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Environmental aspects of on and off-site injection of drill cuttings and produced water

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La Convention pour la protection du milieu marin de l'Atlantique du Nord-Est, dite Convention OSPAR, a été ouverte à la signature à la réunion ministérielle des anciennes Commissions d'Oslo et de Paris, à Paris le 22 septembre 1992. La Convention est entrée en vigueur le 25 mars 1998. La Convention a été ratifiée par l'Allemagne, la Belgique, le Danemark, la Finlande, la France, l'Irlande, l'Islande, le Luxembourg, la Norvège, les Pays-Bas, le Portugal, le Royaume-Uni de Grande Bretagne et d'Irlande du Nord, la Suède et la Suisse et approuvée par la Communauté européenne et l'Espagne.

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The bulk of this paper was adapted from:

A. The Environmental Aspects of Drill Cuttings Re-injection by C W Cottrell, R J Sims and J R Marsden (AEA Technology 16728207_v2.doc), 1999. This original paper also includes descriptions of a series of simulation runs which support the overall conclusions. These have not been included here due to their highly technical nature and length.

B. The other main sources of reference were the OGP (E&P Forum) "Guidelines for produced water injection" and "Guidelines for the Planning of Downhole Injection Programmes" and report RF-98/097 "Disposal of oil-based cuttings" produced under the management of Rogaland Research.

Executive Summary

The disposal of drill cuttings and produced water has become a major concern for operators and environmental controls have been tightened by regulatory authorities. One of the techniques the industry has developed to overcome the disposal problem is to grind up the drill cuttings and then inject them into a subsurface formation where they are likely to remain for the indefinite future. Injection has also been used to dispose of or recycle produced water. The following paper concentrates on drill cuttings but the same principles, with exceptions made in the relevant sections apply to the injection of produced water. Few solutions are without some associated risks and the possible impact on the environment of this disposal route needs to be considered on a case by case basis. With the exception of transport, these risks should be similar for both on and off-site injection operations.

This report details the consideration of these risks and provides an overview of the likely environmental impact.

There are few reported problems associated with the disposal of drill cuttings by re-injection into subterranean formations. Of most concern from the environmental point of view is the contamination of shallow fresh water aquifers or breakthrough to surface, i.e. ground level or seabed. There is little reported evidence of such breakthroughs happening, a result, in part at least, of the target intervals selected being such that the fracture is contained by features such as sand intervals and stress contrasts. At shallow depths (<600m) the minimum stress is often vertical, and in such cases the fracture (if it extends so far) will then propagate horizontally rather than vertically, and consequently not breach shallower zones.

Problems may also arise through the intersection of an induced fracture with an existing well, or the intersection of a new well with a fracture generated by a previous disposal operation. In the former case the casings would generally be expected to be adequate, and if a leak did occur this should be apparent on the well's annulus pressure and could be controlled by ceasing disposal operations and bleeding off any excess pressure. This risk is usually minimised by appropriate selection of the disposal location, e.g. distant with suitable directions for the minimum stress. The risk associated with the penetration of an open disposal fracture when drilling a new well is considered fairly minor. In essence the impact and response would be similar to that for a high pressure water influx (kick) and controlled by normal methods.

There is some risk that the integrity of the disposal well will fail during the operation. Any such failure should quickly be apparent as a discontinuity on the injection pressures, the operation would then cease and the volumes lost would be small. Investigations of the well head (the most environmentally critical item) indicate that wear is likely to be small so the risk in any event is relatively small. Poor quality cement jobs are another area of concern since these can allow channelling of injected material around the well. Careful monitoring of both the cementing operation and subsequent injection pressures is crucial.

One potential problem area is the impact of natural faults. The response in these circumstances is less predictable, and in particular regions of hard rocks should be avoided. Softer rocks which tend to flow would not have the same problem and would be expected to shield disposal intervals.

Although the probability of environmental contamination occurring is small, consideration also needs to be given to the impact of any such contamination. However, chromatographic retention of sensitive substances by clays and shales in the formations is likely to be strong. One risk which is not generally considered is the generation of H_2S in the injected material after disposal. This may result in unexpected levels of H_2S if a disposal fracture is intersected by another well or if other contamination does occur. There are, however, well developed techniques to both avoid and minimise such contamination.

If contamination of a shallow aquifer does occur in the North Sea region it is unlikely to present a significant hazard. The geological and hydrological conditions are such that flow from the point of contamination to land is very unlikely. As in all aspects of potential contamination, each case needs to be

considered on its own merits. The contamination of possible potable water sources would not always be so improbable in locations closer to land or with a different geological situation.

Simulation of the disposal operation for a generic situation representative of the Northern North Sea region confirms the conclusions of previous studies that environmental contamination is unlikely. A conclusion confirmed, at least by those reported, by the results of drill cuttings re-injection operations in the region. In essence, with the particular geology, it is difficult to assign realistic rock mechanical parameters which will allow a fracture to propagate close to seabed. The vertical propagation of the fracture is usually terminated by sand layers with significant leak-off. To obtain fracture growth close to surface, regions of low stress with zero permeability and exceptionally high stiffness are required. This scenario is very unlikely in much of the OSPAR area although it may be possible in certain localities. For this reason the guidance listed below should be followed.

Although environmental contamination from drill cuttings or produced water (re-)injection is considered unlikely in much of the OSPAR area this may not be generally the case. Specific situations should always be investigated before disposal operations commence. It is recommended that in all cases the situation for the proposed disposal well should be simulated and subsequently monitored. Sensible precautions would include:

- Modelling of the situation to obtain an understanding of the main features which will affect the fracture growth and the associated characteristics, and making predictions of injection characteristics for subsequent monitoring and comparison.
- Careful monitoring the quality of any cementing around any well to be used for injection.
- Monitoring the injection parameters (rates and pressures) and comparing with predictions. When deviations are observed operations would need to cease, at least until it was firmly established that the deviation did not indicate undue vertical propagation of the fracture.
- During disposal operations the annulus pressures of nearby wells should be monitored to check for possible fracture intersection with the well. Pressure increase from swelling of reactive clays should also be modelled and monitored.
- A review of the long term considerations should be made so that the risk to potential potable water sources would be established prior to any initiation of the disposal fracturing operations.
- Alternative disposal options for use on a contingency basis should be prepared.

Further detailed guidance can be found in OGP (E&P Forum) Guidelines on injection of both cuttings and produced water [15] [38].

Récapitulatif

L'élimination des déblais de forage et de l'eau de production est devenue une préoccupation de premier plan pour les opérateurs, et la réglementation environnementale a été renforcée par les autorités chargées de tutelle. L'une des techniques que l'industrie a développé pour résoudre le problème de l'élimination consiste à broyer les déblais de forage puis à les injecter dans une formation souterraine où il est probable qu'ils resteront indéfiniment. Bien que le document ci-après soit centré sur les déblais de forage, les mêmes principes, avec les exceptions mentionnées dans les chapitres correspondants, s'appliquent à l'eau de production. Rares sont les solutions qui ne donnent pas lieu à certains risques, et l'impact que cette méthode d'élimination est susceptible d'avoir sur l'environnement devra être considéré au cas par cas. A l'exception du transport, ces risques devraient être les mêmes, que ce soit pour les opérations d'injection sur site ou hors site.

Le présent rapport rend compte en détail de l'étude de ces risques, et donne une vue d'ensemble de l'impact environnemental probable.

Peu de problèmes ont été signalés en ce qui concerne l'élimination des déblais de forage par ré-injection dans les formations souterraines. La chose la plus préoccupante sur le plan de l'environnement tient à la contamination des nappes phréatiques d'eau douce, ou une remontée à la surface, autrement dit soit au niveau du sol, soit au niveau du fond marin. Peu d'indices de ces remontées ont été signalés, ce qui résulte, à tout le moins en partie, du fait que les intervalles cibles sélectionnés étaient tels que la fracture a été contenue par des caractéristiques telles que les distances entre les strates de sable et les contrastes des contraintes. A faible profondeur (<600 m), c'est souvent à la verticale que la plus petite des forces s'exerce, et dans de tels cas, la fracture (si elle s'étend jusque là) se propage ensuite horizontalement et non plus verticalement, et de ce fait même, n'empiète pas sur les zones moins profondes.

Des problèmes peuvent aussi se poser du fait de l'intersection d'une fracture induite avec un puits existant, ou de l'intersection d'un nouveau puits avec une fracture engendrée par une opération d'élimination antérieure. Dans le premier cas, le cuvelage devrait en général être adéquat, et si une fuite se produisait, elle devrait se manifester dans la pression annulaire du puits, et pourrait être combattue par la cessation des opérations d'élimination et en purgeant la pression excédentaire. On minimise en général ce risque en sélectionnant convenablement le lieu de l'élimination, par exemple à l'écart, avec des orientations adéquates et permettant d'obtenir des contraintes minimales. Le risque de pénétration d'une fracture d'élimination ouverte au moment du forage d'un nouveau puits est considéré comme assez faible. En l'essence, l'impact et la réaction seraient semblables à ceux d'un influx d'eau sous haute pression (venue) et seraient contrôlés par des méthodes normales.

