energy usage and minimal technical difficulties to overcome. It is unlikely, however, that this option is acceptable to the public at large.

Physical removal of the material involves some seabed to surface transport system and a dredging technique that can deal with the assorted constituents of the drill cuttings pile. This process satisfies existing legislation, which presently requires all debris created by the oil companies to be removed upon decommissioning. These advantages have convinced us that removal from the seabed is the only acceptable option. Although complete removal of the pile is desirable, this may not actually be fully achievable. Realistically a system could be expected to remove 90% of all materials. The cuttings will then be transported to the surface for the next stage.

Once the cuttings reach the surface, the options for the disposal are to either deal with the material onsite or to transport onshore. The onsite disposal option is to re-inject the drill cuttings into redundant wells. This is a technically feasible option if the infrastructure exists locally. It utilises technology that the oil and gas industry are comfortable in using. This option is very appealing since the process results in completely removing the pollution from human exposure onshore. The drawback with this option is that the infrastructure required only exists in a minority of locations. However, it is not clear whether this system is entirely legal as yet.

This leads to the only viable choice, transporting onshore the material for ultimate disposal. This option itself has variations. The process of dredging involves transporting large volumes of water along with the cuttings. To transport this excess fluid the large distances to shore requires extra energy. An option is to carry out some pre-treatment on the sludge to remove surplus water which can then be disposed of locally providing that the pollution levels are within legislative limits. The level of water removal is obviously dependent on the practicalities and economics of transport and offshore treatment. It is the A team's belief that offshore pre-treatment will be economically necessary and viable. The untreated sludge will have an approximate water content of 90%. Shipping of dry material would require ten times less transportation capacity, hence a more advantageous energy balance.

The entire system from dredging to topside transport can be seen in figure 2.2.

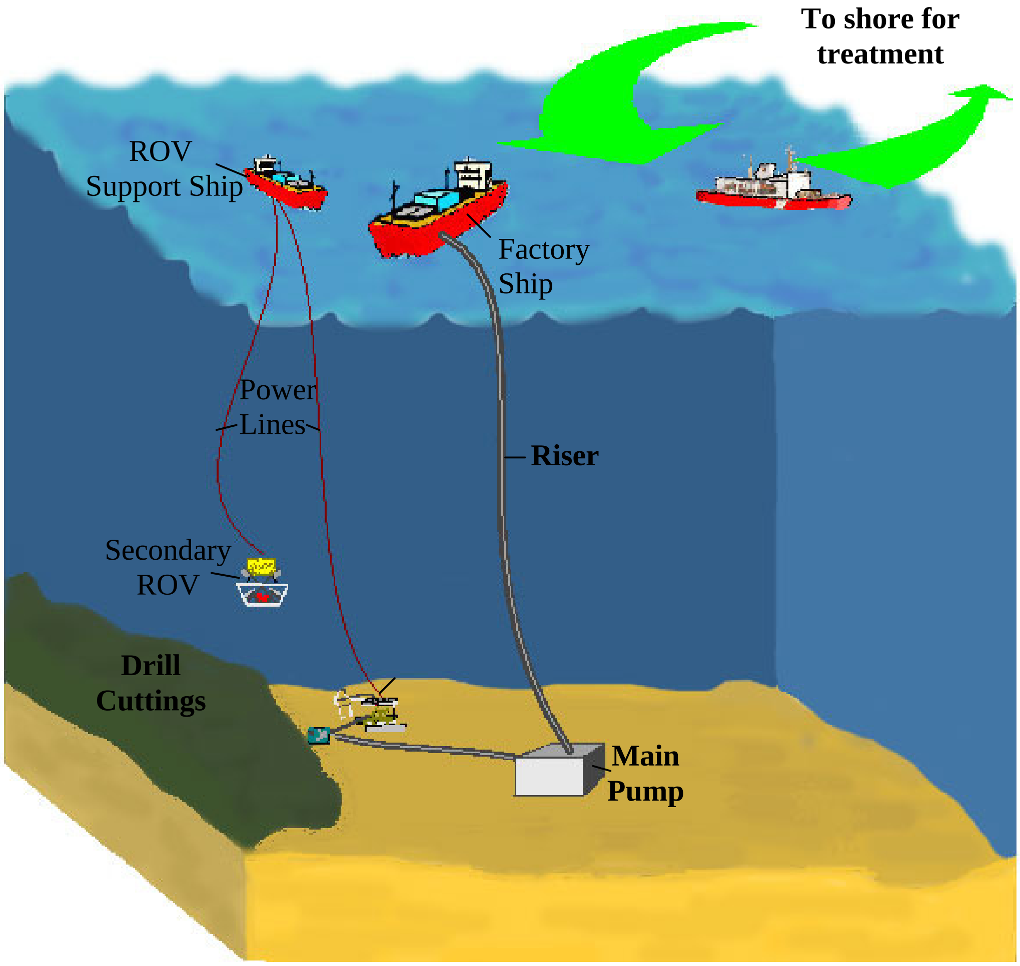


figure 2.2

3

ENGINEERING DESIGN

3

ENGINEERING DESIGN

The following section summarises the components of our system. A full discussion of each sub-system is provided in Appendices for reference.

3.1 ROV SYSTEMS

The first part of the collection process involves collecting the cuttings from the sea floor. This process is carried out by Remotely Operated Vehicles, which is the only feasible option available at such depths. Our dredging module consists of two ROVs. A primary vehicle does the main collection of the cuttings. The secondary vehicle is for removing any large debris, observing the work from a strategic viewpoint and assisting the primary vehicle if difficulty is encountered. These vehicles are powered by, and controlled from, a common support vessel on the surface. Detailed information on both vehicles is supplied in Appendix B.

The primary ROV is a large tracked crawling vehicle. This minimises any disturbance to the pile from manoeuvring thrusters and provides a stable working base for the collection. The cuttings are collected through a dredging pump on this vehicle before their transport to the main surface going pump. The collection head itself is mounted on the end of a long boom, which enables access to areas high up on the pile and between sub-sea obstacles where the ROV may not have access. A winch is also fitted to the vehicle for assisting with any extremely large debris.

The secondary vehicle is a floating ROV that can easily reach any part of the pile. As its main role is removing foreign objects from the pile, it is a heavy work class ROV equipped with large manipulators. It can also be fitted with cutting tools if required in dealing with large objects. Objects will be worked around as much as possible before removal to reduce disturbance of the pile. They will then be placed in baskets and carried to the surface. Its powerful manipulators, large payload capacity and general manoeuvrability give it a strong ability to support the primary vehicle for unforeseen occurrences. It is equipped with several cameras and lights, various navigation instruments and a scanning sonar system for observation purposes.

The vehicles and components used are standard “off the shelf” models that require no special design or construction, apart from perhaps a slight adjustment from their standard configurations. As such they are tried and tested systems which operators already have experience using. The only exception to this is the dredging head itself, which is discussed in detail in section 3.2.

The cost of running an ROV vessel, including hire of the ROVs themselves, is estimated at £40000 per day. It is envisaged that for such a large-scale operation, it would be more practical to buy dedicated vehicles and customise them rather than hire them for specific tasks. Although financial details have not been forthcoming at this time, it is expected that this cost will accurately incorporate the expense of the vehicles apportioned over their operational lifetime.

3.2 DREDGING HEAD

The front end of the entire system is comprised of a drilling and sorting unit. Its primary purpose is drilling into the pile of cuttings, sorting them into grains below and above 70mm in size and then transporting them to the primary ROV.

This front end system is situated at the end of a long boom protruding from the primary ROV. The cuttings and seawater mixture is transferred to the primary ROV through a flexible composite hose. The overall set-up can be seen in figure 3.1.

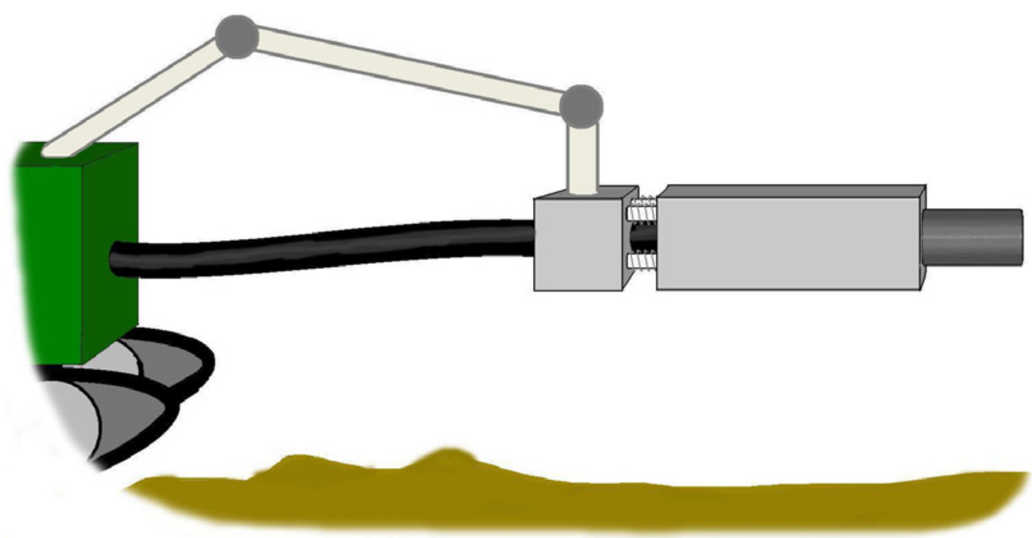


Figure 3.1

The system's main tasks are:

- Disturb the drill cuttings pile enough to disperse the sediment to allow extraction, but not too much so as to prevent contamination of the water column.
- Sort the dispersed sediment into pieces that have a diameter less than 70mm and those that do not.
- Extract the lighter sorted sediment and eject the debris.
- Be able to take a multi-directional impact without damage.

The cuttings dispersal is done by a rotating metal cutting head which protrudes from the unit. This will cut into any encrusted sections of the pile and also disperse the particles ready for extraction. Once suspended, they are sucked into the main hose by means of suction provided by the vertical transport pump situated between the riser and the primary ROV. The rotating head also creates a vortex into the pipe thus increasing the extraction velocity.

The unit is also capable of sorting. Two types of sorting is undertaken; size and weight. The primary ROV pump and the vertical transport pump accepts a maximum particle size of 75mm, therefore any particles approaching this size can not be allowed to enter. In addition to this, excessively heavy objects that get caught in the suction but would 'drag' on the bottom of the pipe can also not be allowed to enter. This paves the way for a compact, simple sorting system on board the unit.

The evolution and detailed design of this sorting system is described in detail in Appendix A. It comprises a grill covering the main hose inlet with a foreign object chute located immediately below. There is also a safety device built into the system that cuts off the suction and then vibrates the grill to remove any material if it becomes clogged.

The unit has a suspension system allowing it to take multi-directional impacts. This incorporates four telescopic suspension struts. This should make the unit very robust and also should reduce maintenance time thus reducing system down time.

3.3 PUMPING STAGE

Upon collection at the primary ROV the cuttings require to be transported to the surface vessel to be treated and stored. This is achievable by several means and the choice of transport has great implications for the removal process as a whole. This choice is, however, required to fulfil a number of performance criteria to facilitate optimal process efficiency.

Team A has made the design decision to employ a powerful rotodynamic centrifugal pump to drive the cuttings mixture, through a riser configured pipe, to the surface.

This decision is based on general superior performance and advantageous implications throughout the entire process, compared to other alternatives. The reader is referred to Appendix C for a detailed analysis, discussion and design for this stage.

3.3.1 Characteristics

3.3.1.1 Pump Characteristics

Given the widely varying operating conditions and characteristics of the working fluid, the pump must be sufficiently powerful to deliver a fairly steady discharge at widely varying pressure differences. Calculations estimate an average head of approximately 75m, while 140m is expected to be a worst case. A high discharge is desirable to facilitate a high removal rate. A pump able to deliver a steady discharge of 125m^3/hr at a maximum head of 200m is therefore chosen. The pump will sit in a cage that concurrently sits on the seabed. The hosing carrying the cuttings from the primary ROV enters the side of the cage with the riser protruding from the top of the pump. The basic set up can be seen in figure 3.2.

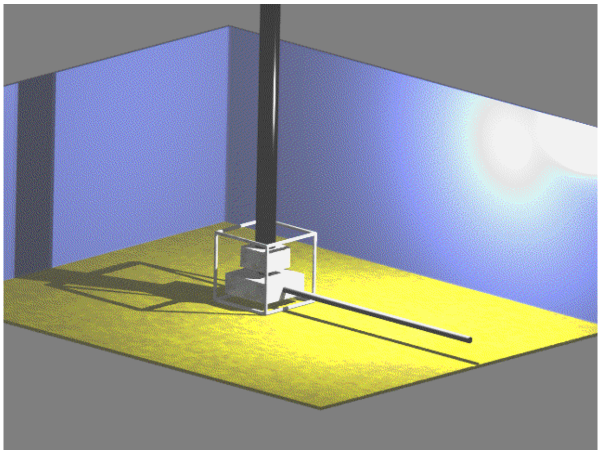


figure 3.2

3.3.1.2 Riser Characteristics

The transport pipe consists of two separate sections, firstly a horizontal section at seabed and secondly a vertical lazy-S configured riser to surface. The material chosen is a composite, incorporating steel and polymers to ensure great strength and toughness while maintaining a high level of flexibility, and is used in both sections. The riser is supported using floating aids.

In order to facilitate the transport of sizeable foreign objects through the vertical riser, the flow velocity is kept at a controlled and elevated level throughout. Calculations estimate that transportation of pebbles up to 70mm diameter is ensured. A pipe diameter of 140mm is used.