Il existe un certain risque que le puits d'élimination perde son intégrité pendant l'opération. Toute défaillance de ce type devrait se manifester rapidement sous la forme d'une discontinuité des pressions d'injection, l'opération étant alors interrompue, les volumes ainsi perdus étant faibles. Les études des têtes de puits (éléments les plus critiques sur le plan de l'environnement) indiquent que l'usure a toutes chances d'être faible, de telle sorte qu'en tout état de cause, le risque est relativement faible. Le fait que la cimentation ne soit pas bien faite constitue une autre préoccupation car un tel état de choses peut conduire à canaliser à la périphérie du puits le matériau ainsi injecté. Une surveillance attentive de l'opération de cimentation ainsi que des pressions d'injection ultérieures est fondamentale.

L'un des problèmes potentiels tient à l'impact des failles naturelles. Dans ces conditions, la réponse est moins prévisible, et il convient en particulier d'éviter les régions de roche dure. Les roches plus tendres tendant à fluer ne posent pas les mêmes problèmes, et devraient faire écran entre les intervalles d'élimination.

Bien que la possibilité d'une contamination environnementale soit faible, il convient néanmoins aussi de considérer l'impact de toute contamination de ce type. Toutefois, la rétention chromatographique des substances sensibles par les argiles et les schistes dans les formations a des chances d'être forte. L'un des

risques qui n'est en général pas pris en compte est la formation de H_2S dans le matériau injecté, après l'élimination. Ce phénomène peut aboutir à des teneurs inattendues en H_2S si la fracture d'élimination est coupée par un autre puits ou si une autre contamination se produit. Il existe toutefois des techniques bien au point pour éviter et minimiser une telle contamination.

Si une nappe phréatique peu profonde est contaminée dans la région de la mer du Nord, il est peu probable qu'elle puisse présenter un danger important. Les conditions géologiques et hydrologiques sont telles qu'il est fort peu probable que l'eau puisse passer du point de contamination à la terre. Dans tous les aspects d'une contamination potentielle, le pour et le contre doivent être considérés au cas par cas. La contamination des sources potentielles d'eau potable n'est pas toujours aussi improbable dans les lieux plus proches de la terre ou dans une situation géologique autre.

La simulation d'une opération d'élimination pour une situation générique représentative de la région septentrionale de la mer du Nord confirme les conclusions des études précédentes, à savoir qu'une contamination de l'environnement est peu probable. Conclusion confirmée, à tout le moins lorsqu'ils ont été communiqués, par les résultats des opérations de ré-injection des déblais de forage effectuées dans la région. En l'essence, dans le cas de la géologie en question, il est difficile d'imputer à la roche des paramètres mécaniques réalistes et de créer ainsi les conditions qui permettraient à une fracture de se propager jusqu'à un point proche du fond marin. La propagation verticale d'une fracture est en général interrompue par les strates de sable, ceci avec une forte pression de fuite. Pour qu'une fracture se développe près de la surface, il faut une région où les contraintes sont faibles, dont la perméabilité soit nulle et dont la rigidité soit exceptionnelle. Ce scénario est hautement improbable dans une grande partie de la zone d'OSPAR, même s'il est possible à certains endroits. Pour cette raison, il conviendrait de suivre les indications données ci-après.

Bien qu'une contamination de l'environnement par des déblais de forage ou par de l'eau de production (ré)injectés soit considérée comme peu probable dans une grande partie de la zone OSPAR, cette situation n'est peut-être pas universelle. Les situations particulières devraient toujours faire l'objet d'une étude avant le début des opérations d'élimination. Il est recommandé que dans tous les cas, la situation du puits d'élimination envisagé soit simulée et ultérieurement surveillée. Logiquement, les précautions à prendre seraient notamment les suivantes :

- Modélisation de la situation, pour comprendre les principales caractéristiques qui influeront sur la croissance de la fracture et sur les caractéristiques connexes, et prévoir ainsi les caractéristiques d'injection en vue d'une surveillance et d'une comparaison ultérieures.
- Surveillance attentive de la qualité de toute cimentation autour de tout puits devant servir à l'injection :
    - Surveillance des paramètres de l'injection (taux et pressions) et comparaison avec les prévisions. Lorsque des écarts sont constatés, les opérations doivent être interrompues, à tout le moins jusqu'à ce que l'on soit certain que l'écart n'est pas l'indice d'une propagation verticale inopportune de la fracture.
    - Pendant les opérations d'élimination, les pressions annulaires des puits à proximité devraient être surveillées, afin de s'assurer qu'il n'y a pas d'intersection entre la fracture et l'un des puits. L'augmentation de la pression, due au gonflement des argiles réactives, devrait aussi être modélisée et surveillée.
    - Il conviendrait de procéder à une étude prenant en compte les considérations sur le long terme, de telle sorte que le risque pour les sources potentielles d'eau potable soit établi avant tout démarrage des opérations d'élimination dans des fractures.
    - Il conviendrait de préparer d'autres options d'élimination auxquelles il serait possible de recourir en cas d'imprévu.

On trouvera d'autres indications détaillées dans les Lignes directrices OGP (Forum E&P) relatives à l'injection des déblais de forage et de l'eau de production [15] [38].

1. Introduction

1. The disposal of drill cuttings and produced water has become a major concern for operators and environmental controls have been tightened by regulatory authorities. One of the techniques the industry has developed to overcome the disposal problem is to inject drill cuttings as ground up material into a subsurface formation where it is likely to remain for the indefinite future. Injection has also been used to dispose or recycle produced water. The following paper concentrates on drill cuttings but the same principles, with the exceptions referred to in the appropriate section applying to injection of produced water. Few solutions are without some associated risks and the possible impact on the environment of this disposal route needs to be considered. The risks to be considered are associated with:

- the disposal operation:
  - Fracture growth to surface or into and contamination of shallow fresh water aquifers
  - Communication of the induced fracture with existing wells in the field
  - Well integrity
  - Fault re-activation
- subsequent to completion of the disposal:
  - Effectiveness of sealing the injection point
  - Impact of changes in fracture dimensions
  - New wells drilling through fracture containing drill cuttings material
  - Long term interaction of injected chemicals and the formation

2. This report details the consideration of these risks and provides an overview of the likely environmental impact.

2. Conclusions

3. There are few reported problems associated with the disposal of drill cuttings by re-injection into subterranean formations. From the environmental point of view, the most concern is the contamination of shallow fresh water aquifers or breakthrough to surface, i.e. ground level or seabed. There is little reported evidence of such breakthroughs happening, a result, in part at least, of the selection of the target intervals being such that the fracture is contained by features such as sand intervals and stress contrasts. At shallow depths (<600m) the minimum stress is often vertical, in such cases the fracture (if it extends so far) will then propagate horizontally rather than vertically and consequently not breach shallower zones.

4. Problems may also arise through the intersection of an induced fracture with an existing well or the intersection of a new well with a fracture generated by a previous disposal operation. In the former case the casings would generally be expected to be adequate, if a leak did occur this should be apparent on the well's annulus pressure and could be controlled by ceasing disposal operations and bleeding off any excess pressure. This risk is usually minimised by appropriate selection of the disposal location, e.g. distant with suitable directions for the minimum stress. The risk associated with the penetration of an open disposal fracture when drilling a new well is considered fairly minor. In essence, the impact and response would be similar to that for a high pressure water influx (kick) and controlled by normal methods.

5. There is some risk that the integrity of the disposal well will fail during the operation. Any such failure should quickly be apparent as a discontinuity on the injection pressures, the operation would then cease and the volumes lost small. Investigations of the well head (the most environmentally critical item) indicate that wear is likely to be small so the risk in any event is relatively small. The quality of cementing is

crucial, as it is for normal producing wells, and there is at least one report of a leak of injected material resulting from a poor cement job.

6. One potential problem area is the impact of natural faults. The response in these circumstances is less predictable, and in particular regions of hard rocks should be avoided. Softer rocks which tend to flow would not have the same problem and would be expected to shield disposal intervals.

7. Although the probability of environmental contamination of seawater and breakthrough or migration of the cuttings slurry or parts of it to surface, i. e. ground level or seabed is small, consideration also needs to be given to the impact of any such contamination, as the material disposed could contain a wide range of oilfield chemicals, although primarily mud components, as well as the drill cuttings. However, chromatographic retention of sensitive substances by clays and shales in the formations is likely to be strong. One risk which is not generally considered is the generation of H_2S in the injected material after disposal. This may result in unexpected levels of H_2S if a disposal fracture is intersected by another well or if other contamination does occur. There are, however, well-developed techniques to both avoid and minimise such contamination.

8. If contamination of a shallow aquifer does occur in the North Sea region it is unlikely to present a significant hazard. The geological and hydrological conditions are such that flow from the point of contamination to land is very unlikely. As in all aspects of potential contamination, each case needs to be considered on its own merits. The contamination of possible potable water sources would not always be so improbable in locations closer to land or with a different geological situation.

9. Simulation of the disposal operation for a generic situation representative of the Northern North Sea region confirms the conclusions of previous studies that environmental contamination is unlikely. A conclusion confirmed, at least by those reported, by the results of drill cuttings re-injection operations in the region. In essence, with the particular geology, it is difficult to assign realistic rock mechanical parameters which will allow a fracture to propagate close to seabed. The vertical propagation of the fracture is usually terminated by sand layers with significant leak-off. To obtain fracture growth close to surface, regions of low stress with zero permeability and exceptionally high stiffness are required. This scenario is very unlikely in much of the OSPAR area although it may be possible in certain localities. For this reason the guidance listed below should be followed.

3. Recommendations

10. Although environmental contamination from drill cuttings or produced water (re-)injection is considered unlikely in much of the OSPAR area this may not be generally the case. Specific situations should always be investigated before disposal operations commence. It is recommended that in all cases the situation for the proposed disposal well should be simulated and subsequently monitored. Sensible precautions would include:

- Modelling of the situation to obtain an understanding of the main features which will affect the fracture growth and the associated characteristics, and making predictions of injection characteristics for subsequent monitoring and comparison.
- Monitoring the injection parameters (rates and pressures) and comparing with predictions. When deviations are observed operations would need to cease, at least until it was firmly established that the deviation did not indicate undue vertical propagation of the fracture.
- During disposal operations the annulus pressures of nearby wells should be monitored to check for possible fracture intersection with the well. Pressure increase from swelling of reactive clays should also be modelled and monitored.
- A review of the long term considerations should be made so that the risk to potential potable water sources would be established prior to any initiation of the disposal fracturing operations.
- Alternative disposal options for use on a contingency basis should be prepared.

11. Further detailed guidance can be found in OGP (E&P Forum) Guidelines on injection of both cuttings and produced water [15] [38].

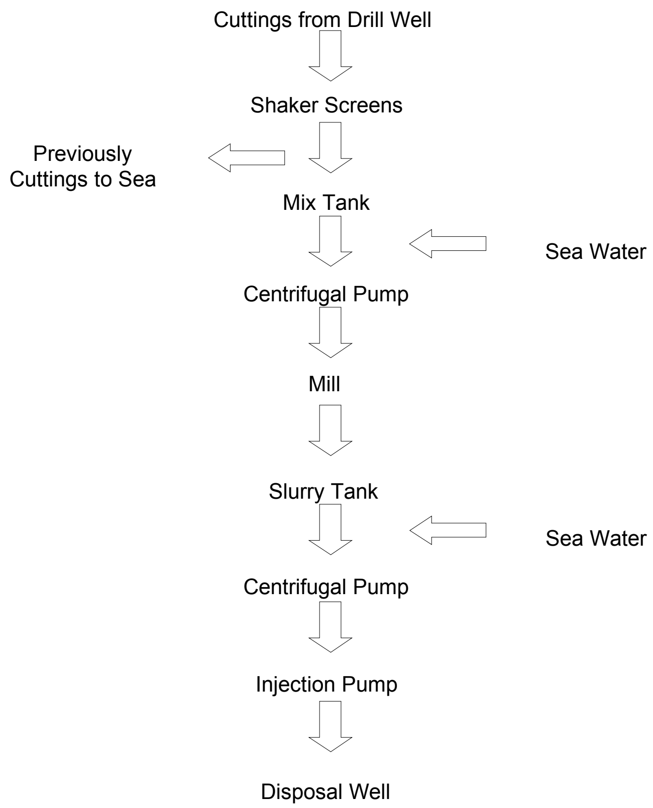
4. Operational and technical aspects of drill cuttings re-injection

4.1 Background

12. The re-injection of drill cuttings was initiated in Alaska [1] and [2] as a cost effective option to comply with environmental regulations relating to their disposal. Subsequently the procedure was adopted in the Gulf of Mexico [3] and other environmentally sensitive regions including the North Sea [4-9] and the Mediterranean [10].
The literature includes considerations of the potential risks and their impact, as well as reporting the operations and the effectiveness of the implementation.

13. An example of cuttings re-injection (CRI) is the pilot process introduced in Shell Expro's Brent field in 1994 [11]. An outline of the process is shown in Figure 1. The cuttings discharged from the shale shakers are fed into a slurrification unit where an initial cuttings slurry is formed by the addition of sea water. This slurry is pumped to the grinding unit. The cuttings are ground to the required specification and then injected into the disposal well.

Figure 1. Brent Alpha/Delta CRI Process [11].



14. Clearly any material that has been trapped or retained by the drill cuttings will be processed and ultimately injected along with the ground drill cuttings.

15. The cuttings are injected either through tubing to an open formation at the base of a well or down a casing annulus which has an appropriate interval which is un-cemented between the two casing shoes. The

design for any particular implementation will depend on the target formation, injection volumes, well flexibility (‘dedicated’, position), casing strengths, etc. In each case the design/planning needs to, and generally has, taken account of possible impacts on the environment.

Fracture growth into and contamination of shallow fresh water aquifers

16. The main environmental concern is the potential for breaching the surface (seabed) or the introduction of contaminants to fresh water aquifers, particularly if these are shallow and might be used as a source of potable water or for agricultural applications. The concern relates to the fracture growth, particularly vertically, from the injection interval. In general the contamination of such aquifers distant offshore is of less concern as the aquifers are unlikely to be used as potable sources. A view would still need to be taken as to whether there is flow in these formations which might result in production of the contaminants on shore at a much later date.

17. This fracture growth depends on a number of factors, primarily, the in-situ stress distribution, Young’s Modulus, Poisson’s ratio, injection volumes, injection rates and the formation lithology. A number of (3D/pseudo 3D) rock mechanics codes exist which have been used to predict the likely propagation of induced fractures. The predictions, however, are dependent on the parameters indicated above, which are often not well known. However, sensitivities are generally carried out covering a wide range of values and the planned implementations generally take account of the most pessimistic scenarios.

4.2.1 In-situ stress distribution

18. Ideally a low stress interval bounded above and below by high stress zones is most desirable for the cuttings disposal. However, such situations are dependent upon nature and their absence does not necessarily preclude a successful implementation without excessive upward growth to the surface or a shallow aquifer. Depending on the injection volume, the vertical growth of the fracture may still not approach any prohibited regions.

19. If a sandstone is selected as the target horizon then it can also be possible to induce a low stress region by cooling the formation by the injection of cold water ahead of the disposal.

20. At shallow depths (600m) the minimum stress direction is often vertical, in which case the fracture will propagate horizontally rather than vertically, consequently reducing the risk of breaching the surface or contaminating a shallow aquifer [11, 12].

4.2.2 Characteristics of Target Strata (Lithology impact)

21. Cuttings injection is commonly to a clay/shale or sandstone formation. These formations can have quite different effects on the fracture propagation.

Clays/shales:

22. Injection into clays/shales will generally result in minimal fluid leak-off and the fate of the cuttings slurry is dependent upon chemical reaction/interaction with the surrounding clays. In the North Sea the Tertiary shales are usually reactive with water based fluids, over time the water carrying fluid reacts with the swelling clays (refer Sections 4.4 and 5).

23. Sand layers can act as effective barriers to vertical propagation of the fracture in a clay/shale formation when the clay/shale formation is the target repository for the injected material. When the fracture initially penetrates the sand layer, leak off of the liquid occurs leaving a filter cake/dehydrated slurry which restricts further flow and plugs the fracture so that the fracture will extend in a different direction, e.g. laterally underneath the sand. Every time the fracture tries to penetrate the sand the same screen out effect will occur, providing an effective block to vertical propagation [6]. The effectiveness of the block is

dependent to some extent upon the thickness of the sands. Very thin sands can be penetrated by the fracture so that vertical migration could then continue. However, even then continued fluid loss at the sand will increase the pressure drop across the sand interval and promote lateral extension of the fracture. The effectiveness of the screen out is enhanced by incorporating larger particle sizes in the slurry so that the screen out is rapid when the fracture hits a permeable (sand) interval [13]. Laboratory data reported in [7] supports the screen out theory for when the fracture penetrates a permeable sand.

24. In these circumstances the whole injected volume will need to be contained within the induced fracture network in the clay/shale and the fractures will tend to be extensive.

Sandstone:

25. In a permeable sandstone, high leak off and dehydration of the slurry will result [4, 12]. In these circumstances small particle sizes are incorporated in the slurry to minimise the rate of fluid loss and filter cake build-up, and the risk of screen out. Providing screen out is avoided (and injection blocked) then the induced fracture needs only to contain a portion of the liquid as well as the solids. The fracture is likely to be shorter and thicker than those generated in low permeability clay/shale formations. As a result the fracture is less likely to break out of the injection zone.

26. Alternating sand shale stratigraphy can provide a strong impairment to vertical fracture growth. Because of differences in mechanical properties the sand zones will expand more than the shales, leading to shearing and slip at the sand-shale interfaces. Climbing fractures will tend to flatten and migrate along the planes of weakness [12].

4.3 Communication of the induced fracture with existing wells in the field

27. The induced fractures can be, and usually are, laterally very extensive. Consequently there is always some chance that the fracture will intersect the well track of an existing well. The main risk here is that the fracture/well intersection is at an open annulus - not that unrealistic if the configuration of the disposal well is typical of that of the standard well in the field. The impact of such an intersection is that the annular pressure will increase to the fluid fracturing pressure, partially compensated by any fluid head in the annulus. It would generally be expected that the casings would be strong enough to withstand the pressure (unless special casings were used in the disposal well), but in any case the capability of the casings to withstand the pressure would need to be checked. The main risk is associated with the high pressure on the annulus at the well head. When conducting a cuttings disposal operation the annular pressures of existing wells would need to be regularly monitored. If a significant pressure increase was observed in any well then its correlation with the disposal well injection should be checked and, if confirmed, injection halted. The annular pressure can then be bled off once the fracture closes with the absence of the injection pressure. A leak in one of the casings near surface or at the well head would cause environmental contamination of the sea or a shallow formation and needs to be avoided. The quality of cementing is crucial, as it is for normal producing wells, and there is at least one report of a leak of injected material resulting from a poor cement job.