3.3.2 Safety and Reliability

In order to ensure superior reliability, the pump has been designed with a safety factor of approximately 2 when considering the head encountered. This redundant strength also helps in clearing blockages and heavy foreign objects.

A number of safety and control systems are incorporated in the pump design to ensure safe and steady operation under extremely varying and volatile conditions. The pipe is designed to be erosion resistant, lasting the length of the project. However, as safety is paramount to all stakeholders involved, this subject will be continually evolved pending experimental trials and gained experience.

3.4 TOPSIDE PROCESS

Upon delivery of the sludge to the surface via the riser the, topside process begins. The aim is to treat and transport the material in a manner which is environmentally safe. This process can be subdivided into categories as shown:

- Separation of liquids from solids
- Extraction of clean water from liquids for disposal overboard
- Crushing of solids to produce a finely ground substance
- Transportation of fine powder, toxic liquids and recovered oil to shore
- Transportation of fine powder and toxic liquids to treatment site
- Treatment and disposal
- Possible utilisation of products produced

Figure 3.3 shows the process from riser to landfill.

3.4.1 Separation of Liquids and Solids

From the riser, a sludge consisting of drill cuttings and approximately 90% seawater will require processing. This is carried out on a treatment ship which will remain at the site throughout the entire operation. To separate the solids, a shale shaker is used for large particle sizes followed by a Hydrocyclone system from Flo Trends Inc. [ref 1]. This extracts fine solids and oil from the water in order for it to be disposed overboard as seen in figure 3.4. At this stage some hydrocarbons are also recovered. The larger sediment from the shale shakers is then crushed to a fine powder for transportation.

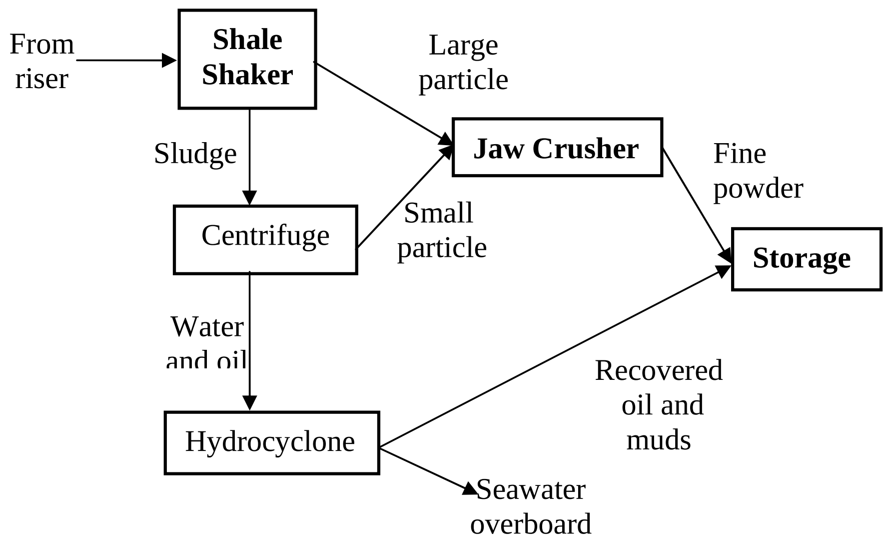


figure 3.3

3.4.2 Transportation of Recovered Cuttings

The fine powder, hydrocarbons and toxic liquids are stored onboard pending pumping across to the transport ship during suitable weather opportunities. This allows the system to damp out weather downtime, to which ship to ship transfer is susceptible. Both ships have built-in pumps for this purpose. The transport ship, once capacity is reached, transports the material to shore. Hydrocarbons can be exploited for fuel purposes but the powder and liquid must be treated before disposal or utilisation.

[ref 1] http://www.flotrend.com

3.4.3 Transportation to Treatment Site

The onboard ship pumps are used to convey the cuttings and liquids to dock-side silos, for temporary storage. From here, the remaining products are transferred via dedicated road vehicles which then drive to one of three treatment sites in the North East of Scotland. For far-north fields, the ship docks at Lerwick, Shetland where disposal and utilisation is also carried out. For other fields, the ship docks at either Aberdeen or Peterhead. Again the treatment sites are located nearby these docking areas.

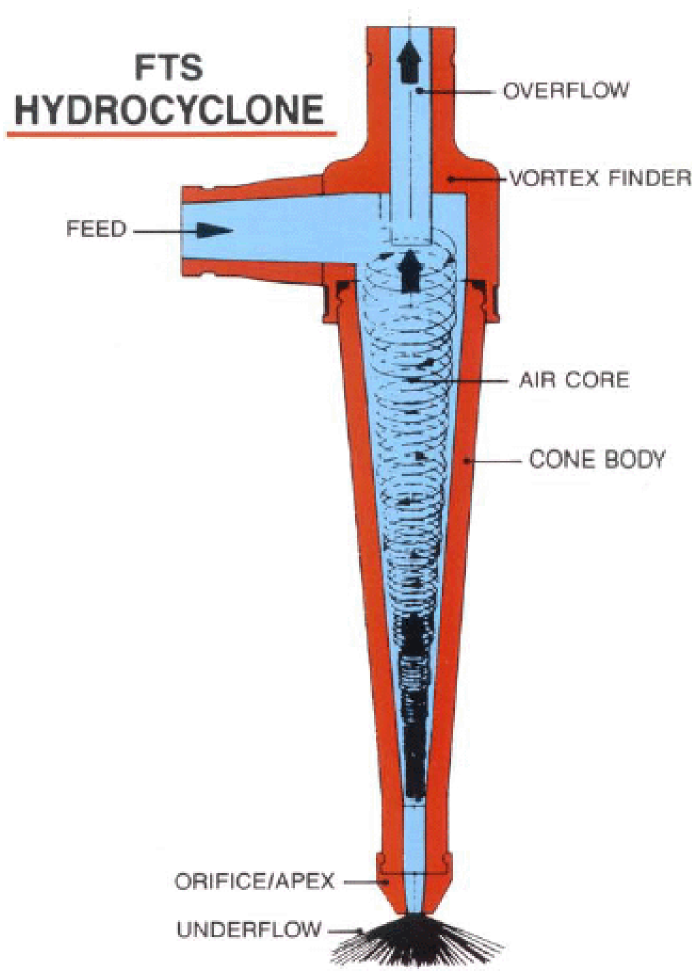


figure 3.4

3.4.4 Treatment and Disposal

The intended method of cleaning the recovered solids is to use Thermal Desorption. This removes toxic elements from the materials to enable normal and safe land filling. At the moment, legislation limits alternative methods of disposing the cleaned cuttings. It has been suggested they can be safely used as a material for building bricks or for use in farm soil. If these options become legally viable then these methods would be used as opposed to land filling.

3.5 SAFETY LEGISLATION

Throughout this tender the emphasis has been on presenting a process and system design that satisfies the needs of all stakeholders involved. This has been done, promoting design features and other points that add value and practicability to the process.

The issue of legislation, especially regarding safety standards and practices, has not been emphasised, not due to its unimportance, but rather due to its assumed presence. The A-Team would like to ensure the client that all components used in our system are manufactured by contractors who operate in full accordance with modern safety standards, and are commitment to quality assurance and control through practises of ISO 9000. All equipment will be designed to comply with relevant British standards (BS EN) and Det Norske Veritas (DNV) standards, and will in addition be CE marked where relevant. This ensures full compliance with modern safety regulations world-wide and enables the client to use our system wherever they wish.

Secondly, all practises employed onboard the surface vessels and throughout the process as a whole will comply fully with all relevant safety procedures commonly used by offshore operators. These are too numerous to list here, but suffice to say that they cover every procedure used in our removal process. Any company hired as a process operator requires compliance to these standards.

4

PRODUCTIVITY AND COSTS

4

PRODUCTIVITY AND COSTS

4.1 PRODUCTIVITY AND COSTS

The following data on the operating costs, duration of the recovery project and the overall productivity are based on the removal and disposal of an average drill cutting pile. The cost estimates should be considered as an initial attempt at calculating the overall cost required.

The system proposed in this document removes the cutting pile from the seabed along with a large volume of seawater. The recovery rate has a 10:1 water to solids ratio. The relevant statistics for an average pile considered in this report are:

Average Pile Volume:	20,000m^3
Sludge Recovered (10% solids):	200,000m^3
Throughput Rate:	125m^3/hr
Duration of Recovery:	100 days

A number of assumptions have been made for this estimate. These include a 50% downtime allowance. This figure is based on data taken from the practical experience documented in the UKOOA Phase II report. It accounts for weather downtime and reliability issues.

The detailed cost for the project can be divided into a number of stages:

- Pre-Recovery Work
- Offshore Treatment
- Transportation
- Onshore Treatment and Disposal

The costs associated with pre-recovery work include estimates for surveys of the cuttings pile. This is considered as an essential process before the removal project can commence. The survey cost will depend on the size of survey vessel required, the amount of equipment, crew costs and the length of time which in turn depends on the pile size. Taking this into consideration, the cost per day for a hydrographic survey team and vessel is about £8500. As the majority of the cuttings piles are within the platform footprint, it will be difficult and time consuming to survey the whole area. Therefore it is assumed that the survey time will be a minimum of 10 days.

For offshore treatment, the cost estimate depends on the rental and purchase costs for the treatment equipment. This estimate does not include running costs for equipment, maintenance, and costs for specialised crew. Allowances for these have been made in the total project cost.

The transportation cost is split into estimates for the treatment ship, collection ship and ROV support ship. The daily rate for each of these includes the cost for crew, maintenance and fuel. Total transportation cost varies with the oil market, the time of year the project is carried out and on how long each vessel is required. For the average pile considered, the project duration is 100 days. The factory vessel and the ROV support vessel are required for the full period. The collection vessel will make three journeys during this time, collecting 7000m^3 on each visit. Each journey will take an average of a week, depending on the location of the cuttings pile. This includes travel time to and from the factory ship and loading/unloading time. Therefore the collection vessel is only in use for three weeks.

The final cost estimate regards the onshore treatment and disposal. The solids recovered undergo thermal desorption to remove any excess hydrocarbons. These costs involve estimates for solids processing, onshore haulage and disposal and landfill tax. The transport and disposal costs depend upon final disposal location. An average cost will therefore be assumed for the estimate. The landfill tax depends on whether the solids are treated or untreated. For environmental reasons the solids will be treated before final disposal, reducing the overall cost for tax.

4.2 Project Activity Chart

Activity	Description	Duration	Dependencies
010	Pre-recovery survey	10 days	None
020	ROV Operation	100 days	010
030	Removal Operation	100 days	010/020
040	Offshore Treatment	100 days	030
050	Initial Collection	7 days	030/040
060	Second Collection	7 days	030/040
070	Final Collection	7 days	030/040
080	Onshore Treatment		050/060/070
090	Onshore Disposal		080

4.3 Summary Of Total Costs

Pre-Recovery Work

Survey Vessel; £4000/day for 10 days	£40,000	
Survey Team; £4500/day for 10 days	£45,000	£85,000

Offshore Treatment

Centrifuges; £430/centrifuge/day	£172,000	
Jaw Crusher	£25,000	
Ball Mill	£95,000	
Contingencies	£3,000	£295,000

Transportation

Factory Ship; £20,000/day for 100 days	£2,000,000	
Collection Ship; £15,000/day for 21 days	£315,000	
ROV Vessel; £40,000/day	£4,000,000	£6,315,000

Onshore Treatment and Disposal

Processing; £380/m^3	£7,600,000	
Haulage and Disposal; £48/m^3	£960,000	
Landfill Tax; £4/m^3	£80,000	£8,640,000
Gross Cost		£15,335,000
Insurance		£153,350
Profit @ 12%		£1,858,600
Total Cost		£17,347,950

5

CONCLUSION

5

CONCLUSION

Our system consists of a number of key processes which combine to provide a cohesive solution to the drill cuttings problem.

Initially, the cuttings are collected by a dredging head and then fed through to the main pump and riser. A pair of ROVs perform this operation. After transportation to the surface, the excess water is separated, treated and disposed of. The remaining solids are ground to a powder and, together with the recovered oil, are transported to shore for further treatment. All these processes utilise the best technology currently available, thus ensuring a high level of reliability. This approach also minimises the additional development costs which untried technology would require.

Safety is of paramount importance to the whole design and is achieved by reducing human intervention to a minimum. The use of remote vehicles and pumping transfer (rather than skips) are examples of this. The environmental risks due to loss of containment are minimised by using a fully enclosed system from collection to disposal. Our chosen disposal method ensures further contamination is minimised through superior treatment and recycling of the cuttings. Significant emphasis has also been placed on environmental integrity by ensuring that the seabed will eventually be returned to its original condition.

Our solution provides a robust system, that has been designed with simplicity in mind. We have strived for ease of operation that ensures that unforeseen difficulties are quickly identified and resolved, resulting in a practicable and maintainable system. This approach results in a reduced downtime, thus improving the timescale and resulting in a cost-effective and efficient solution. We are confident that these factors make our system very competitive without compromising safety or environmental issues.

We look forward to entering into a partnership with you to develop our conceptual solution into a fully operational system. We are aware that the overall cost of this operation is significant and exact specification in relation to cost is a matter for review. All major components of our system will be sourced from companies with which we can build a relationship with in order to achieve the high standards required. We believe our concept is the only solution that will be acceptable to all involved. It is our intention to be at the forefront of this emerging industry and to ensure continuous development of our process as levels of expertise and technology in the area increase.