28. Operators have tried to minimise the risk of intersection with another well by generally choosing a disposal well on the fringes and one where the fracture propagation is in a direction which is not likely to be towards one of the existing wells in the field [14]. An alternative is to inject deep where wells are more distant from each other [5].

4.4 Intersection of new wells with fractures containing cuttings

29. Concern regarding the penetration of an open fracture by a new well is generally considered to be fairly minor [6]. Fluid pressure would at most be of the order of the overburden gradient, although this could be significantly higher than the mud weight and there could be some inflow. However, the influx would be of limited volume, although the initial rate could be quite high, as the disposal fracture would start to close in the region of pressure relief, i.e. the intersection at the well bore. After an initial influx the fracture will close. Long-term effects will be small as the casings to be used would be similar to those used in the disposal well for which it was deemed to be safe.

30. Also, when injecting just into shales the fluid leak-off is minimal and the fate of the cuttings slurry is dependent upon the chemical reaction/interaction with the surrounding shale. The Tertiary shales in the North Sea are usually reactive with water based fluids, over time the water carrying fluid reacts with the swelling clays with the slurry becoming increasingly more viscous (and dehydrated) within the fracture. The ‘swollen’ clay region adjacent to the fracture will be localised. The net result is that the clay will be soft and the slurry will be effectively solid, consequently intersection by a subsequent well can be expected to fairly trouble free. The worst case is likely to be a tight spot in the well where the already softened clays have squeezed into the well bore [4].

31. In the case of sands the main impact of the cuttings disposal will be a general increase in the fluid pressure, the ground up cuttings being dehydrated and effectively solid. Unless the sand is of very limited volume the increase in fluid pressure will be small and consequently there will be minor, if any, effect on the pressures likely to be experienced when drilling a new well. An aspect not previously considered is that H_2S could be associated with any inflow as a result of microbial activity on the injected material in the fracture or formation (refer Section 5.7).

4.5 Well integrity

32. If a well bore fails during the disposal operation then there could be some contamination of the sea (if close to the wellhead) or shallow aquifers (depending on the depth of the failure). Any contamination should be minor as any such failure would be expected to have an associated discontinuity in injection pressure, at which time the disposal process should be suspended until the cause of the change was established. The volumes lost in these circumstances should be small.

33. The main concern regarding the integrity of the disposal well is the effect of erosion on the well head (where velocities are highest) and casings. Experiments have been reported which indicate that erosion of the wellhead is relatively minor providing injection rates (velocities) are constrained, after injection of 38 000 bbls at 5 bpm the erosion caused less than 10% loss of the nominal wall thickness [8], or only localised polishing after 13 000 bbls [9]. These experimental results are supported by theoretical calculations [6]. The safety margin considered in the design of wellhead and casing equipment is substantially larger than this.

4.6 Local Faults/Fractures

34. The proximity of faults close to the injection/disposal zone has the potential for serious problems [**15**].

- The local stress regime could be distorted as a result of the historic tectonic activity.
- The faults could provide conduits for the waste material to flow away from the selected zone and potentially contaminate shallower aquifers or even break through to seabed.
- The fault(s) could be reactivated by the fracturing pressures associated with drill cuttings re-injection with potential consequences relating to any induced local tectonic movements.

35. Monitoring of the injection pressure should provide an indication of changes in the local stress regime away from the well or if the fault is acting as a conduit for the injected material. In those cases the response would need to be analysed and, if necessary, injection terminated. If a fault was reactivated the impact might be more dramatic and this injection near such faults should be avoided.

36. In general a faulted region of relatively hard rocks should be avoided for the cuttings disposal operation. Softer rocks which tend to flow, e.g. clays, salt, would not have the same problem and would be expected to shield disposal intervals, or in the case of the clays be potential target zones. As always, case-by-case modelling is essential before injection commences.

37. On the other hand the presence of natural fractures and vugs within the target zone (particularly a tight interval) is likely to be advantageous. The cuttings slurry would move through the fracture network as a viscous fluid, displacing the in-situ fluid ahead of it. The fluid would stay in the target zone with pressures reflecting fluid dynamics rather than fracturing requirements.

5. Environmental Management

38. Residual materials from drilling and completion operations consist mainly of drill cuttings, drilling fluids and completion fluids. All processes involved in disposal or recycling of these residual materials will have an environmental impact. These impacts may in some cases be harmful for the environment and in other cases insignificant.

39. The successful completion of drilling an oil well depends to a large extent on the properties of the drilling fluid. The properties of the drilling fluid are controlled by the many additives which are used, many to tailor the drilling mud to a given application. Consequently there are a multitude of materials which are used in drilling muds. Almost all of these materials will adhere to drill cuttings used for re-injection. This section considers the environmental management and impact of potential interactions between re-injected cuttings and associated materials with the rock and fluids of the formation into which injection occurs. References [16] and [17] discuss the various properties and uses of drilling fluids as well as reviewing the sources of many of the components.

40. There are few reported problems associated with the disposal of drill cuttings by injection into subterranean formations. From the environmental point of view the concern is the potential contamination of shallow fresh water aquifers or breakthrough to surface, i.e. ground level or seabed. There is little reported evidence of such breakthroughs happening, a result, in part at least, of the selection of the target zones being such that the fracture is contained by features such as sand intervals and stress contrasts. In the United States, the EPA regulates injection taking into account factors such as the industrial activity producing the injected material, the location of the well and the type of material to be injected. In the Netherlands produced water has been injected for disposal onshore since 1970, in depleted gas reservoirs only, where geological and reservoir properties (e.g. presence of a cap rock, fracture behaviour) are well known in order to ensure confinement and containment. Where there is any doubt or uncertainty as to the geological conditions in the receiving reservoir a "mini-fracture" may be made to validate the injection model

41. Negative environmental impacts associated with injection appear to be minor, and research conducted indicates that the risk of breakthrough to the surface – i.e. the major concern with injection – to be minimal. The major potential drawback to offsite injection is that injected drill cuttings might leave an injection zone that is not under direct control of the waste producer and come in contact with ground water or sea water.

42. Environmentally, cuttings injection may be considered in many cases to be the preferred solution. Although emissions of combustion products from the introduction of heavy and sophisticated equipment on the rigs do lead to an impact these are little different from the impact associated with onshore recycling. As discussed below, the latter have additional problems associated with disposal of contaminated water and solids. An additional benefit from injection may be that it helps combat the subsidence which has been observed at some production sites.

5.1 Drilling fluid components

43. Drilling fluids are complex mixes often formulated to meet the demands of the well to be drilled. They are normally classified by the base fluid used: water for water based muds; oil for oil based muds and a number of different hydrocarbons for synthetic based muds. The base fluid is customised by the addition of other chemicals. Among the most common constituent is a weighting agent to increase the density of the mud in order to control the formation fluid pressure to prevent blowouts. Weighting agents include, *inter alia*, barite and oxides of iron. Other chemicals are added including bentonite clays (to increase viscosity) and organic polymers, thinners and inorganic chemicals. Appendix A contains information on typical mud compositions with a summary of the main components described below.

5.1.1 Materials to increase density.

44. An important function of a drilling mud is the control of formation fluid pressure to prevent blowouts. Any substance that is denser than water and that does not adversely affect the properties of the mud can be added to raise the density. Various finely ground solid materials that have been used to successfully raise the drilling mud density are shown in Table A.1, Appendix A.

5.1.2 Thinners: Mud-conditioning agents

45. Thinners are added to mud to reduce flow resistance and gel development. They also have a number of other properties and so are often referred to as mud conditioning agents. Materials commonly used as thinners for clay-water muds can be broadly classified as:

1. plant tannins
2. polyphosphates
3. lignitic materials
4. lignosulfates

46. Plant tannins, lignitic materials and lignosulfates are all organic compounds. Polyphosphates, such as sodium acid pyrophosphate, sodium tetraphosphate and sodium hexametaphosphate, are inorganic materials which are effective deflocculants and soften hard water by forming soluble complexes with calcium and magnesium ions. Polyphosphates will revert to orthophosphate in water at about 100°C.

5.1.3 Oils

47. Diesel has been used for many years as a component of oil based muds. This practice has been discontinued and replaced first by low toxicity oil (i.e. those with a hydrocarbon fraction containing <0,5% aromatic compounds) and later with synthetic or pseudo oil based muds. Although low tox. oil and synthetics are less toxic than diesel they still do not easily degrade in cuttings piles. Drill cuttings may be contaminated by low tox and synthetic fluids as well as crude oil. Since 1997 the discharge limit of <1% by weight of oil on cuttings has meant that there have been developments in technology to reduce the oil on cuttings, but there will still be oil contained in injected materials.

5.2 Literature survey

48. No reports of studies of the fate of the components which might be included in cuttings related material and the formation were found. There have, however, been a number of studies of the effects of drill cuttings on marine sediments. These studies give an indication of the fate of some of the components of drilling muds in the short term (<1 year). Because there are some similarities in environment between a seabed cuttings pile and injected cuttings material, such as anaerobic conditions and a lack of macrofauna, the results give an indication to the long term fate in a formation.

49. Dow et al [19] carried out a study of the effect of drill cuttings on a model marine sediment system. They used an onshore tank system to model marine sediment contaminated with water, diesel oil, and paraffinic oil based cuttings from offshore drilling installations. The relative environmental impact of the different cuttings was assessed over a 12-month period in terms of changes on hydrocarbon chemistry and sediment microbiology. Dow et al found that the oxidation potentials (Eh) dropped rapidly in the first 5 months in the oil contaminated material with an average difference of 500 mV between oil contaminated and an uncontaminated control. Sulfide levels were found to increase over the first 7 months (80 mg l^{-1} paraffin oil based cuttings) dropping to 10-20 mg l^{-1} after 12 months. They found that that there were many more sulfate reducing bacteria in paraffin and diesel based cuttings than in water based cuttings, although there was little change in the numbers over the last 5 months of the trial. The most active SRB populations in paraffin based oil cuttings may reflect the reduced toxicity of cuttings lower in aromatic hydrocarbons. Dow et al also recorded a more rapid loss of low molecular weight hydrocarbons from both paraffin based and diesel-based cuttings than higher molecular weights. This group carried out a detailed study of the loss of a number of poly-nuclear aromatic hydrocarbons (PNAH) many of which, such as benz(a)anthracene and pyrene, appeared resistant to degradation over the 12 months of the trial. There was no study made of the inorganic components.

50. Sanders and Tibbets [20] sampled drill cutting piles around platforms in the North Sea and concluded that there is a greater degradation of n-alkanes and more SRB activity when low-toxicity oil had been used. It is likely that the aromatic fractions of diesel suppress microbiological activity.

51. Leuterman et al have investigated the concentration, bioavailability and potential for bioaccumulation of trace metals from barites [21]. This group analysed three barite samples for a number of trace metals, Table 5.0-1.1. In Barite 2, zinc (66,4%) and lead (32,8%) were the major components of the contaminants, whereas in Barite 3 lead (96,6%) was the major contaminant, representing approximately 0,02 g g^{-1} of the original barite sample.

Table 5.0-1.1: Percentage contribution of each metal to the total metal loading of each barite sample based on aqua regia digests [21].

Metal	Percentage contribution of each metal to the total metal loading of each barite sample (%)		
	Barite 1	Barite 2	Barite 3
	Medical Grade Barite (for reference)	North Sea Barite (barite with typical metals concentrations)	High Metals Containing Barite
Total metal loadings	<1,9 µg g^{-1}	18 070 µg g^{-1}	22 733 µg g^{-1}
Arsenic	1,7	0,2	<0,01
Cadmium	2,6	0,1	0,02
Chromium	50,3	0,03	0,02
Copper	13,1	0,3	0,1
Lead	10,5	32,8	96,6
Mercury	0,5	0,1	<0,01
Nickel	9,9	0,02	0,03
Zinc	11,5	66,4	3,2

5.3 Environmental Impact

5.3.1. Degradation

52. A summary of the main factors influencing biodegradation of organic matter is listed below [22].

- Chemical structure of the base molecule
- Salinity
- Bacterial count
- Nutrients
- Oxygen
- Light
- Time of exposure
- pH
- Substance concentration
- Temperature

53. While light is not a factor in the degradation of components of cuttings disposed of in a fracture, the impact of the other factors will vary significantly. As solutions move away from the disposal fracture the pH will largely be governed by the natural pH of the water in the formation as this is frequently difficult to alter due to the buffering capacity of the rock. Oxygen levels will fall over time so that the environment becomes fairly rapidly (tens of days) anaerobic. Salinity and the concentration of other substances, both organic and inorganic, will depend upon exchange reactions and adsorption on the rock. Temperature will be governed by the depths of the formations into which the disposal fracture has propagated.

5.3.2 Hydrocarbons

54. Hydrocarbons are generally only degradable under aerobic conditions [22]. Once the hydrocarbon has been injected into a formation, as part of a cuttings re-injection slurry, then the hydrocarbon will be stable because the formation is an anoxic environment. There may be some degradation of the hydrocarbons as a result of co-oxidation in the anoxic environment [23, 20]. Sanders and Tibbetts [20] summarised the microbiological processes occurring in seabed sediments as shown in Figure 2. Similar processes would be expected to occur in a formation after the cuttings injection, although the high initial populations of bacteria that are present in seabed sediments would not be expected.

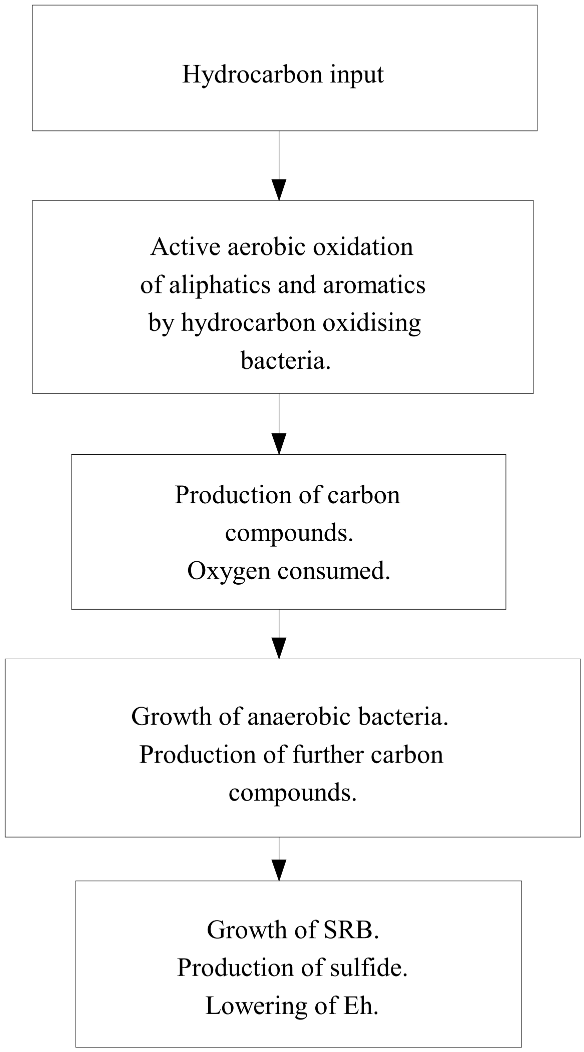


Figure 2. Microbiological Processes Involved in the Degradation of Hydrocarbons in the Seabed Sediment, from Reference [20].

5.3.3 Common inorganic chemicals

55. A large number of inorganic chemicals are used in drilling fluids, see Appendix A. While many of these are readily water soluble and may be lost during the washing of drill cuttings, some will inevitably contaminate the drill cuttings. Those that are the more readily water soluble will dissolve in water passing through the placement fractures and move away into the formation with the water. Some inorganic ions will exchange with ions in the rock in the formation while others will move at a similar speed to the formation water. The re-dissolution of exchanged ions will depend upon a number of factors such as the mineralogy, the pH and ionic strength of the solution and the temperature. There are computer programmes which will model these processes, for example CHEMTARD [24], PHREEQE [25] and HARPHRQ [26], primarily developed to predict the movement of radioactive pollutants in ground water, which have extensive databases, for example CHEMVAL [27] and HATCHES [26].

56. Some of the inorganic chemicals, such as phosphates, will form the nutrient sources to support biodegradation. Sulphate reducing bacteria will produce H_2S from sulphates.

57. In their study on the bioavailability of trace metals from barites, Leuterman et al found that by 60 days some of the trace metals had migrated into the surrounding sediment [21]. Similar processes would result in the metals being released from barites in the fracture which would then move with the ground water. Heavy

metals were found in cuttings waste by Hartley and Watson in their investigation of the cuttings pile around the North West Hutton platform in the North Sea in 1992 [28], Figure 3.

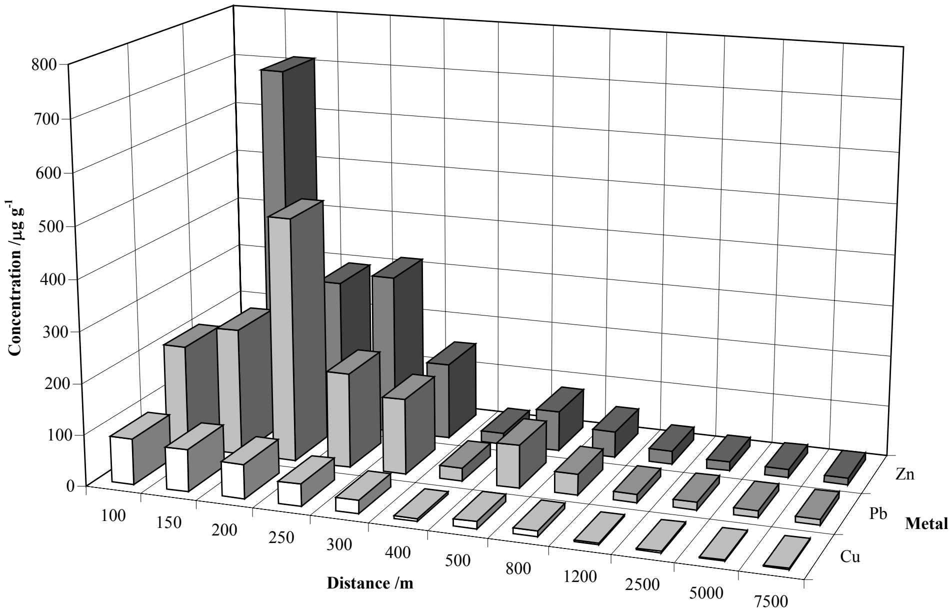


Figure 3. Metals from North West Hutton Drill Cuttings Pile[28].