APPENDIX A

FRONT END SYSTEMS

A.1 Conceptual Introduction

The front end of the retrieval system will comprise of a dredging head attached to the end of a long boom protruding from the primary ROV. It may encounter many different conditions throughout its use and therefore must be capable of handling many different situations and be highly robust. Human intervention at a local scale is kept to a minimum. This maximises throughput and efficiency. The front-end goals can be subdivided into these 4 main headings:

- Disturb the drill cuttings pile to disperse the sediment and allow extraction without contaminating the water column.
- Extract the lighter sorted sediment and reject the heavier.
- Separate the dispersed sediment into pieces that have a diameter less than 70mm and those that do not.
- Be able to withstand a knock from any direction without resulting in severe damage to the system.

A.2 Dredging Head Solution

Drill cuttings piles have been found to have a flaky structure. When agitated these are easily suspended into a sludge mixture. It is known that the membrane becomes more solid and effectively forms a barrier with increased toughness. The problem of removing the piles now becomes more complex as the initial barrier has to be penetrated before the underlying sludge can be removed. In addition to this, the piles also contain foreign objects of varying size, shape and composition e.g. welding rods and scaffold brackets. Some of this debris can not be transported to the surface via the pumps as there is a maximum particle size that the pumps can handle. If they attempt to pump any objects above this size, there is a risk of inducing damage. Once the particles are contained within the main riser, only those below a critical mass can be pumped. The problem now includes sorting objects by size and mass as well as penetrating and removing the cuttings piles.

A.2.1 Disruption Solution

The intended method to remove the piles is to suspend the particles in front of a duct for a hose that will connect to the main pump. The suspended particles are sucked into the hose and transported to the primary ROV pump. Suspending these particles gives us the opportunity to move only those that fall below a certain weight as the heavier objects will simply follow a trajectory that will miss the duct. For such objects a tube is incorporated into the final design of the front end to disperse them. The weight of the objects that are captured by the flow can be effectively chosen by simply varying the flow rate of the seawater through the hose.

Problems may arise from over suspending the particles. This is when they become disturbed so much that they leave the reach of the suction area. The particles may escape into the water column resulting in a very thick cloud of sediment. This would obscure the view of the primary and secondary ROVs. If this were to occur, then a temporary cessation in activity would allow the cloud to subside. Unfortunately, also causing a temporary break in suction and consequently a decrease in efficiency. As detailed in section 1, the contents of the drill cuttings piles are highly toxic. Over suspension of the particles into the water column is therefore very environmentally damaging and should be avoided.

A system must therefore be designed that can break through the hardened surface of the pile and then suspend the resultant particles. Suspended particles are either ejected through the foreign object route or sucked into the hose and on to the primary ROV pump.

A.2.1.1 Possible Brushes Method

One method of suspending the particles is to disrupt them with revolving brushes in the direction of suction. This disrupts the particles while providing power to break encountered surfaces. The nature of a brush (long, uni-directional cylinder) means that it can only disturb the particles in one direction. This results in the requirement for more than one brush and a system of angled brushes would have to be used. The initial proposal (figure A.1) can be seen to be very complex. To drive all four brushes, a complex system of motors and drive shafts would have to be used. It is desired for the front end to be simple as the system has to be robust to limit the amount of interruptions during operation. In the proposed system there is too much complex mechanics which decreases the robustness of the system. In addition to this, there is not much room for intended additions, for example a clutch.

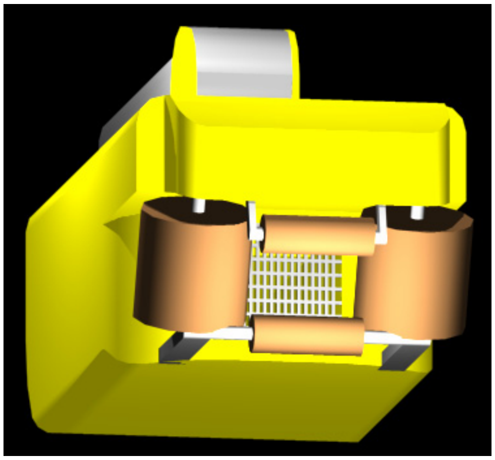


figure A.1

A.2.1.2 Drill Head Method

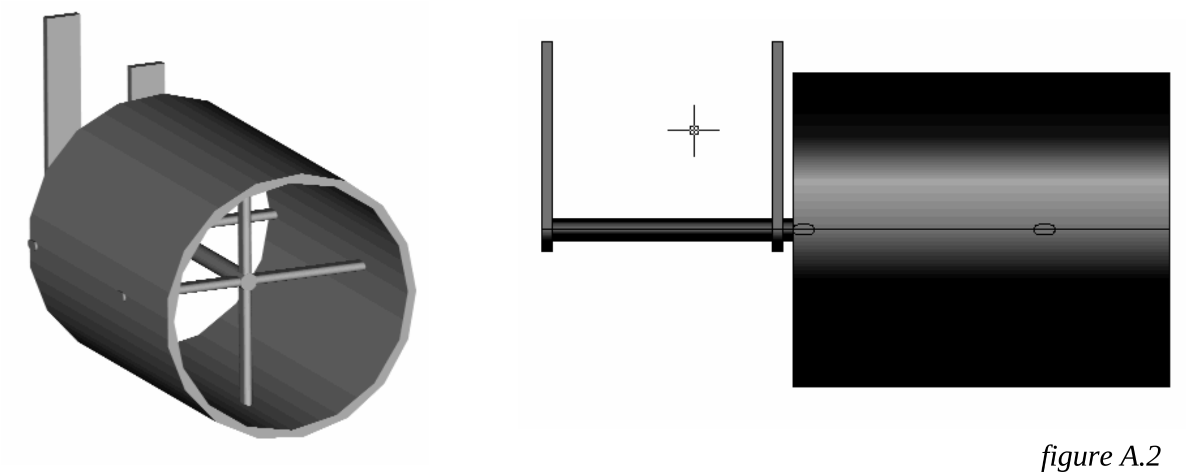


figure A.2

A better design is proposed consisting of a rotating hollow cylindrical cutting head perpendicular to the cutting pile surface. The cutting head disturbs the particles and suspends them both inside and outside the head. The tip of the head should be at such a distance from the hose entry that it still lies inside the suction area so that the particles are subject to the suction. The proposed cutting head is shown in figure A.2

The cutting head can be rotated in two different ways. The first possible rotation method is to vary the rotational speed by an oscillating value (figure A.3). This creates a random disturbance of the particles and as a result, a very dense cloud. The main problem with this method is that the maximum positive (or negative) rotational displacement translates to a fairly large linear displacement. This becomes a problem if the cutting head comes in contact with a solid immovable object, e.g. a scaffold pole. The motor will try to turn the cutting head by the remaining displacement, which could cause motor burn or even damage to the head itself. Because of this, a clutch system will have to be added to the drive and for a clutch system to work effectively requires linear rotation.

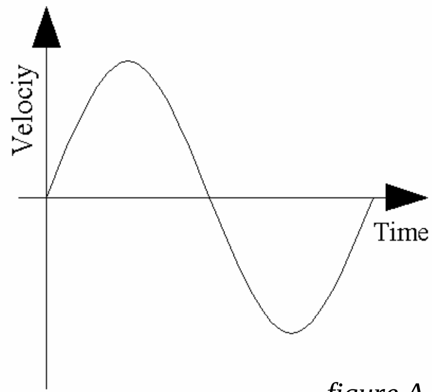


figure A.3

A linear rotation will not produce as large and dense a cloud, but it does have certain other merits. A continuous rotation and perpendicular suction would cause a vortex style of fluid transfer. A vortex fluid movement is much more efficient than trying to move particles that are on already random streamlines. Fluid mixing and particle opposition is vastly reduced. The vortex inside the cutting head is very effective as the fluid is not under influence from the environment fluid. In contrast to this however, outside the head, the vortex can be harder to sustain as it is directly influenced by distortions such as currents and objects.

A.2.2 Sorting

The pump on board the primary ROV is only capable of handling particles under a critical size. The pump can not pass any particles over this size as it is dangerous for the pump. Damage may result if this is ignored and consequently costs and downtime will rise. This would decrease the overall robustness and reliability of the system.

Sorting of the particles can be done in various ways. One possible method is to use a shaker. This involves shaking a metal grid with spacing of the order of 70mm. The smaller substance that is allowed to pass through the pump will fall through the gaps while the substance over the critical size would reach the end. Implementing this into the front end system is a complicated operation, as the host fluid is water, not air. Because of the increased viscosity, the shaker would not be very effective. For this reason, the particles would have to be brought into a host fluid of air before shaking. This is difficult to achieve underwater and is not economical.

Another possible method is to use a grill protecting the hose entry. The grill spacing would be in the order of 70mm. This stops any large particles entering the hose. This is initially a very simple method but does have some complications. The grill can easily become blocked if large yet light objects are sucked on to it. There must therefore be a method of removing these objects with minimal down time. One way to do this would possibly involve stalling suction then vibrating the grill. The particles would then fall off. The other problematic consideration is that these particles that fall from the grill either by vibration or sheer weight would need to go somewhere, so a foreign object tube of some description would have to be employed.

Taking into consideration all the options, it is our belief that the second method is by far the best, and possibly the only solution. This is detailed below.

A.2.3 Suspension Considerations

The front-end unit will be susceptible to operator misuse and therefore must be able to take multi-directional knocks. To design the unit to withstand these knocks is a fairly complex task. One possibility is to simply make the unit very robust. Harder metals can be used, i.e. Steel instead of Aluminum, and the thickness of the metals could be fairly high. There would also be a high number of supporting struts for the cutting head axle to take any cutting head knock. All these modifications make the unit more robust but this extra robustness results in a higher price. The increased weight caused by the tougher and thicker metals would make the unit very heavy. Weight is very important for this unit as it is at the end of a long boom. The heavier the unit is, the more problems arise for the rest of the system. The boom initially would have more stresses on it and would have to be built accordingly. In addition to this, more powerful motors to activate the joints would be needed, and as a result, the energy balance of the system comes into question. A heavier front end unit at the end of the beam also brings a dangerous cantilever situation into focus, the possibility of tipping to ROV greatly increases. In such a situation, the secondary ROV would provide the needed support, however, damage might have already resulted to the ROV, boom or front end unit. The need for a light yet stable solution is apparent.

A.3 DETAILED DESIGN

A.3.1 Cutting Head

The cutting head is driven by a hydraulic or electric motor situated offset from the drive axle axis to allow the hose placement. The need for a clutch which will activate after a certain load is encountered is discussed previously and as a result, a clutch will be placed in-between the motor and the cutting head. Final transfer of the rotation to the head is achieved via an enclosed drive belt or chain linked to an axle running through the hollow section of the head. Using fins to connect this to the head will help in the internal vortex generation.

A.3.2 Sorting

To sort the heavier objects from the lighter ones, a simple foreign object chute is employed. Once the objects subjected to the suction leave the rotating head, there will be a small distance between the head and the hose entry. This distance will be large enough to allow the heavier objects trajectories to miss the hose entry. They then simply fall down the space below lying behind the area that is being worked on. This set up can be seen in figure A.4.

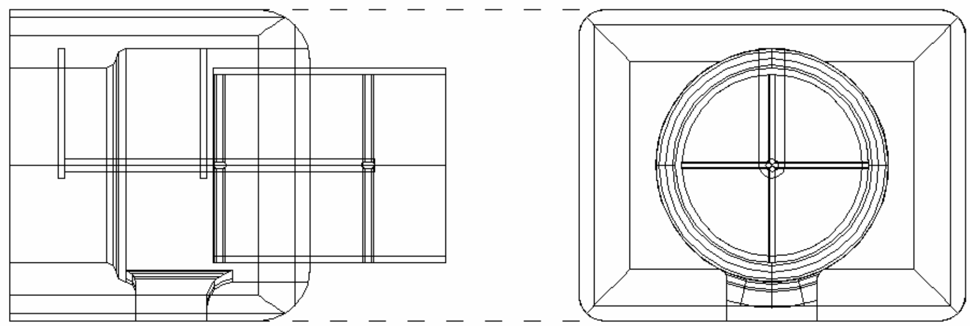


figure A.4

To sort the size of the objects entering the hose is a more pressing matter. The primary ROV pump is capable of passing objects up to 70mm before causing damage to the compression stages. No objects above this size must be allowed to enter the hose. The discussed and decided method to do this is a simple idea with complex implementations.

The use of a simple grill covering the hose entry would be the simplest idea. The grill spacing is in the order of 70mm so that no objects above this diameter enter. Objects above this size simply hit the grill and in most cases exit through the foreign object chute. This simple idea however, has two problems attached to it. They both stem from the single assumption that we will encounter very large and light objects. There is then the possibility that the grill will become clogged with these objects. In that situation, the suction becomes a large problem and damage may result. The first and foremost procedure to be done, in that situation, is to either stop the suction all together by stalling the pumps or to redirect the suction through a route that by-passes the now clogged grill.

Stopping the pumps is not a feasible solution if we want an efficient system. Instead, the redirection of the flow accepting only seawater is a superior method. This will be done by redirecting the flow through an auxiliary duct located on the upper surface of the unit. The upper surface is out of the way of the drill cuttings pile so that the suction only influences seawater and not the piles or the foreign object rejections. The redirection of the section is done by means of a door closing over the main duct to expose the auxiliary duct.