5.3.4 Lost circulation materials

58. Lost circulation materials are unlikely to move intact far from the fracture in which they are initially placed. They will, however, slowly biodegrade, with the natural materials such as nut shells and fibres acting as a nutrient source and yielding H_2S. There is also likely to be initial aerobic biodegradation yielding small organic molecules which could act as chelating agents for inorganic species which will be present in the injected material.

59. The degradation of the lost circulation materials is also likely to form colloids which are known to assist the transport of inorganic species in groundwater [29, 30]. The colloids are polyelectrolyte biopolymers and play a key role in the migration and retardation of heavy metals in the environment. Their structural, chemical and physical properties depend on their origin, particularly on their precursor substances and the conditions prevailing during their formation. Larger colloids will be retained by filtration in the porous media, depending upon the pore size. The smaller colloids will tend to stabilise inorganic colloids and may travel over long distances through groundwater or formation water movement.

60. Greenfield et al have reviewed the microbiological and chemical degradation of related organic materials during storage of radioactive waste which in many cases occur under similar conditions to that after CRI [31]. Greenfield et al concluded that a number of complexing agents will be generated, especially from cellulose based materials, which may enhance the movement of heavy metals.

5.3.5 Drilling oils

61. The use of oils such as diesel and low tox. oil (<0,5% aromatic compounds) as components of drilling fluids is currently in decline. They have been largely replaced by synthetic based fluids. Esters can be hydrolysed in both acid and alkaline solutions. Acetals are stable in alkaline solution but rapidly hydrolyse at low pH. In both cases smaller, water soluble molecules are formed, which will be more easily biodegraded in the presence of oxygen. The smaller water soluble molecules are also likely to aid the solution and transport of inorganic species. Biodegradation rates for all of these fluids in cuttings piles in North Sea conditions are thought to be very low.

62. There are significant quantities of diesel and low tox-oil contaminated drill cuttings around the base of platforms in the North Sea, estimated to be close to 8000 m^3 [22] or 50 000t [32]. This material could be recovered, and processed for injection, as this would reduce the potential liability for industry or government presented by an abandoned cuttings pile [32]. The aromatic content, in particular the PNAHs, which will still be present in the cuttings on the seabed [19], even after many years, may inhibit the growth of bacteria in the formation after CRI.

5.4 Mobility of components

63. The long term mobility of the many components injected during CRI can only be assessed with a detailed knowledge of the formation and its mineralogy. Fractures may lead to a rapid movement of the components, whereas interaction of the components with the rock minerals may lead to slow chromatographic separation. Predictions of the mobility could be assessed using one of the number of computer models which have been developed to predict the movement of organic and inorganic components through rocks arising from storage of radioactive waste. The MIGRATION conferences [33] have included a large number of papers on the movement of inorganic and organic compounds through the natural geologic environment, discussion of computer models and associated data bases.

64. The possibility of drilling mud components, once they have been disposed of by surface disposal, contaminating surface streams and ground water up to a considerable depth (>500 ft) has been recognised in the USA [34]. As a consequence, restrictions have been placed on the use of oil based drilling muds and chrome lignosulfonate. There is therefore the possibility of material placed at <500 ft by CRI contaminating groundwater.

5.5 Summary of Environmental Impact

65. One of the major possible routes for the cuttings material reaching the surface environment is by propagation of the placement fractures to the surface so that material, either in suspension or solution, reaches the seabed. This has not happened for subsea CRI projects to date such as in Brent [11] or Sfax (Tunisia) [10, 35]. Should the CRI material reach the seabed, studies which have been carried out to date will give an indication as to the fate of the materials and resulting impact on the environment, for example references [21] and [28].

66. Fractures could also propagate to adjacent formations with groundwater connectivity. This would result in water soluble components from CRI appearing in groundwater. The majority of these components would be inorganic species, which may include heavy metals, the propagation of which may be enhanced by the presence of organic degradation products from the many organic components [36].

67. It should also be considered that fractures could propagate to adjacent wells. This may result in contamination of produced water with the drilling mud components.

68. Propagating fractures may result in transport of H_2S, resulting from biodegradation of the organic components of the CRI mixture, reaching the seabed, adjacent wells or aquifers.

69. In the future there is also the possibility of drilling through the formation which has been used for CRI, especially if long reach or deviated drilling had been used for the CRI well. This may not have an environmental impact, but may unexpectedly produce quantities of H_2S.

5.6 Long Term/Geological Considerations

70. Drill cuttings reinjection in the Brent area is considered to have very low potential (<1 ppm) for contamination of onshore aquifers. The following points lead to this conclusion:

- Most aquifers used for water supply in the UK are unconfined, and sea level is essentially the sink for these aquifers. In some areas in other countries (e.g. Texas Gulf Coast), meteoric waters (i.e. rainwaters) are known to penetrate to considerable depths, up to at least 2 km.
- The reservoir stratigraphy of the Brent area does not correlate to an onshore succession. Flow up faults is a more likely route of escape for any fluids related to drill cuttings reinjection. At present, the North Viking Graben may be regarded as a generally stable tectonic regime, and fracture propagation from reservoir depths to the sea-bed is very unlikely in a time scale of 100 000 years. Such an event would require a major change in regional tectonism, at rates far higher than those currently known to operate from measurements of plate motion, mantle plume development etc.
- Chromatographic retention of sensitive substances is likely to be strong in intervening shales/clay rich rocks.
- Over a 100 miles, a flow rate of 1 ft/day corresponds to a time of over 1400 years. For a one darcy rock this requires a pressure differential of 0,04 psi/ft, or a total of 20 000 psi. Obviously such a pressure differential is unrealistic - and takes no account of the huge volumes associated with such a flow. A more realistic but still large figure of 200 psi differential extends the time period to more than 140 000 years, even if continuous flow paths did exist and any pressure differential was in the 'right' direction. Consequently contamination from flow is likely to be in the million years for the distances from Brent to shore- if it occurs at all.

71. However, these observations are substantially restricted to the Brent scenario (distance and geological correlation). For fields which are closer to shore, e.g. Beatrice, the risk factors would normally be expected to be higher (though still very low). However, in the Beatrice specific case, although relative close to land (~15 miles) with equivalent lithological outcrops, it is effectively cut off from fluid connectivity by substantial faults. Also, the logic invoked for drill cuttings reinjection not affecting onshore aquifers would be very different in a hydrothermally or tectonically active zone, though these do not currently exist to any significant extent in the UKCS.

6. Environmental Aspects of Produced Water (re)-injection

72. Experience to date has shown that re-injecting produced water is an attractive, environmentally-sound solution to water disposal with experience gained in the Gulf of Mexico, Alaska, the North Sea and onshore worldwide. Overall the issues are similar to those for the (re)-injection of cuttings, the main difference is the target strata. Cuttings are normally injected into reservoirs that are above the producing reservoir, whereas produced water disposal is generally into the producing reservoir. There have been limited trials with injection in shallower reservoirs but these have only had mixed success to date.

73. As disposal is generally into the producing reservoir, the opportunity for escape, either into aquifers or to the surface is extremely limited. This, and other issues associated with produced water (re)-injection, is currently the subject of an International Joint Industry Project (www.terratek.com).

74. A significant difference from the injection of cuttings is that injected water may be used to stimulate production with the injected fluid being used to maintain reservoir pressure. This technique is used widely. A reduction of oil into the sea may be achieved by this method. Some other differences between the injection of water and cuttings are listed below:

- Produced water is normally injected into permeable horizons while cuttings are also injected into clay/shale formations.

- For the injection of cuttings it is necessary to fracture the target strata, while produced water usually is injected into a permeable horizon without fracturing.
- So usually the formation above of the target strata of a cuttings injection is a permeable horizon, for example sandstone, while the barrier of permeable strata, usually used for produced water, are clays with low permeability.
- The consistency of cuttings slurry and produced water is different because cuttings slurry contains grain-size solids while produced water is liquid.
- For the injection of produced water, in most cases it is not necessary to fracture the target strata. In these cases fracturing should be avoided.

7. Alternative Means of Disposal

7.1 Overboard

75. Following OSPAR Decision 2000/3 the discharge of cuttings contaminated with SBM will effectively be banned. Discharge of cuttings contaminated with water based muds will, however, remain an option for the foreseeable future.

7.2 Skip and Ship to Shore

76. There has been a substantial growth in the skipping and shipping to shore of cuttings contaminated with SBM. This trend will continue, with a likely similar growth in the disposal of OBM contaminated cuttings. This option will probably remain the most common means of disposal for oil contaminated cuttings. However, it is not without its problems. An estimate has been made of the relative energy balance for this option versus injection and the results are summarised in the table below [37]. These numbers include emissions from fuel usage in the transport of the cuttings. In some cases an argument might be made that supply boats returning to shore may otherwise be empty and so no added emissions burden is generated if these vessels are used to transport cuttings. There are other occasions, as when drilling extended reach High Temperature and Pressure wells, when cuttings are produced at such a rate even in narrower hole sections as to necessitate extra supply vessel sailings.

Table 0-1 Examples of Estimated total CO_2 Emissions to Air from Different Disposal Options for Contaminated Cuttings [37]

Process	**Emissions (kg/tonne)**
Seabed deposition	Insignificant
Cuttings reinjection	18
Soil cultivation	120
Land treatment with distillation	180
Land treatment with burning	475

77. It has been estimated that approximately 160 000 tonnes of OBM/SBM contaminated cuttings are generated annually from oil and gas operations in the North Sea[1]. If there was a requirement to bring all this material ashore then it is likely that this would put a severe strain on landfill sites and will also increase the likelihood of a spill.

[1] Estimate from SEBA. Though this is unconfirmed and subject to annual variation.

7.2.1 Risks involved in transport (including on- and off-loading operations)

78. With all shipping/transport there are associated risks, including spillage and increased risk of accidents resulting from increased transport frequency. The handling of drilling muds currently contributes the largest number of reported spills from offshore drilling operations. The additional handling and transportation required when the OSPAR Decision 00/03 comes into effect may lead to additional spills.

7.2.2 Transport to land vis a vis off-site transportation

79. Land site handling of drilled cuttings requires several operations, including rig site storage and handling (bags or storage tanks), transport to onshore treatment site (sea transport with its associated risks) and onshore treatment (burning and distillation). The CO_2 emissions, and hence energy usage, from land site handling is larger than the emission from injection (Table 6-1). This, and the additional risks from spillage would tend to suggest that land site handling should only be used when there is a possibility of applying some of the material from the treatment plant for re-use/re-cycling potential, or in increasing plant growth through soil cultivation.

8. Off-Site (Re)-Injection

80. Where the cuttings are to be injected into a well at the platform, there would be essentially no transportation of the cuttings. If the injection well is in a location remote from the well then the cuttings will need to be transported to the injection site. The stages involved in this exercise include; storage, loading, transport, off-loading, slurrification (which may also be done prior to loading) and injection.

81. The transportation of cuttings off-site for re-injection would incur no additional significant environmental impacts from the current practice of transporting cuttings to shore for treatment and disposal. There may be some additional risk from the increased number of transfer operations involved in off-site re-injection but these will not be significant. As far as the transportation of cuttings itself, the risks in sending cuttings to onshore or offshore destinations will be similar and emissions will relate directly to the distance travelled.

9. Conclusions from simulation studies

82. In a study undertaken for the DTI, Cottrell *et. al.* (AEA Technology 16728207_v2.doc), 1999 presented results from simulation runs and presented the following conclusions based upon the study of a typical well configuration in a UKCS Brent environment, with the primary window for the cuttings reinjection being at 3,000 ft TVDSS at the top of the Hutton Sand Unit I, immediately beneath an intermediate casing shoe.

- Layer permeability, or leak-off coefficient, plays a dominant role in determining whether a hydraulic fracture containing re-injected cuttings is able to grow upwards through the Hutton Sand Units II, III and IV.
- The presence of tight horizons above the injection window can prevent leak-off and can enable the continued upwards growth into overlying horizons.
- Leak-off controls the growth of the fracture, not only at the onset, but also towards the end of the injection.
- When the areal extent of the fracture within a permeable layer is sufficient so that leak-off approaches the injection rate, the growth of the fracture through the permeable layer is arrested. A small increase in the injected volume might then be accommodated by some downwards and outwards growth and some opening of the fracture aperture within tighter layers.

- Variations in elastic properties of the layers appear to play a much less dominant role in influencing the vertical growth of the fractures, although increased stiffness leads to reduced fracture apertures. Injected volumes might then be accommodated only by increased fracture length.
- In isolation, the occurrence of low in situ stresses in the upper horizons causes negligible differences in fracture apertures, and has no influence on vertical and lateral extents of the fractures.
- Different slurry viscosities appear to result in only marginal differences in fracture growth.
- Fracture toughness appears to play only a minor role in controlling fracture growth.
- Where the horizons overlying the injection window are under conditions of relatively low stress whilst exhibiting zero permeability and exceptionally high stiffnesses, fractures may grow close to surface. However, such a scenario is highly unlikely.
- The capacity for a fracture to approach very close to surface was demonstrated in a number of scenarios, but only under highly unlikely conditions.
- As one approaches close to surface the vertical or overburden stress may become the minimum stress s_3, such that any induced fracture will not propagate in a vertical plane but will turn horizontally. The FRACPRO model is incapable of simulating this phenomena.
- Where the minimum stress s_3 remains horizontal, a significant stress increase in the upper layers might be sufficient to provide a stress barrier against propagation of the fracture. Such a stress increase is characteristic of many soft shallow Tertiary shales and clays.
- Where vertical constraint occurs due to such a stress barrier, growth of the fracture might continue outwards through less stressed formations.
- Different slurry injection rates appeared to result in no significant differences to the ultimate fracture geometries
- No significant differences between fracture geometries were noted when slurry densities were varied.

10. References

[1] Minimisation and Recycling of Drilling Waste on the Alaskan North Slope, J P Schumacher, E Malachosky D M Lantero and P D Hamilton, SPE 20428, *JPT* June 1991, pp 722-729.

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Appendix A

Typical Components of Drilling Fluids

Drilling fluid components

Materials to increase density

An important function of a drilling mud is the control of formation fluid pressure to prevent blowouts. Any substance that is denser than water and that does not adversely affect the properties of the mud can be added to raise the density. Various finely ground solid materials that have been used to successfully raise the drilling mud density are shown in Table A-1.

Table A-1: Materials to increase mud density

Material	Principal component	Specific Gravity	Hardness, (Moh's Scale)
Galena	PbS	7,4-7,7	2,5-2,7
Haematite	Fe_2O_3	4,8-5,3	5,5-6,5
Magnetite	Fe_3O_4	5,0-5,2	5,5-6,5
Iron Oxide	Fe_2O_3	4,7	6
Illmenite	FeO, TiO_2	4,5-5,1	5-6
Barite	$BaSO_4$	4,2-4,5	2,5-3,5
Siderite	$FeCO_3$	3,7-3,9	3,5-4
Celestite	$SrSO_4$	3,7-3,9	3-3,5
Dolomite	$CaCO_3$, $MgCO_3$	2,8-2,9	3,5-4
Calcite	$CaCO_3$	2,6-2,8	3

Minor components in the various materials also need to be taken into account when considering the environmental impact. For example, barite which is virtually insoluble in water (solubility product of 1,05 x 10^{-10} $mols^2/litre^2$), may contain calcium sulfate as gypsum or anhydrite. Sulfide minerals such as pyrite and sphalerite, if present, may undergo oxidation with the formation of soluble iron salts. Some samples of the mineral may contain trace impurities such as cadmium or mercury, see for example Table A-2. Iron oxides may contain surfactants from processing the ore leading to wetting and foaming.

Clays

Bentonite increases the viscosity and decreases fluid loss of freshwater muds in its natural form, and, when modified, performs the same function in water and oil based muds. Bentonite includes any member of the montmorillonite group. The chemical formula can be expressed as 0,33 $Na(Al_{1,07}Mg_{.33}O_3)_{0,4}$ SiO_2. H_2O.

Attapulgus clay

Attapulgus clay is usually called attapulgite, which makes up 80-90% of the commercial product. Montmorillonite and other clays plus quartz, calcite or dolomite make up the remainder. Attapulgite has a fibrous texture. Chemically it is crystalline hydrated magnesium silicate, with partial replacement of magnesium by aluminium, iron and other elements. Its crystalline structure means that it breaks up into numerous needle-like particles upon shearing, with the degree of viscosity dependent on the particle size.

Asbestos

Although clays are the major thickening agent for drilling fluids, asbestos has found limited applications. Asbestos can be added to the water to improved the carrying capacity of the drilling fluid. The principle component of commercial asbestos is chrysotile. The fibrous nature of chrysotile leads to the development of 'brush-heap' structures when it is dispersed in water.

Organic polymers

Organic polymers that are used in drilling fluids may be broadly classified according to their origin and composition. Some polymers such as starch occur naturally, other may be semi-synthetic, such as derivatives of starches and gums. Finally there are the synthetic derivatives, such as the polyacrylates and ethylene oxide polymers.

Starch

Starch is used in drilling mud to reduce filtration. It is subject to fermentation by many micro-organisms (yeast, moulds, bacteria), unless the mud is saturated with salt or the pH is about 12. To stop fermentation biocides, such as paraformaldehyde, are often added. Starch is degraded by heat and agitation. With continued circulation at temperatures of 200°F (93°C) and above, starch breaks down rapidly, leaving shorter chain fragments in solution.