To detect that the grill is clogged is also a pressing matter. We need a system that detects the blockage in the fastest possible time to limit any damage or suck back through the pumps. The best way to do this is to detect not just the blockage, but also as the grill becomes clogged bit by bit. As the grill becomes clogged, a pressure differential will build up between the front of the grill and just inside the hose. When the grill is not clogged, the velocities of the fluid inside the hose and outside the hose will be the same, therefore the pressure differential, ΔP, will be ≈ 0. As the grill becomes clogged, the velocities will change, therefore ΔP will become non-zero. The grill will be fully clogged when ΔP reaches a critical value. To measure this, all that is needed is a pressure sensor in front of the grill and one in the hose. They will provide real time data to the surface support ship. This data is decoded and a real-time update of ΔP is shown. A critical value will be set and once ΔP reaches this the grill is known to be clogged. The data for pressure sensor will be a simple tube filled with a water medium connected to a pressure sensor on board the ROV.

The next problem is one of unclogging the grill from a remote position. There were many thoughts for the solution to this problem and the one chosen is the most robust and effective. The proposal is to shake the grill by means of a vibrating device. The vibration is initiated at one end of the grill with the other end being hinged to the main body. With the absence of suction, the vibration will unclog the grill and the objects should simply fall out the foreign object chute. The vibrating device can be either an electric or hydraulic motor with an offset cam. If hydraulics are used then a self reciprocating hydraulic piston could be used. The vibrating device will also send an operation signal to the main ROV to communicate that it is active.

A.3.3 Suspension

The chosen solution to this problem is by means of a system of four telescopic suspension struts. They have to be strong enough to support the force of the cantilevered weight. They will flex independently or together to give the freedom of movement in all three planes; x, y and z. A cutaway of this system can be seen in figure A.5.

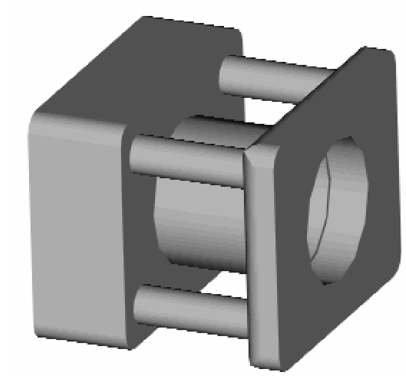


figure A.5

This configuration is very robust so can take a knock in any direction. It is important to note here that the working envelope must allow for very little pre-load on the suspension. If the operator pre-loads the suspension and then makes an operator error on the already pre-loaded spring, there would be very little margin of error to work with. For this reason, when the suspension becomes compressed, an installed sensor will detect the compression and send a signal to the surface support ship. If the suspension depression is above a critical value, which is to be set very low, an audible alarm will sound to warn the operator to amend his mistake.

A.3.4 Information Transfer to and from the Primary ROV

The front-end unit has many transfer lines that need running to and from the primary ROV. These can be split into two main categories of Data Transfer and Power Supplies.

For data transfer, the list of data is given as:

To the unit:

- Main cutting head motor RPM selection
- Trapdoor motor RPM selection

To the ROV:

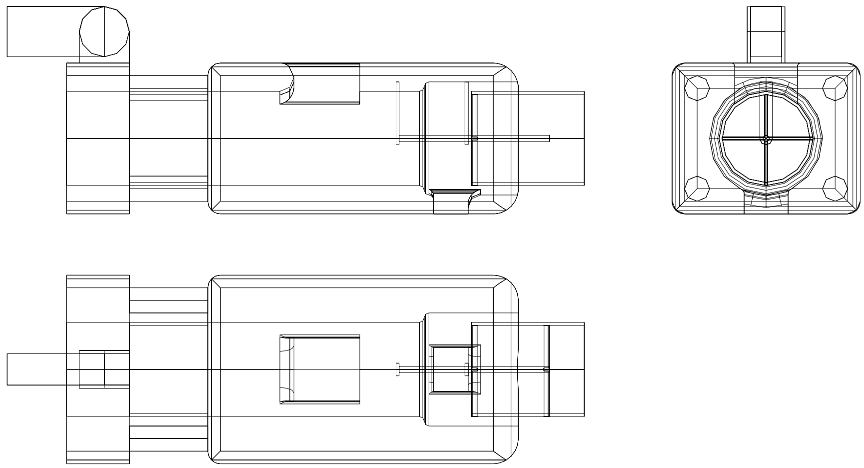
- Outside pressure sensor data
- Inside pressure sensor data
- Main cutting head motor RPM
- Trapdoor motor RPM
- Vibration unit operation signal
- Suspension depressions

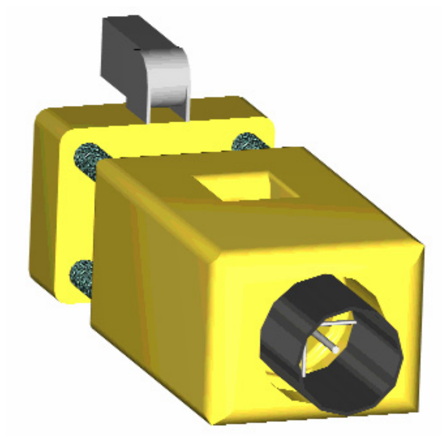
It is intended to use a standard copper 10BT communications link. Each computer will communicate using TCP/IP protocols with triple redundancy. TCP offers fast, reliable data transfer across suitable links. Triple redundancy is a commonly used method which safeguards against many breakdowns in communications links in the application of safety-critical systems. This will offer a very fast and extremely reliable communications system to minimise risk of failure and contamination to the water column.

Power supply to the unit will be achieved by means of a hydraulic and electric connection. The units to be powered are as follows:

- Trapdoor motor (hydraulic/electric)
- Main cutting head drive motor (hydraulic/electric)
- Vibration unit (hydraulic/electric)

These will all be sent to and from the ROV by means of an umbilical running along the main boom.





Full CAD drawings can be seen above. The top drawing illustrates the front, side and top elevations while there in a 3D render below.

APPENDIX B

ROV SYSTEMS

B.1 Conceptual Introduction

The task of the ROVs is to physically collect the cuttings from the seabed. Due to the large working times required to remove the large piles, and considering safety aspects of working at such depths, it is desirable to have as little use of human divers as possible. The use of Remotely operated Vehicles (ROVs) will facilitate this. ROVs are capable of operating reliably for long periods of time (with sufficient spares, they can achieve 90% reliability) and a properly designed system can operate independently of any human assistance on the sea floor.

The removal of the drill cuttings piles is a complex operation, the piles having unpredictable terrain, composition and large amounts of debris present. Therefore the front end system comprises of two ROV vehicles. The primary vehicle does the main removal of the cuttings with a dredging pump. The secondary ROV is intended to support the main dredging vehicle while removing any large debris, which would impede the collection process. This may involve providing alternative viewpoints for the collection work, or "rescuing" the primary vehicle if it becomes entangled or stuck in soft ground. It is also able to facilitate simple repairs without bringing the vehicle to the surface.

B.2 Solution Comparison

The primary vehicle will be a large crawling vehicle, which will move along the seabed on tracks. This provides a stable base for the powerful dredging head, and avoids disturbance of the cuttings from thrusters, which a floating ROV may cause near the pile. The use of suction to collect the cuttings is preferred when compared to methods such as bucket or trailing hopper dredging. This is primarily due to the lesser disturbance to the pile and the additional removal of any potentially contaminated water within the closed system.

For manoeuvrability purposes, the secondary vehicle is a floating ROV. This enables access to the top areas of the pile for removing debris and provides a flexible observation platform. For the removal of large debris it is equipped with powerful manipulator arms and therefore takes the form of a heavy work-class ROV. For very large items of debris a crane from the surface ship can be attached by the secondary vehicle, or if access is not available (e.g. underneath the platform structure), a winch mounted on the primary vehicle can be used. Small objects will be placed in a basket on the sea floor and carried up as bulk.

The basic workgroup consists of just one of each of these vehicles, but in theory could be scaled up to use several vehicles in the operation. This would incur greater expense and more resources from the supply vessel(s) on the surface. Although due to the large nature of the problem, it may prove more beneficial to increase the scale of the project, thereby reducing the operational time required.

For both vehicles, the possibility of using a deployment cage was investigated. This is a device which lowers the vehicle from the ship to the seabed from which the ROV emerges to perform its tasks. It gives the advantage of removing any trailing umbilicals from the immediate area of work, as the only vertical portion of the cable goes to the cage and not the vehicle itself. However, they can only be used to deploy relatively small ROVs, and since the vehicles required are rather heavy duty, it would not be practical to deploy them from a cage.

The ROVs are controlled and powered from a ship on the surface. They are supplied by the vessel's own electric generators, as are the control consoles. These consoles fit into an area of equivalent size to a standard container. There are separate consoles for navigation, the manipulators and tools, the assistant vehicle and a main console with thruster control, power control and fault detection. Both vehicles can be deployed from the same vessel making the mission co-ordination much easier, and avoiding the expense of multiple control ships.

B.2.1 Primary vehicle

The dredging pump is attached to a customised collection head on the end of a short boom, which in turn is connected to the body of the vehicle. The boom is jointed midway along its length for increased manoeuvrability. This allows access to cuttings that the vehicle may not otherwise be able to reach, for example if supports on the platform structure impede its movement.

A possible problem with a crawling vehicle is that it could become stuck in unstable or soft ground. The working pattern should be to clear around the edge of the pile, as there is no guarantee that the pile will be solid enough to take the vehicle's weight and allow it to work from the top down. Care must be taken that slumping of the pile does not bury the ROV, but the use of the boom allows collection to take place a distance in front of the vehicle or even slightly higher than it would normally reach. Visibility may be seriously undermined once the pile is disturbed causing the secondary vehicle to be used to view the proceedings from a different angle, or use alternative sensors such as sonar imaging to inspect the operation.

B.2.2 Secondary ROV

The secondary ROV will have to remove various items of scrap dropped onto the pile, including: scaffold poles, tools, ropes and even large objects such as pipes or containers. Because of this, a powerful vehicle has been selected with heavy duty manipulators. These manipulators will clear the way for cuttings removal and avoid damage to the dredging pump from large objects. Large items of debris may be dismantled before removal. Standard angle girders and wire cutters are available from supplier catalogues for this purpose. They would be mounted as end effectors on one of the manipulators, and powered by the vehicles own hydraulic source.

Modern ROVs are controlled by advanced navigation systems, which perform the small control adjustments required for the operator, and can move the vehicles along pre-determined paths with great accuracy. The control software is also capable of automatically holding the ROV steady, even in variable current conditions. Also, graphics displays are available showing various aspects of the ROVs condition, power supply and any faults, as well as video for recording images from the operations.

A baseline positioning system is used by many systems to show the relative positions of all units in the area. Acoustic beacons are deployed by the ROV at the start of the operation to enable this. Receivers on each vehicle can then be used to calculate their exact position relative to these beacons. This can be used for strategic deployment of the entire collection system, including primary and secondary ROVs as well as the main pump.

B.3 DETAILED DESIGN

B.3.1 Primary vehicle

A possible vehicle for the primary ROV is the Pipeline Trenching tractor from SMD (figure B.1). This is normally used for the digging of pipeline trenches on the sea floor, but instead of the water jet pump used for trenching, it will be fitted with a dredging pump to collect the cuttings. The exact choice of vehicle is not critical, as many manufacturers produce ROVs that are equally suited to the required tasks. The above was chosen for its relative low weight and its adaptability to different conditions. The following systems are added to this basic unit to meet the specific requirements for its operation.

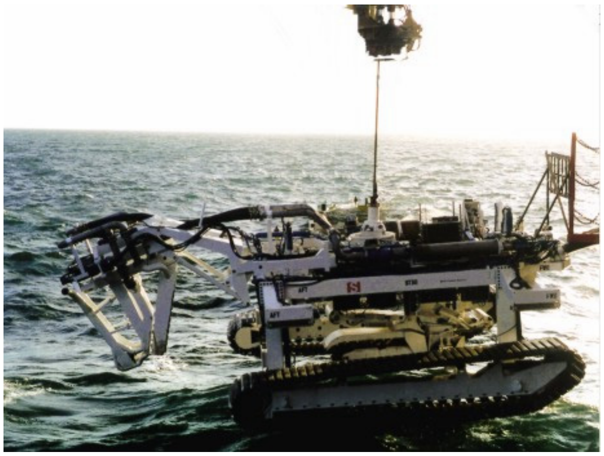


figure B.1

B.3.1.1 Pump

Dredging pumps are normally used for clearing the seabed from around pipes or other installations prior to inspection or maintenance, with the removed material being deposited nearby. In this instance, the cuttings will be transported through a pipe to the larger surface-going pump, for transport to the ship. Since this is a horizontal transport, very little head is required – it must only overcome friction in the pipe and match the flow rate of the larger pump at the end. The dredging pump is a standard model, operated by the vehicle’s own hydraulic power. It is capable of passing solids of up to 3” in diameter; any larger objects will be prevented from entering by the collection head.

B.3.1.2 Collection Head

The end of the pump system consists of a custom designed collection head, which ensures a safe and efficient collection of the cuttings. This is described in detail in Appendix A.

B.3.1.3 Boom

Although exact designs have not been finalised yet, the boom will incorporate at least two degrees of freedom to allow manoeuvring of the collection head without moving the vehicle. It will be 2.5m long, to give greater reach without proving unwieldy or causing unwanted moments, which may tip the vehicle.

B.3.1.4 Winch

The primary vehicle is also fitted with a hydraulic winch mechanism. This is driven by the ROVs own hydraulics, requiring 2800psi, 5GPM. It is mechanically attached to the outer frame of the vehicle. Since it will not need to pull over long distances, a thick cable with a high weight capacity is desirable, even though this reduces the maximum line capacity. Therefore a 75m long polyester line (7/8" diameter) is used, and with this the drum has a 6800kg pulling capacity.