Guar Gum

Guar gum, like starch, is a natural polymer, obtained from the endosperm of seeds of the guar plant. Guar gum is a non-ionic, branched chain polysaccharide. It degrades rapidly above 150°F (65°C). Like starch it is attacked by micro-organisms. Enzymes, normally present in the gum break down the gum with the formation of acidic substances.

Xanthan Gum

Xanthan is a water soluble polysaccharide produced by bacterial action (by *xanthomonas campestris*) on carbohydrates. It is stable to 212°F (100°C). Xanthan gum is also used as a crosslinking agent with chromium compounds.

Sodium Carboxymethylcellulose

Sodium carboxymethylcellulose (CMC) is a water dispersible cellulosic polymer which does not ferment under normal conditions of use. Thermal degradation of CMC is accelerated as temperature approaches 300°F (150°C). At higher pH values CMC is precipitated with calcium and magnesium ions.

Hydroxyethylcellulose

Hydroxyethylcellulose (HEC) is prepared by reacting alkaline cellulose with ethylene oxide. It is typically used up to 275°F (135°C).

Acrylic Polymers

These are a group of synthetic polymers which have a broad range of composition and properties. They may contain varying numbers of amide ($-CONH_2$) and sodium carboxylate groups ($-COONa$).

Alkylene Oxide Polymers

Some surfactant-like polymers such as $C_6H_5O(CH_2CH_2O)_{30}H$ and nonylphenoxyethanol ($C_9H_{19}C_6H_4OCH_2CH_2OH$) have been used with calcium surfactant muds and defoamants respectively.

Thinners: Mud-conditioning agents

Thinners are added to mud to reduce flow resistance and gel development. They also have a number of other properties and so are often referred to as mud conditioning agents. Materials commonly used as thinners for clay-water muds can be broadly classified as:

1. plant tannins
2. polyphosphates

3. lignitic materials
4. lignosulfates

Plant tannins, lignitic materials and lignosulfates are all organic compounds. Polyphosphates, such as sodium acid pyrophosphate, sodium tetraphosphate and sodium hexametaphosphate, are inorganic materials which are effective deflocculants and soften hard water by forming soluble complexes with calcium and magnesium ions. Polyphosphates will revert to orthophosphate in water at about 100°C.

Common inorganic chemicals

Table A. -2: Common Inorganic Chemicals Used in Drilling Fluids

Chemical name	Formula	CAS number	Uses	Typical concentrations
Ammonium (acid) phosphate	$(NH_4)_2HPO_4$	7783-28-0	Used with polyanionic cellulose polymer as a shale inhibitor	2 to 8 lb/bbl
Ammonium bisulfite (as a water solution)	NH_4HSO_3	10192-30-0	Oxygen scavenger to reduce corrosion of iron	
Ammonium sulfite	$(NH_4)_2SO_3.H_2O$	10196-04-0	Oxygen scavenger to reduce corrosion of iron	
Calcium bromide	$CaBr_2$ $CaBr_2.6H_2O$	7789-41-5	To prepare dense salt solutions	
Calcium chloride	$CaCl_2$ $CaCl_2.H_2O$ $CaCl_2.2H_2O$ $CaCl_2.6H_2O$	10043-52-4	Used in hole stabilising oil muds, preparation of dense salt solutions, lowering of freezing point of water muds.	10 to 200 lb/bbl
Calcium hydroxide	$Ca(OH)_2$	1305-62-0	Used in lime muds, high calcium ion muds, and for removal of soluble carbonates.	0,5 to 20 lb/bbl
Calcium oxide	CaO	1305-78-8	used in oil muds for the removal of water used as slaked lime in water muds.	
Calcium sulfate	$CaSO_4$ $CaSO_4.2H_2O$	07778-18-9 10101-41-4	Slightly soluble in water, used as a source of calcium ions in gypsum muds.	2 to 8 lb/bbl
*Chromic chloride	$CrCl_3.6H_2O$	10025-73-7	Used in cross linking xanthan gum.	0,1 to 0,5 lb/bbl
*Chromium potassium sulfate	$CrK(SO_4)_2.12H_2O$	07788-99-0	Used in cross linking xanthan gum.	
Copper carbonate	$CuCO_3.Cu(OH)_2$	12069-69-1	Used as a sulfide scavenger.	
Magnesium chloride	$MgCl_2.6H_2O$	7791-18-6	Added to brine used in drilling carnalite to avoid hole enlargement.	
Magnesium hydroxide	$Mg(OH)_2$	01309-42-8	Used as a buffer, or stabiliser, in acid soluble completion fluids in conjunction with polymers.	
Magnesium oxide	MgO	1309-48-4	Used as a buffer, or stabiliser, in acid soluble completion fluids in conjunction with polymers.	0,5 to 2 lb/bbl
Potassium carbonate	$K_2CO_3.1\frac{1}{2}H_2O$	00584-08-7	Used as an alkalising agent in potassium treated muds.	
Potassium chloride	KCl	7447-40-7	Primary source of potassium ions for potassium polymer muds.	2 to 60 lb/bbl
Potassium hydroxide	KOH	1310-58-3	Used to increase pH of potassium treated muds and to solubilise lignite	0,5 to 3 lb/bbl
Sodium	$NaHCO_3$	144-55-8	Used to counteract cement	0,5 to 5 lb/bbl

Chemical name	Formula	CAS number	Uses	Typical concentrations
bicarbonate			contamination of bentonite water muds.	
Sodium carbonate	$NaCO_3$	497-19-8	Used to remove soluble calcium salts from make up waters and muds, plus some use in clay benefication.	0,2 to 4 lb/bbl
Sodium chloride	NaCl	7647-11-5	Used as produced or as prepared brine in completion and workover operations; to saturate water before drilling rock salt; to lower freezing point of mud; to raise the density and act as a bridging agent in saturated solutions; and in hole stabilising oil muds.	10 to 25 lb/bbl
Sodium chromate	Na_2CrO_4 $Na_2CrO_4.10H_2O$	07775-11-3	Used as a constituent of chrome lignosulfate and chrome lignite compositions for increased thermal stability; inhibit corrosion in salty muds.	0,1 to 2 lb/bbl
Sodium dichromate	$Na_2Cr_2O_7.2H_2O$	10588-01-9	Used as a constituent of chrome lignosulfate and chrome lignite compositions for increased thermal stability; inhibit corrosion in salty muds. Note that dichromate becomes chromate in alkaline solutions.	0,1 to 2 lb/bbl
Sodium hydroxide	NaOH	1310-73-2	Used in water to raise pH; solubilise lignite, lignosulfonate and tannin substances; to neutralise hydrogen sulfide.	0,2 to 4 lb/bbl
Sodium phosphates		7601-54-9	Defloculants for clays in fresh water and thinners for mud	0,1 to 1 lb/bbl
Sodium sulfite	Na_2SO_3	7757-83-7	Used as an oxygen scavenger.	0,05 to 0,1 lb/bbl
*Zinc bromide	ZnBr	7699-45-8	Used to prepare dense salt solutions	
Basic zinc compounds	$ZnCO_3$ ZnO $Zn(OH)_2$	03486-35-9 01314-13-2 20427-58-1	All slightly soluble, hence do not affect mud properties, but do remove hydrogen sulfide as zinc sulfide.	0,5 to 5 lb/bbl
*Zinc chloride	$ZnCl_2$	7646-85-7	Used to prepare dense salt solutions	
*Zinc chromate	$ZnCrO_4$	13530-65-9	Corrosion inhibitor	0,1 to 0,5 lb/bbl
*Zinc sulfate	$ZnSO_4.H_2O$	7733-02-0	Used with sodium dichromate as corrosion inhibitor	0,1 to 0,5 lb/bbl
* The use of Chromium and Zinc products is strongly discouraged in the OSPAR area.				

Lost circulation materials

Many substances have been recommended for regaining circulation. A wide range of readily available, inexpensive materials have been used. Some of which are listed below [18].

> Calcium carbonate, woody celluloses, polymer cross linking agents, walnut shells, shredded cellophane, flaked cellophane, groundnut shells, granular bentonite, shredded cane fibres, biodegradable polysaccharide, vegetable fibres, thermoset rubber, vermiculite flakes.

These are usually used as mixtures, heterogeneous in shape, size and strength, as experience has shown that these are more likely to effect a seal than a single size material. There are many other materials which been used in the past such as coal, hog hair and asbestos [16].

Oils

Diesel was used for many years as a base oil for drilling muds. This practice was effectively banned by PARCOM in 1984 and diesel was replaced with low-toxicity mineral oils (i.e. those with a low aromatic content). Although these fluids are much less toxic than diesel, they still do not biodegrade readily and PARCOM Decision 92/2 progressively reduced allowable discharges on cuttings towards an effective ban. Synthetic drilling fluids were introduced to address this problem, but since they too have been found not to biodegrade under field conditions, discharge of these is now tightly controlled by OSPAR Decision 2000/03. Although there have been various developments in cuttings cleaning technology towards the <1,0% limit, cuttings could be re-injected with a coating of either low-toxicity mineral oil or synthetic fluid.

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