B.3.2 Secondary ROV

A suitable ROV is the HYSUB ATP 250 model from ISE group (figure B.2). This is a large, work-class ROV suitable for heavy lifting and recovery work, and has a variety of sensors and cameras to oversee the work. Most ROVs of this type do however operate in very similar ways. This vehicle also has its own miniature assistance vehicle within it, which has cameras and small manipulator. This will be useful for general assistance for the secondary vehicle.

figure B.2

B.3.2.1 Structure

The vehicle frame is made from welded marine grade aluminium and the structure is an open-frame style to allow free water flow to the thrusters. The frame is fitted with anodes to protect against corrosion. Stainless steel mesh screens can be used to cover the base and sides of the vehicle to prevent internal damage from foreign objects. Sensitive electronic and hydraulic components are contained in pressure resistant housings.

B.3.2.2 Ballast

The vehicle is equipped with “hard” ballast in the form of foam blocks, which bear the vehicle’s weight in the water. This is designed with a large vertical distance between the centre of gravity and the centre of buoyancy, to give a stable working platform. Lead weights are fitted to the bottom to compensate for different equipment payloads and to adjust the balance of the vehicle. There is also a variable “soft” ballast provided by air in four tanks. This can be varied to account for different payload weights. The air for this system is transferred through the umbilical cable, from a compressor on the surface. There is also an on board air reservoir to allow faster operation of the ballast.

B.3.2.3 Propulsion

Propulsion is achieved by 12 hydraulic thrusters; four of each for forward, lateral and vertical movement. These each consist of a standard piston motor connected to a propeller via a bearing supported shaft. The vertical thrusters are 12” in diameter; the others are all 16” diameter. The propellers are fully interchangeable for ease of maintenance and repair.

B.3.2.4 Control

The telemetry system transfers control information to the vehicle, and data from the vehicle in full duplex mode. It has a data rate of approximately 56kbits/s. Data is transferred along the umbilical cable, along fibre optic cable, and telemetry microprocessors are present on the ROV and at the surface.

B.3.2.5 Navigation

There are various sensors, which assist the vehicle in navigation. An altimeter and gyro both assist in accurate positioning. There are several automatic positioning functions, e. g. auto heading and depth, which can be used to accurately move the vehicle. The ROV has several video cameras: on both sides and at the aft, as well as stereo and colour cameras on the front. These cameras are situated on pan and tilt settings and are illuminated by 500W lights. Forward-looking sonar is also available for poor visibility. These instruments all show their displays on the navigation console on the surface vessel.

B.3.2.6 Electrical supply and Hydraulics

Power is transferred down the umbilical from a generator on the surface vessel. It is transformed down to 1200V for transmission to the ROV. This is then transformed in the vehicle's distribution box for use at 460V. Fault detection circuitry monitors the on board power distribution.

Electrical power is used for the cameras, lights and on board telemetry and control processors. The hydraulic generators are electrically powered, but other devices on the vehicle are hydraulically operated.

Most of the onboard tools and motors are hydraulically operated, power coming from two 125Hp hydraulic power packs. The power packs contain hydraulic pumps powered by 1200V, 3-phase motors. The normal operating pressure for the hydraulic system is 3000 psi.

B.3.2.7 Umbilical

This carries the electrical power, telemetry and video signals and ballast air supply. It has two armoured layers of wound plough steel, and is rated to carry 100 tons. This not only protects it from accidental breakage, but it can effectively be used to take the vehicle's weight if a problem develops. There are several conductors for each system inside the umbilical.

B.3.2.8 Manipulators

Manipulators on the vehicle are heavy duty, rated to lift up to 295kg. Most debris will be much smaller than this, but there will likely be a few large objects present in most piles. The manipulators have 7 degrees of freedom, making them extremely manoeuvrable, and are fitted with gripping clamps at the end. They are controlled at their own specific operation console.

B.3.2.9 Assistant Vehicle

The HYSUB ATP 250 comes with a smaller 10Hp vehicle as standard. This can be used to support the vehicle in many tasks, increasing work rate and providing additional observation abilities. It will also be helpful if the secondary vehicle becomes entangled or damaged. In this way it can provide backup support for the secondary vehicle in the way which that does for the primary vehicle, thus reducing the need for diver intervention in an emergency.

The assistant vehicle is attached to the ROV via a 50m cable, and normally resides in a bay at the rear of the vehicle. Power and control signals are transferred to it through this cable. It is equipped with two cameras and a 4 function manipulator, and has a 7kg payload. It is not suitable for heavy work, but can assist in smaller tasks, being operated by a separate control console on the surface.

B.3.3 Technical Summary – Secondary Vehicle

Dimensions	
Height	2. 5m
Width	2. 5m
Length	4. 9m
Structure	6061-T6 aluminium
Displacement	7 T
Maximum depth	1000m
Electric power	460V AC 3 phase 60Hz 300KVA
Hydraulic power	2 x 125Hp power packs
Cameras	2 SIT (fore/aft), 1colour, 1 stereo, 2 mini (sides)
Payload	3000kgs (variable)
Propulsion	3 directions x 4 hydraulic thrusters
Thrust (approximate)	
Fore/aft	5000lbs
Lateral	4000lbs
Vertical	2000lbs
Umbilical cable	600m long, 100T breaking load, 3" Diameter
Navigation instruments	altimeter, gyrocompass, imaging sonar
Assistance vehicle	10Hp, 250Kg, 50m tether

APPENDIX C

PUMP TRANSFER

Upon exit from the primary ROV the collected mixture needs transportation from the seabed to the surface treatment and storage facility in a continuous and reliable manner. This can be considered as the second of three main stages in the removal process, namely collection, transportation and treatment.

C.1 Conceptual Description

Upon exit from the ROV the cuttings travel horizontally along the seabed through a pipe to the main transport pump generating sufficient head to move the cuttings to the surface. The flow velocity is sufficient to transport sizeable pebbles and foreign objects as well as providing good suction at the ROV inlet. The main transport pump can be considered to be the heart of the removal process, providing the driving force required. In order to obtain total containment of contaminating substances, the cuttings are transported through a flexible hose from the ROV to the pump, and through a pipe riser from the pump to the surface.

A pump and pipe system is needed that can satisfy all these criteria yet still be robust, maintainable and relatively inexpensive.

C.2 Conceptual Comparison and Discussion

The manner in which this transport is achieved is a significant design point in the removal process. There are numerous alternatives, which will accomplish this, all with their relative advantages and disadvantages. It is important to clearly specify the design criteria most important for the successful completion of the removal process such in a manner as is acceptable for all stakeholders involved.

Team-A focuses on the following points in the transportation process.

- Practicality
- Simplicity
- Reliability
- Safety
- Containment
- Cost effectiveness
- Time

Throughout the design, an emphasis has been put on practicability and simplicity in order to achieve superior reliability and flexibility of application. The A Team has therefore chosen to implement technology already proven to be reliable and adaptable.

Safety is of utmost importance and every design precaution is taken to minimise and simplify human interaction with the removal process as well as employing stringent safety standards to the design of individual components.

Containment of polluting substances is of great importance and must be kept at a minimum at all times. This is an underlying aim of the entire removal process and is a great factor in any design decisions taken.

Finally efficiency is also of great importance, both economically and when considering the energy balance involved. In order to utilise the summer months, with reduced weather downtime, a fair throughput and rate of removal of the process is desired. This will minimise project duration and increase effectiveness.

C.2.1 Design Alternatives

A fair number of alternatives for seabed to surface transport have been considered and evaluated according to the criteria above. Their distinctive advantages and disadvantages are highlighted and compared, especially considering their impact on the rest of the process. This feasibility review is conceptual in nature.

C.2.1.1 Mechanical Transport

This section evaluates the feasibility of using mechanical lifting devices to transport the cuttings from seabed to surface. These devices range in complexity from very simple to very intricate and as such have different performance characteristics.

The simplest mechanical transport is the lifting of baskets containing cuttings using cranes from surface vessels. This process involves the cuttings being placed in these baskets by means of ROV activity, lifting to surface and finally disposal into treatment process.

The advantages of this method are simplicity and reliability. There is little that can go wrong when considering the process itself. Downtime due to weather conditions will not be serious and the amount of energy spent is very small compared to other alternatives. The method is cheap and has the potential for attaining considerable removal rates.

The disadvantages are numerous and serious however. The most serious fault is a complete lack of containment. Both the ROV activity and transport to the surface will potentially expose the cuttings to fresh seawater, thus polluting the entire water column, defeating the purpose of the process. Another worry is the high level of human interaction required, raising serious safety concerns, especially when receiving the basket onto the surface vessel in bad weather conditions. An additional drawback is the discontinuous nature of the process making steady and continuous use of the treatment facilities difficult to attain.

This is a cheap and reliable alternative but is inadequate when considering the aforementioned points. Other drawbacks make it non-ideal when considering practicability, and so the method is not considered feasible.

It therefore has become apparent that to contain the contaminants involved, an enclosed system must be used. Practicability suggests that this can only feasibly be achieved using a pipe and pump system, the details of which will be studied here on in.

C.2.1.2 Pumping Transport

The main alternative to mechanical transport is using pumps to force the cuttings to the surface through a flexible riser. This method offers considerable advantages, mainly through aspects such as complete containment and minimal human interference as well as reduced weather down time and increased practicability and flexibility considering the continuous removal of cuttings. The design is simple utilising a main transport pump as the driving force in the process and using a flexible pipe to contain and transport the cuttings to the surface. This flexible pipe, arranged in an S-bend riser configuration, makes the process resistant to surface weather conditions. The driving force supplied by the pump facilitates both the collection of cuttings and ejection of cuttings into the treatment plant onboard the surface vessels. The rate of removal is indirectly determined by the discharge of the pump.

Positive displacement pumps can effortlessly achieve high heads and high discharges, and thus seem ideal at first instance. However, there are two significant drawbacks inherent to such pumps. Firstly the flow is discontinuous, affecting both transport of foreign objects and suction at the collection point. Secondly, the close fitting tolerances necessary for such pumps to operate are a concern due to the abrasive nature of the medium transported. Abrasive sand and grit are likely to reduce the lifetime of such a pump.

Rotodynamic pumps require slightly more energy to achieve the head and velocity required, but they do circumvent the drawbacks highlighted above. Large radial pumps are available which are designed to transport fluid containing a high percentage of solids, including sizeable pebbles and foreign objects. Thus reliability is dramatically improved while the nature of flow is advantageous on all points.

This feasibility study thus concludes that a strong radial pump with flexible riser pipes is the solution of choice for the removal process, see table C.1

Method	Practic.	Simple	Reliable	Safe	Contain	Cost	Rate
Basket	√	√	√	X	X	√	X
Conveyor Belt	X	X	X	√	√	X	√
Positive Displ	√	√	X	√	√	√	X
Roto Dynamic	√	√	√	√	√	√	√

Table C.1

C.3 FINAL CONCEPTUAL DESIGN SOLUTION

Having compared the alternatives, using a rotodynamic pump and riser configured pipes is arguably the better solution. It satisfies all the design criteria and is the best choice when considering all stakeholders involved, especially the operator and the client. The three most important aspects of the solution are the good characteristics and design opportunities considering practicability, reliability and safety.

Team A is conscious that the most precious assets to our client, during operation, are time and human resources. Having satisfied ourselves that our solution is superior to other alternatives, we offer a design that we are confident will serve the client well, regardless the circumstances.

Detailed design along with reliability, performance and safety considerations are found in the following sections.

C.3.1 Detailed Design of Pump Stage

Of primary importance is the ability of the pump to transport the cuttings under widely varying circumstances. The greatest source of this variation is the dynamic nature of the fluid pumped. Depending on the removal rate of cuttings attained by the ROV, the fluid could be pure seawater or conversely sludge containing as much as 30% solids. This constant variation of solids content has been found to cause severe problems in experimental tests conducted in the North Sea. Clearly the pump and its control system must be capable of handling such matters. In addition, the pump must deliver such a discharge as to ensure that foreign objects are not allowed to settle but are carried along with the flow to the surface.

This section will concentrate firstly on the fluid dynamics of the process, estimating the performance requirements of the pump. Secondly a detailed practical design is outlined in which features relating to safety and reliability are highlighted.

C.3.1.1 Fluid Characteristics

The dominant fraction of the pumped fluid is seawater. The amount of cuttings and sludge present in the flow will at all times depend upon the ability and efficiency of the ROV and operator. Previous experiments indicate an average volume level of 10% solids.

The dynamic level of cuttings has two significant fluid dynamic effects. Firstly the density will vary accordingly to the cuttings, as the cuttings have an average density of 2700 kg/m^3 compared to that of seawater 1003 kg/m^3.

Secondly the viscosity will change due to the high levels of oil and sludge present. It is extremely difficult to estimate the exact nature of the cuttings in this respect. Instead, Team A has chosen to employ a worst case ethos, for improved safety, and therefore assume slurry viscosity to be that of unused engine oil, approximately 1500 times more viscous than water. This matter will be more accurately resolved when preliminary tests are carried out and the changing viscosity can be experimentally determined.

The nature of the cutting solids is known from experience to range from fine grain size to grain size and will thus mix into the fluid in a near homogenous manner. However, as they may coagulate into greater lumps, as well as the presence of foreign objects such as pebbles, rocks or metal objects is likely, the fluid may contain sizeable foreign objects. The size of these is limited by the ROV to be less than 70mm.

C.3.1.2 Pump Requirements

There are two components to the head required of the pump. The first is the static lift required, depending only on the vertical height difference and the density of the fluid. Secondly there is a frictional component depending on several factors, most importantly the viscosity of the fluid, the flow velocity and the pipe characteristics.

Prior to calculating the required pump characteristics it is important to state the factors affecting the design:

- The normal discharge is limited to <150 m^3/hr
- The desired flow velocity is >2.25 m/s
- Average cuttings density is 2700 kg/m^3
- Cuttings viscosity 0.001120 m^2/s
- Seawater viscosity 0.00000442 m^2/s
- Linear viscosity relationship between cuttings and seawater.
- Roughness factor for riser 0.00667
- Riser length 300m

Using these limitations together with graphical representations for drag and friction coefficients it is possible to attain accurate estimates for the head losses encountered.

Using a flow velocity of 2m/s and a pipe of diameter 150mm and length 300m, the effect of varying cuttings fraction is clear to see, see table C.2.

Solids %	Pipe D [m]	Discharge [m3/hr]	Reynolds	Roughness k/d	Friction f	Friction loss [m]	Static Lift [m]	Total Head loss [m]
0	0.14	125	218447	0.00714	0.00850	19	0	19
10	0.14	125	2788	0.00714	0.01200	27	34	61
20	0.14	125	1400	0.00714	0.01143	25.3	68	93.3
30	0.14	125	935	0.00714	0.01712	38	102	140

Table C.2

C.3.1.3 Flow Calculations

As stated above, the flow is required to transport all collected cuttings to the surface, including foreign objects. This is the second requirement of the pump. Together with the discharge limit and head required, this forms the three variables which govern the state of flow at all times. The pipe characteristics are directly determined by these variables.

As the maximum foreign object size passed through the ROV is 70mm, this is used as a worst case test for the flow. The flow should support a sphere shaped pebble of density 2700 kg/m^3 and diameter 70mm in vertical flow. The means of support is provided by friction and pressure drag forces. This necessitates some simplifications in order to perform calculations.

Firstly the pebble size is not considered to affect the nature of flow around it. This is a significant simplification, but it should be stressed, that this does not decrease the safety factor. The omission affects the drag negatively. In practise, the flow velocity and pressure difference around the pebble will increase dramatically with size, thus increasing the drag.

Secondly the effect of the grain cuttings is neglected when considering the effect of solid impingement. The flow is considered to be viscous only. This approximation again decreases the drag effect.

The calculations are performed using graphical estimations for the drag coefficient based on the Reynolds number of the surrounding flow. This drag force is balanced against the force of gravity, giving a net force on the pebble

The main variables of the calculations are the flow velocity and the fraction of cuttings in the flow. Thus four cases will be considered, starting at seawater and increasing the cuttings content up to 30%. Each case will consider several flow velocities and examine their effect. The results are shown in tables below.

- Pure seawater flow

Diameter [m]	Flow speed [m/s]	Reynolds	Cd	Viscosity [m^2/s]	Drag [N]	Mass of particle [Kg]	Gravity [N]	Net force [N]
0.07	0.5	24272	0.45	0.00000144	0.253	0.485	4.755	-4.501
0.07	1	48544	0.51	0.00000144	1.148	0.485	4.755	-3.607
0.07	1.5	72816	0.49	0.00000144	2.481	0.485	4.755	-2.274
0.07	2	97087	0.49	0.00000144	4.410	0.485	4.755	-0.344
0.07	2.25	109223	0.48	0.00000144	5.468	0.485	4.755	0.713

- 10% cuttings fraction

Diameter [m]	Flow speed [m/s]	Reynolds	Cd	Viscosity [m^2/s]	Drag [N]	Mass of particle [Kg]	Gravity [N]	Net force [N]
0.07	0.5	310	0.7	0.00011300	0.394	0.485	4.755	-4.361
0.07	1	619	0.55	0.00011300	1.238	0.485	4.755	-3.517
0.07	1.5	929	0.48	0.00011300	2.430	0.485	4.755	-2.324
0.07	2	1239	0.45	0.00011300	4.050	0.485	4.755	-0.704
0.07	2.25	1394	0.44	0.00011300	5.012	0.485	4.755	0.258

- 20% Cuttings fraction

Diameter [m]	Flow speed [m/s]	Reynolds	Cd	Viscosity [m^2/s]	Drag [N]	Mass of particle [Kg]	Gravity [N]	Net force [N]
0.07	0.5	156	0.9	0.00022500	0.506	0.485	4.755	-4.248
0.07	1	311	0.7	0.00022500	1.575	0.485	4.755	-3.179
0.07	1.5	467	0.58	0.00022500	2.937	0.485	4.755	-1.818
0.07	2	622	0.52	0.00022500	4.680	0.485	4.755	-0.074
0.07	2.25	700	0.5	0.00022500	5.696	0.485	4.755	0.941

- 30% Cuttings fraction

Diameter [m]	Flow speed [m/s]	Reynolds	Cd	Viscosity [m^2/s]	Drag [N]	Mass of particle [Kg]	Gravity [N]	Net force [N]
0.07	0.5	104	1	0.00033700	0.563	0.485	4.755	-4.192
0.07	1	208	0.75	0.00033700	1.688	0.485	4.755	-3.067
0.07	1.5	312	0.7	0.00033700	3.544	0.485	4.755	-1.210
0.07	2	415	0.6	0.00033700	5.400	0.485	4.755	0.646
0.07	2.25	467	0.56	0.00033700	6.379	0.485	4.755	1.625

It is evident, from the tables above and interpolation of data, that the critical velocity is approximately 2.25m/s. At this flow velocity the pebble is kept suspended and will travel slowly towards the surface. Although 2.25m/s is the critical flow, it is important to keep in mind, that these calculations assume worst case conditions as impingement and increased pressure difference over the pebble are neglected. Thus the calculations provide satisfaction that this velocity will safely and reliably deliver objects of this nature to the surface. This will be experimentally examined and verified during tests.

It is in the interest of reliability that the average flow in the riser pipe is kept as low as possible. Although a higher flow velocity will transport heavier particles, this significantly increases erosion damage from the abrasive solids on the riser bends.

This is a significant problem as small leakages are hard to detect and can cause significant pollution before they are corrected.

C.3.1.4 Pipe design

Using an average flow velocity of 2.25m/s and a discharge of 125m^3/hr, the riser pipe is designed using 140mm diameter pipe. The material will be a composite construction of steel and polymers, to ensure good erosion resistance and high flexibility.

The configuration of the riser is a lazy S, with an estimated length of 300m.

C.3.1.5 Practical Pump design

The pump is built into a support frame, built according to BS EN 12079, in order to provide protection and a stable platform to work on. This frame allows the pump to sit slightly above the seabed to prevent excessive intake of sediment through the relief vanes. The pump is designed not to be suspended from the surface vessel but rather to sit on the seabed. This is done to keep the platform stable and reduce the risk of breakage due to surface vessel drifting or loosing control. This set up can be seen in figure C.1

Directly underneath the pump inlet, a small collection chamber is situated where the cuttings enter. In this chamber they are stirred by a small impeller in order to ensure a near-homogenous mix of cuttings and seawater. The impeller is driven by the same drive shaft as the main pump impeller.

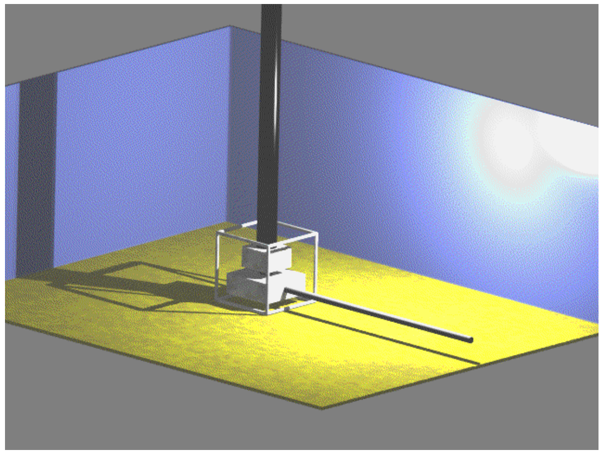


figure C.1

At the pump outlet a pressure transducer estimates the head it facing at all times. This reading has two consequences. Firstly it automatically and intelligently feeds instructions back to the drive, regulating power and speed of the pump in order to keep the flow steady. Secondly, if the head becomes too great, relief vanes positioned at the pump inlet open gradually to let in a higher fraction of seawater. This is done to gradually decrease the head required, and to reduce the suction head at the ROV collection inlet. This correcting action allows the pump to resume normal activity in a short time.

The pump is driven by electric motors supplied by electric generators situated onboard the ROV control vessel. The drive control consists of intelligent control of both the power supplied by the generators as well as an electric gear on the motors themselves. This ensures efficient running of the pump while maintaining a high level of control and fast response to changes in demand.

C.4 Safety and Reliability Issues

A criterion of utmost importance is that of safety and reliability issues. These are likely to have the greatest impact upon the speed and efficiency of the removal process and the safety of human life and equipment. Every effort is made to ensure that the detailed design of the pumping stage incorporates these criteria. The most important design features enhancing performance in this respect are given below.

C.4.1 High Capacity

The tables in previous sections represent normal operating conditions. This is however a highly restricted representation. It is important, in the cause of reliability and safety, that the facilities are operated at a level significantly lower than maximum. Thus although the pump is likely to be working at an average head of around 80m with a discharge of 125 m^3/hr, it is important that it has the reserves needed to perform at a higher capacity.

This heightened performance is called upon when problems are encountered, such as clogging of the riser bend, or prolonged pumping of extreme solids fractions, in case the relief vanes fail. This backup power can be essential in clearing problems without the need of shutting the system down. Thus it is desirable that the pump is capable of pumping at least 200 m^3/hr and is capable of delivering a head of at least 150m. This ensures that foreign objects and other blockages are cleared effortlessly. Also reliability of the pump is increased dramatically as it normally operates at a reduced capacity.

Additionally, the design takes into consideration that no practical testing has been done in-situ, at this point in time. The great capacity available allows for increased production at the operator's discretion if the conditions are deemed to be favourable, allowing for great practicability and flexibility.

C.4.2 Breakage Seals

As a last resort backup, in the case of complete loss of control of the surface vessels where connections, pipes and wires are broken due to excessive forces, dragging or other disasters, it is important that pollution is still contained. This may be accomplished by the design of special controlled breaking points on the different components. Thus at the ROV outlet, the pump inlet and outlet and at the pipe connection to the surface vessel, special seals are constructed. These have the role of breaking under certain forces and closing the pipes using mechanical emergency valves. This ensures that containment of pollution is kept in the event of disaster. Also it prevents destruction or damaging of components such as the pump or ROV as they could be dragged with a drifting surface vessel.

APPENDIX D

TRANSPORT AND DISPOSAL

D.1 CONCEPTUAL INTRODUCTION

This appendix proposes that one standard ship be used for the removal of any of the cuttings piles in the North Sea. This ship will remain in situ, at the top of the riser, throughout the duration of the recovery project and can be considered as a 'factory ship'. The cuttings are treated once they are pumped to the surface. This factory ship will store the remaining products until they can be transferred to a second vessel for transportation to shore.

The pipe riser brings up a mixture at about $130m^3$/hr of which on average 10% is solids. The remaining volume is water. Once onboard the factory ship, the mixture of cuttings and water goes through a treatment phase. This phase involves separating the water from the cuttings, cleaning the water and discharging it overboard, and grinding the solids into a powder. All retained material is stored in onboard silo holds. The complete phase is outlined below:

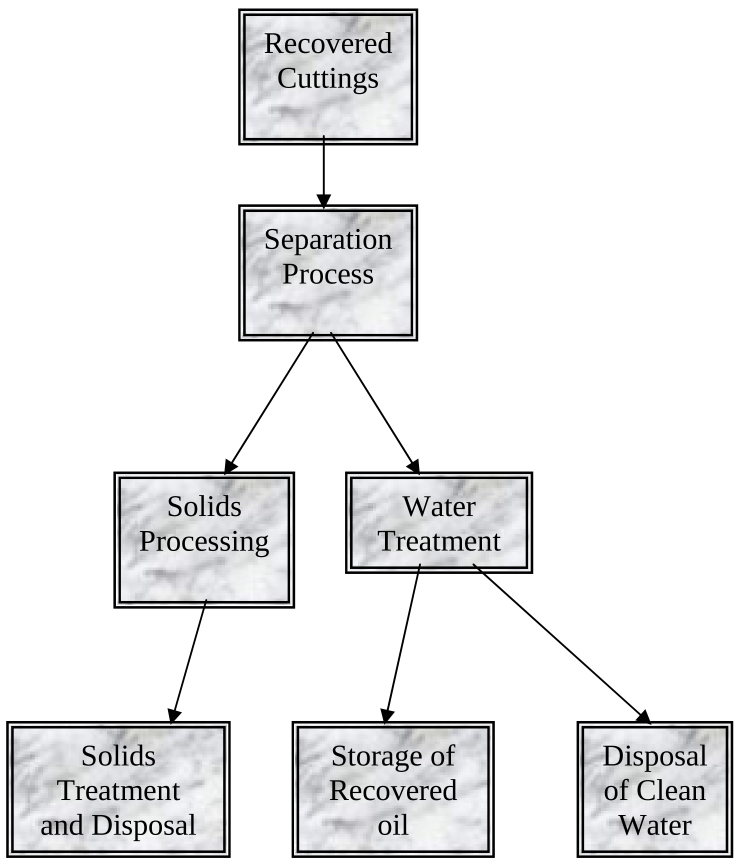


figure D.1

D.2 SOLUTION COMPARISON AND DISCUSSION

As with every aspect of the removal process, alternative solutions are reviewed and considered in order to ensure that the stakeholders are presented with the ideal solution. This section examines different methods of obtaining safe, clean and efficient disposal of the collected drill cuttings while ensuring minimal environmental pollution and damage.

The safe disposal of drill cuttings has been studied in great detail. As of 2000, no oil based cuttings containing oil concentrations of greater than 1% can be discharged into the sea. With OSPAR and oil industry guidelines requiring the removal of pre-existing cuttings piles for decommissioning, several different disposal options have been considered in this report. One option has been chosen and developed to produce an optimal solution.

The options available are:

- Re-inject cuttings and water into disused or purpose found wells
- Separation of fluids and solids, then:
- Dispose of cleaned fluids and solids offshore
- Dispose of cleaned fluids offshore and solids onshore
- Dispose of cleaned solids offshore and liquids onshore
- Dispose of solids and liquids onshore
- Transport slurry onshore then separate and treat for disposal.

Option 1 has primarily been rejected due to environmental issues. Although there is no current legislation against this process, studies are being undertaken to establish whether this is a viable option for the future. Re-injection is a platform based method and would require a working platform or a purpose built platform. This may require inter-field transfer of the cuttings and would be very expensive. At present this option is not a proven solution for the removal of sub-sea piles.

Initial appraisals suggest that option three is the most viable, but after studying some of the pre-treatment stages and types of shipping vessel available it has been rejected. The transportation of an unnecessarily high proportion of liquid would result in a questionable energy balance. Costs would be high and there is the risk of pollution from contaminated material throughout the process until the waste is treated onshore. These factors also rule out other options for onshore treatment. It has therefore been decided to separate the fluids and solids offshore. Seawater is treated and disposed of offshore while the drill cuttings are transported back to shore for treatment and disposal.

D.2.1 Separation and Treatment of Water

The pipeline delivers approximately 90% seawater and 10% sludge. To avoid transporting unnecessary liquid, the seawater is separated from the cuttings and treated before disposal overboard. There are several techniques used to separate water from solids. One basic method is to use a centrifuge, however this will not treat the residue water sufficiently and a separate treatment stage is thus required. Flo Trend Systems, Inc. offer several products for de-watering and mud cleansing. For this purpose their hydrocyclone has been chosen to treat the water before disposal.

D.2.2 Transportation

With offshore treatment chosen as the best method, a transportation method to shore is required. Transportation must be safe and cost-effective as it is a capital intensive stage of the removal process and requires the highest level of human interaction.

One option is a ship carrying several large containment skips. These skips are filled with treated cuttings and when capacity is reached the ship returns to shore for offloading. This offloading is accomplished by the use of cranes. It is found from experience and public statistics that the use of cranes and skips dramatically increases risk to human life and as a result this solution is discarded in favour of a safer alternative.

A variety of other options were considered for this phase. These involved ships with the ability to transfer products to shore using onboard pumps. A trailing suction-hopper was initially considered as it has pump-ashore capabilities and capacities allowing for removal work to be carried out on a rotation basis. This option has been discarded, as these ships are not designed to work at distance greater than 20 miles from shore. Secondly, a product tanker was considered. They have bow loading systems that allow products to be easily pumped on and off the ship. However due to their size, these ships would have to be docked at a port specially equipped for this type of ship.

Supply vessels were chosen as the only feasible option. They have large capacities, pumping capabilities for cargo transfer and can be docked at most ports. Once onboard the seawater is separated from the cuttings and the cuttings are stored in onboard bulk silos.

Once at shore, the cuttings will be transferred into road vehicles and transported to one of three sites situated in the North of Scotland. These sites include

- Aberdeen
- Peterhead
- Lerwick

These sites will clean the cuttings to less than 1 part per measure, which is the required amount for normal landfill. The Aberdeen and Peterhead sites can handle up to 12 000 tonnes per year each whereas the Lerwick site can process 6 tonnes per hour which equates to 50 000 tonnes per year. This is enough to handle our needs operating at approximately 50% downtime.

Due to the locations of oilfields, it may be beneficial to use one special site for treatment over another. For example, if a field is in the far north it would be time and cost effective for the ships to transport cuttings to Lerwick

D.2.3 Onshore Treatment of Cuttings

One of the largest concerns for the disposal of drill cuttings is the environmental effects. To ensure the needs of the individual stakeholders are met it is necessary to treat the cuttings appropriately before disposal. Several methods of treatment are available for this problem.

D.2.4 Landfill

One method is to dispose of the cuttings untreated in a site that accepts them. This has several problems however. Throughput is an issue as these sites are not large and require a great deal of management to prevent toxins leaking from the sites. This can be overcome by building several sites purely for this purpose. This is considered to be the cheapest method for disposal but as there are serious concerns over environmental issues, an alternative is desired.

D.2.5 Bioremediation

Another method similar to that above but environmentally friendlier is that of bioremediation. Bioremediation uses natural organisms to degrade harmful substances to harmless ones. As drilling muds are highly hydrocarbon based they are ideal for such a process. Several organisms may be used for such substances, but rapid results are only found with aerobic bioremediation. This requires oxygen and therefore only the top layers of deposited cuttings would bioremediate unless some sort of system is used to turn over cuttings after a period of time. A recent study has shown that there exist organisms that undertake anaerobic bioremediation of hydrocarbons. This is a very slow process especially at low temperatures. In Alaska, a method of bioventing has been designed which warms up the substance undertaking bioremediation, which also provides oxygen allowing for aerobic bioremediation to take place. This system has greatly accelerated the process.

After consideration, it has been decided not to use bioremediation for treatment since it is so slow. It is however thought that it could be used to detoxify the seabed after the removal of cuttings. This is desirable as the drilling muds seep into the seabed and this reduces any changes in faunal activity to a minimum. Recent studies show that these changes are already detectable up to 6 km away from platforms.

D.2.6 Treatment Methods for Cuttings

For full treatment of drilling muds there are many methods available. These include:

Thermal Desorption:
This separates organic substances from solid materials. The process is very similar to common distillation and separating, differing mainly by the operating conditions and equipment. Several processors within the UK prefer this method.

Distillation
This is a process of distilling volatiles from non-volatiles in several stages through the action of boiling and evaporation. When carried out at lower temperatures, oil can be re-utilised, as it has not been chemically cracked. At higher temperatures, hydrocarbons are cracked forming heavier compounds of hydrocarbons. Old cuttings

and drilling muds will require high temperatures. Technologies for this process include SRD (Soil Recovery Denmark) and TCC (thermo-mechanical cracking and conversion)

Solvent Extraction:
In this process, organic materials in the cuttings are dissolved through mixing with hexane. This mixture is then centrifuged to separate the solids from liquids. The liquids are distilled to separate oil and solvents whilst the solids are heated to remove residual solvents. Using this method allows all materials to be reused.

Stabilisation:
This method is used to prepare unclean cuttings in such a way that they can be safely reused or landfilled. The main process consists of mixing the cuttings with various inert binders to prevent ‘leakage’ and improve the properties for reuse. The cuttings are effectively sealed in inert binder material. The volume of the cuttings increases dramatically with this process.

Incineration:
Here, the cuttings are passed through incineration chambers. This process is mainly used for high toxicity waste as it eradicates most organic substances and chemicals. Fumes from incineration are passed through filters and solid cuttings can be landfilled.

Due to the location of the platforms being decommissioned, it has been decided to use thermal desorption for onshore treatment. The three sites in the North of Scotland which accept cuttings and treat them using this method also offer disposal of the treated cuttings for a cost of approximately £260 per metric tonne.

At the moment there are legislation issues being studied about the use of cleaned drill cuttings as fertiliser and for material for building bricks (x). At the time of writing, the outcome of this is unsure but this may be a convenient disposal method.

D.3 Detailed Design of Offshore Treatment and Transport

D.3.1 Separation of water and cuttings

The first stage of the treatment process is the separation process. This is carried out using shale shakers and centrifuges, in line with current separation practices. Shale shakers keep the solid cuttings on a mesh while allowing the liquid to pass through. They work well if the cuttings are small and make up less than 5% of the mixture. The effectiveness of the shaker depends on its size and the size of the mesh. The mesh size determines the size of particle removed by the screen. A number of screens are used; each placed at an angle for improved performance. The first screen has a slope of 0° and the second uses a slope of 1°. This allows for maximum de-watering due to a longer retention period on the first screen. The next stage is the use of centrifuges. These are more efficient than shale shakers for cuttings removed by dredging. However, the maximum particle size the centrifuges can handle is 20mm. Therefore the shakers will be used to remove particles greater than this size before the mixture is passed to the centrifuge. One centrifuge can process $5m^3$ of cuttings per hour and up to $60m^3$/hr of seawater. It is proposed that as $125m^3$/hr of mixture is recovered, 4 centrifuges in parallel are be used. These centrifuges are able to process $20m^3$ of cuttings and up to $240m^3$ of water per hour. Each centrifuge weighs 11 metric tonnes and has a footprint of 5m x 4m. Therefore the total deck space required is $80m^3$, having a weight of 44 tonnes.

D.3.1.1 Water Treatment

After the separation process, there are two products remaining, the cuttings solids and the water/oil mixture. The oily water is fed through a Hydrocylcone. This unit spins the mixture in a vortex and the water is dissipated through the bottom of the unit. Water is cleaned to acceptable limits for disposal back into the sea. Oil is recovered from the top end. To handle our capacity, a set of 8x4" hydrocyclones is required. This single unit can handle up to 500 gallons per minute, which is approximately $140m^3$ per hour. From this, the oil can be stored for reuse and the water can be pumped back overboard.

D.3.1.2 Solids Treatment

The final product left is the cuttings solids. These will be ground up into powder form for further transportation and disposal. The solids-processing is divided into two sections, the primary crushing and the secondary crushing. The primary crushing is carried out using a jaw crusher, which takes in larger pieces of the cuttings and crushes them to a size of 6mm. A typical jaw crusher has an input space of 24" x 12" and can process 15 to $20m^3$/hr. The secondary treatment is carried out by ball mills. These grind material by rotating a cylinder with steel grinding balls that continually fall back onto the cylinder and onto the material to be ground. A typical ball mill can grind material of about 6mm in size into a finer powder of particle size 20 to 75 microns. For a throughput of $20m^3$/hr, the ball mill has a size of ϕ2.7m x 7m with a weight of about 72 tonnes. The appearance size will be 13.2m long by 5.89m wide by 4.78m tall. The solids from the shale shaker and the centrifuge are collected and fed to the jaw crusher using a screw conveyor. The output from the primary stage is transferred into the ball mill by use of a second screw conveyer. This allows the cuttings to be reduced to a fine powder before being stored on the factory ship.

D.3.1.3 Surface Vessel

A supply vessel was chosen for this part of the project for various reasons. They are primarily designed to transport large amounts of fuel, drilling muds, cement or liquid mud from shore to platforms. They also have open deck space for the transportation of a variety of cargoes from drill pipe to storage tanks. The tanks below deck containing dry bulk are discharged through flexible hoses by compressed air and the tanks containing liquids and drill muds are normally situated alongside pumps used to discharge the contents to the platform. This will make unloading the vessel relatively straightforward and reduce the need for cranes, therefore increasing safety.

In the centre, the ship has a double hull. This is the section of the ship where all liquid cargoes are carried. This is an additional safety feature that will be beneficial for the project in question. As well as this, most supply vessels have bow and stern thrusters, which enable the vessel to make small correcting movements as the pipe travels across the cutting pile. Larger supply vessels are equipped with dynamic positioning systems which allow the vessel to remain at a relatively fixed position without the use of anchors, thus eliminating the possibility of the anchors getting tangled with the riser.

A typical supply vessel in the range of 75 –85m will have two diesel engines, which power the main propulsion thrusters. In addition to this the ship will be equipped with shaft generators and auxiliary generators for use in harbour, and a set of emergency generators. The cargo deck will have a tonnage of around 2500-3000 tonnes with deck strength of 5t/m^2, and a clear area of about 900m^2.

There will be two products remaining after the treatment stage – (1) a dry powder like residue and (2) an oily liquid. These products need to be temporarily stored onboard the factory vessel before being transported to transfer vessel. Supply vessels contain 10 to 12 bulk silos below deck that are used for storing a range of products. These tanks can hold between 1000m^3 to 16,000m^3 depending on the size of the ship. Since the factory ship has two main purposes, the treatment of the recovered material and the storage, a ship with a large aft deck and ample below deck storage is required. A large supply vessel, in the range of 75 – 85m long will be used. Throughout the project, the majority of the below deck tanks will be used to provide temporary storage space, but space will be required for fuel for the ship and water for the crew. Taking this into consideration, the vessel should have storage space below deck amounting to 15,000m^3. These tanks can never be completely emptied as they provide balance and stability for the ship whilst stationary. The liquid bulk will be stored in the central tanks, where the ship is double hulled. From the factory ship, the liquid and dry bulk products will be transferred to a second supply vessel that will then take these products to shore for the final stage of this phase. The factory ship will be unloaded using discharge hose's, which should be of sufficient length to safely transfer cargo between the two vessels. As the attachment of hoses between vessels restricts their ability to manoeuvre it is important that the cargo transfer is carried out in as short a time as is safely possible. Liquid products from the ship tanks are unloaded using pumps at discharge rates of 100- 300m^3/hr and the dry bulk is transferred using compressed air at rates up to 1500m^3/hr at pressures of approximately 100bar.

D.3.1.4 Transportation

The second vessel involved in the topside process is also a supply vessel. This ship is used to bring the treated cuttings back to shore and to re-supply the factory ship with fuel water etc. at regular intervals. For a cuttings pile of volume 20,000m^3 it will take around 100 days to remove all the cuttings. Therefore, assuming that the pipe and the treatment system work at a steady rate, the factory ship will have processed about 7000m^3 per month. The most economical solution would be to have the second supply vessel offload the cargo from the factory ship once every month. The factory ship is capable of storing enough supplies for this length of time and will be restocked every month at the same time as the second vessel collects its cargo. The two ships will sit side by side connected only by discharge hoses, which transfer the cargo. A smaller supply vessel could be used, as it does not require the same clear deck space. A ship in the range of 60m long is the best option as this has about 10,000m^3 of storage. However, almost 3000m^3 will be taken up with new supplies and its own supplies. That leaves 7000m^3 to be split between the dry powder and the oil product recovered. For safety all the liquid should go below deck. The amount of space required below deck for the liquid will depend on the cutting pile in question. To allow for this uncertainty, a number of additional cylindrical bulk storage tanks can be fitted to the aft deck of the vessel. These tanks will hold the excess dry powder.

For a 60m supply vessel, the average deck strength is 5t/m^2, giving a cargo tonnage of about 1200 tonnes. The assumed clear deck area is around 470m^2. By using a number of 6m containers the storage space can be increased. Each tank is 6.09m long, 2.4m wide and 2.6m tall, and can hold 20m^3. The empty weight of each container is about 2 tonnes and the weight of the contents will be about 40 tonnes, giving a total weight of 42 tonnes. The ship will have a total of nine extra containers fixed to its aft deck and will be set out in three rows, each of three containers. Therefore the total deck area for these containers will be 130m^2 with a combined weight of 378 tonnes. This provides additional storage of 180m^3 for the dry powder.

The average volume of cuttings piles depends on their situation in the North Sea. For the smaller piles, that take a shorter time to recover, the factory ship can travel around collecting from these piles before its cargo is transferred. This option is only feasible if the fields are relatively close together. For the large piles, in the range of 30,000m^3 up to 60,000m^3, the process outlined above will still be used. The differences would be that the project time would extent, and the second transfer-to-shore vessel would probably have to make more collection trips.

The third vessel involved in the topside process is the ROV vessel. The purpose of this vessel is to operate both the ROVs used in the recovery project. ROV vessels should be equipped with a deck crane, an ROV frame, ample electrical power supplies on the aft deck and a moon pool to operate the ROVs through. The size of the moon pool in the hull will depend on the vessel used in the project. Ideally, the vessel will have a launch and recovery system along with the moon pool. This will minimise the effects of the vessel motion on the ROV, and will allow better operating conditions in rougher weather conditions. The aim of this feature is to provide safer control over the deployment and recovery of the ROV. ROV vessels can have mini platforms installed, which can be used to deploy a second ROV, as is the case with this project. The larger vessels are also equipped with a helideck, which enables the ship to remain at sea for the whole project while still carrying out crew changes. ROV vessels also have ample space for fuel and other supplies allowing them to stay at sea for periods of longer than 40 days without being resupplied. This vessel will also have deck space for skips containing debris removed from the cuttings piles.

In total three vessels will be used to carry out the topside phase of the recovery process.

D.3.1.5 Unloading, Further Transport and Disposal

Once at the port, the second supply vessel will have to be unloaded so that the cuttings can be taken to their final destination. On most supply vessels, pumps are provided to unload the liquid products. The dry bulk products are unloaded using compressed air. Liquid products from these tanks can be easily discharged using pumps on the ships at rates of $80m^3$/hr – $140m^3$/hr and dry bulk can be discharge at rates as high as $160m^3$/hr at a pressure in the region of 160bar. Due to the amount of material to be unloaded and transported further on land, it would be practical to unload the products directly into dockside silos. If this were not done, a large number of trucks would be required to wait at the dock until the ship is completely emptied. From the silos, the cuttings can then be transferred to trucks, at a steady rate, before going to their final destination.

The cylindrical tanks on deck are fitted with their own discharge valves, in the region of 100mm in diameter, and discharge lines. They can be unloaded using either a gravity discharge system or a pneumatic/gravity combination discharge system. Each tank is also fitted with an air inlet pipe. As the tanks are permanently fixed to the ship, these discharge systems could easily be used to transfer the dry powder and the recovered oil into the silos. Alternatively, the pre-existing pump systems onboard the ship could be used to unload the deck bulk tanks.

From the treatment process, a number of products are left – the treated seawater, which is disposed overboard, the dry powder-like residue and the oily liquid. The cuttings were de-watered offshore so the dry residue can be classed as a solid. However, they will require some form of heat treatment before final disposal to landfill as most of the oil will have remained on the solids after the separation process offshore. Legally this treatment will have to reduce the residual oil content on the cuttings to less than 1%. In the UK there are 50 landfill sites that are capable of taking this type of waste. In total they have the capacity to accept 360,000 tonnes of sludge (i.e. untreated waste) per year and 1.5 million tonnes of solids per year. However, the cuttings will have to spread among a number of sites, therefore it would be preferable for them to be transferred at a steady rate as opposed to in a concentrated amount. Most of the landfill sites are situated in central and southern England. This creates a logistical problem as all the cuttings removal work is carried out in the North Sea. This gives two options, firstly the ship can be docked at a local Scottish port for unloading, and then the dry residue can be transported to a landfill site by either road or rail. Secondly, the supply vessel could dock at a port near one of the landfill sites and the cargo transferred from there. Either of these options is viable.

The same cannot be said for the oil recovered, as this will consist of a variety of chemical products. This means that it cannot be reused in drilling muds. Instead, it will either be sent to a refinery and refined along with crude oil, or it can be burnt as fuel. On the whole, the landfill capacities in the UK are sufficient to deal with the cuttings piles in the North Sea.

APPENDIX E

SAFETY STUDY

E.1 Contingency Plans

Having strived to design an as reliable and safe removal process as possible, it is important to recognise that no system is perfect and that contingency plans are required for an unforeseen event. With a flexible system where practicality has been an important design criteria, unforeseen events need be serious before process efficiency is significantly affected.

Such events can be of a disastrous nature where control of the process is lost completely or even becomes insignificant. It is clear, that in any such event, human life is of greater importance that environmental damage. Thus the removal process must have backup facilities to limit pollution when such events occur, as well as clearing it up when things have settled down. Such disastrous events can for example be extreme weather conditions, surface vessel fire, explosions, collisions or sudden severance of riser pipe. Such instances are indeed very rare, but are real concerns for offshore operators. All personnel and components on the surface vessel will adhere to relevant safety standards, as are practised by all offshore operators. The safety of human life and equipment is hence not a responsibility of the removal process design itself. Instead the process should strive to limit environmental damage when such disastrous events occur.

Pollution will occur mainly as a result of direct ejection of cutting solids, that is a loss of containment. This will occur either intentionally or as a result of leakage. As seen in the detailed design sections, steps have been taken to minimise the risk of involuntary cuttings loss, such as breakage seals and intelligent pump control. However, instances will occur, when cuttings need to be ejected on purpose. This will occur mainly if the main pump stalls or sets out for a prolonged period of time. Depending on the characteristics of the mixture in the riser, it may be necessary to eject the its contents in order to avoid settling inside the pipe. This will be achievable by opening exhaust valves just above the main pump, and will be the operators' decision. If ejection is not performed a solid column, which the pump may not be able to clear, may form inside the riser.

Such ejection of cuttings will necessarily result in dispersion and serious contamination of the water column. It may not be possible to prevent this at seabed level, but facilities must be available on the surface vessel to clean up any oil slicks of moderate size, that may form on the water surface.

It must be stressed that every effort has been made to ensure that such events do not happen during the project lifetime. Our design has been designed to be reliable and practicable under most circumstances in order to ensure that downtime and other problems are kept to a minimum. Nevertheless, backup facilities to clean up resulting pollution will be available and ready at short notice.

E.2 Hazop Studies

As mentioned throughout the report, safety and reliability are important design criteria. Each stage has incorporated specific design solutions to achieve optimal performance while remaining safe and reliable. These have been described in the detailed design.

This section is dedicated to the systematic examination of each stage in the removal process with regard to possible failure modes and their remedy. The results are represented concisely in tables displaying the possible failure mode, its likely cause and its remedy. It is important to note that the solution to the failure is given either as a design step already incorporated in the process, or a simple remedial action required of the operator. The results are shown in tables E1-4.

Problem	Likely Cause	Consequence	Design Solution
Umbilical entanglement	Presence of obstacles, pilot error	Vehicle becomes immobilised	Multiple vehicles for assistance
Primary vehicle becomes stuck	Soft / uneven ground	Vehicle becomes immobilised	Large tracks, assistance from other vehicle
Vehicles entangled	Umbilical caught on structure / other cable	Vehicle becomes immobilised	Assistance from other vehicle
Power supply severed	Umbilical broken	Loss of power and control	Strong, reinforced cable
Pump blocked by debris	Large object entered collection pipe	Severe damage to motor pump	Strong, correctly sized filter on collection head
Collection head blocked	Object stuck on collection filter	Collection stopped	Removal method on collection head
Poor control of collection head	Unstable base / large forces on boom from nozzle	Poor collection efficiency / damage to vehicle	Strong boom, stable base from vehicle
Object dropped onto cuttings pile	Object not held securely by ROV / crane	Suspension of pollutants in water column	Careful work patterns, powerful manipulators
Power failure on vehicle	Electrical / hydraulic fault	Vehicle becomes immobilised	Bring to surface for repair. Assisted by other vehicle / lifted by strong umbilical.

table E.1

Hazard	Process Impact	Environmental Impact	Possible Cause	Remedy
ROV Pump Failure	Vast reduction of suction	Sections of the sediment cloud may escape suction	Hydraulic or power failure. Pump mechanical failure	Provide material protection for hydraulic and power cables. Over engineer pump. In situation withdraw cutting head from pile.
Grid vibration motor malfunction	Grid over clogging. Full loss of suction.	Sediment cloud may escape suction	Hydraulic or power failure. motor mechanical failure	Provide material protection for hydraulic and power cables. Over engineer motor. In situation withdraw cutting head from pile.
Duct selection door motor failure	(1) If stuck on auxiliary chute then operation can not continue. (2) If stuck on main chute then declogging can not commence, thus full suction loss.	(1) None. (2) Sediment cloud may escape suction.	Hydraulic or power failure. motor mechanical failure. Foreign object in duct stopping door movement.	Provide material protection for hydraulic and power cables. Over engineer motor. Over engineer foreign object system.
Cutting head failure	Particle dispersal stopped until fixed.	None	Hydraulic or power failure. motor mechanical failure.	Provide material protection for hydraulic and power cables. Over engineer motor.
Hose to ROV blockage	Suction loss. Build up of matter in hose.	Sediment cloud may escape suction.	Large particles building up in hose. Hose turning too sharply.	Over engineer foreign object system. Design hose to be fairly tense to avoid too steep turning.

table E.2

Hazard	Process Impact	Environmental Impact	Possible Cause	Remedy
Pump Failure	Halted until repaired. Settling of cuttings in riser.	Possible ejection of cuttings from riser. High contamination	Mechanical failure Power failure Breakage of cable	Over-design pump. Design retrieval and repairs to be fast.
Blockage of transport pipe from ROV to pump	Halted until cleared	Probable ejection of cuttings in pipe. High contamination.	High cuttings ratio. Settling due to pump failure. Insufficient vel. High prop. of clay muds.	Restrict length of transport hose. Maintain sufficient flow velocity to avoid. Over-design pump. Make pump reversible
Breakage of Pipe-pump or pipe-ROV links.	Halted until repaired.	Probable loss of cuttings. High contamination.	Loss of control, e.g. extreme current forces on pump module or dragging by surface ship	Insert safety valves at joints to limit discharge. Design joints to break in a controlled manner. Design joints on surface ship to be easily dismantled if necessary. Stringent weather constraints.
Clogging of main riser S-bend.	Efficiency reduced until cleared.	None	Sediment accumulation in bending sections.	Over engineer pump to be capable of increased velocity flushing.
Leakage-Breakage of riser and transport pipe.	Reduced due to leakage. Halted due to breakage.	Serious contamination at leakage. Extreme at breakage	Erosion or fatigue effects weakening the riser material. Difficult to detect due to constant pressure changes.	Difficult to detect leakages. Over-engineer riser to be stronger than necessary. High SF factor.
Insufficient pumping capability (Head).	Reduced or halted until problem is cleared.	Possible ejection of high-density cutting mud. Severe contamination	Reduced power of pump. Extreme high ratio of cuttings pumped. Head provided insufficient for static lift.	Over engineer pump to provide safety factor. Design safety vanes on pump inlet to control cutting/water ratio.
Total blockage of riser	Process Halted	Possible extreme contamination due to ejection.	Pump failure and settling of entire column.	Difficult to avoid. Design pump to be capable of flushing solid blockages. Include safety valve to eject cuttings as they settle.

table E.3

Problem	Likely Cause	Consequence	Design Solution
Pump Blockage on Ship	Seizure of Pump	Process Halted	Use reliable pump Operate at reduced capacity.
Contaminated water shipped overboard	Failure of water hydrocyclones	Severe environmental impact	Two-stage Mud cleaning and water separation system
Muds/Cuttings React during transportation	Mixing and settling	Harmful gases released to atmosphere	Muds separated from cuttings before shipment
Transferring skips – falls and drops	Crane for transferring: either operated wrong or failure of component	Possible death to manual workers, contamination to local surroundings	No skips. Use pumps instead
Spillage of chemical on land	Road-transport vehicle crash	Local contamination – environmental impact	Reduce amount requiring land transport Pre-treat offshore
Polluting in landfill	Not cleaned to high enough standard as solids too large	Environmental impact	Crushing stage on ship.

table E.4

DEPARTMENT of ENGINEERING

This tender document was submitted as part of the MEng Degree 8th May 2002

The A team comprises of:

Dougal Benzie

Allan Bruce

John Clarke

Alasdair Cook

Runi D Joensen

Ailsa Robinson

Ian Williams