Minimizing environmental impacts and maximising hole stability– the significance of drilling with synthetic fluids in New Zealand

M Norman, S Ross, G McEwen,* and J Getliff

M-I L.L.C., PO Box 42-842, Houston, Texas 77242-2842, Email mnorman@midf.com
** Previously with Global Vermiculture Ltd.*

Abstract

This paper describes the development and subsequent field trial in New Zealand of a novel synthetic-based drilling fluid system designed specifically for onshore drilling operations. The primary consideration behind the design of the fluid system was to obtain a soil friendly invert emulsion drilling fluid with the same technical characteristics as standard invert emulsion or oil-based fluids.

Although the resulting drill cuttings are designed to be benign when landfarmed and the rate of biodegradation of hydrocarbons have been maximized through the choice of fluid constituents, bioremediation can further enhance the waste management process.

Consequently, the authors will describe how following the field trial of the drilling fluid, the drill cuttings were transported to an organic waste treatment site so that experiments could be performed using a bioremediation process that utilizes earthworms. Although worms have been used for some years in Australia and New Zealand to convert organic wastes into organic fertilizer,[1] this represents the first time the process has been used to treat drill cuttings.

Introduction

While a number of novel drilling fluid systems have been developed in recent years, their design has focused on the technological and environmental challenges of operating in the offshore environment. Even though the same fluid systems can be used to drill wells on land, their environmental profile has never been fully optimized for this purpose, although there has been some work done on the type and amounts of salts used in fluids for land operations. The disposal of the cuttings is a major issue with land drilling, particularly in remote areas. Conversely, offshore operators have a number of disposal options, such as discharges to the sea and cuttings re-injection.

The traditional method of dealing with drill cuttings generated from land operations has been landfarming. Other options include composting, bioreacting, solidification, washing and thermal treatment.[2] However, in most countries regulatory limits on the electrical conductivity of salts, total oil and grease, and heavy metals make the remediation of cuttings to regulatory approved levels a slow and lengthy process.

Disposal of drill cuttings contaminated with hydrocarbon-based drilling fluids is an area of significant concern for operators. The synthetic-based PARALAND fluid, described in this paper, is engineered with chemicals specifically chosen for their biodegradation and toxicity characteristics and expressly designed for treatment and disposal by biological methods. The fluid is designed to enable cost-effective drilling via the high-performance characteristics of an invert, synthetic-based fluid system. Concurrently, it is specifically designed degrade using land-based bioremediation techniques, such as landfarming, composting, slurry phase bioreactors and biopiles with minimal organic and inorganic residues.

Worm-driven bioremediation, or vermidigestion, is a novel method of treating organic waste. The most interesting feature of this process is its tendency to generate no “real” waste at all, with the end product being an organic fertilizer farmers can utilize to enhance plant growth. However, it is possible that other types of organic waste may be more appropriate for such treatment and produce a better quality worm cast than that obtained with drill cuttings.

Thus, the aim of this study was to demonstrate the efficacy of applying worm-driven waste management, or vermiculture, to drill cuttings. It was hoped that the worms could process the minerals present in the drill cuttings and incorporate them into the "worm cast," which has valuable properties as a fertilizer and may provide an alternative solution to the problem of disposal of cleaned drill cuttings.

If the degradation stage of the trial is successful, additional experiments will be performed to demonstrate the beneficial effects of the resulting "Vermicast" fertilizers and the additional benefits of incorporating the cleaned drill cuttings within the fertilizer.

It is thought that optimum benefit will be obtained from the synergistic use of the new drilling fluid system and Vermiculture technology, the worms being used to add value to the cleaned cuttings and further reduce disposal costs. Owing to the novelty of this approach for the remediation of drill cuttings, this was intended to be a brief preliminary experiment aimed at demonstrating the degradation of hydrocarbons (present in a synthetic-based drilling fluid) when applied to the worm bed and subjected to worm-driven waste management.

Drilling fluid design criteria

The basic aim of the project was to design a drilling fluid system that does not negatively impact the soil when the cuttings are spread on land. A secondary aim was to carefully select the individual components of the fluid system (base fluid, emulsifiers, internal phase (salt and water), weight material and fluid loss additives) to generate drill cuttings that actively enhance the soil quality and subsequent plant growth.

From the start of the project, it was clear the environmental test regime had to be very different from that normally used for offshore drilling. The main focus for discharge of invert emulsion-laden drill cuttings to the sea is toxicity and anaerobic biodegradation. However, onshore the focus is on toxicity and aerobic biodegradation. However, it cannot automatically be assumed that the toxic effect of a chemical on marine organisms is the same as that to terrestrial plants and animals, the resulting soil chemistry and its subsequent potential for plant growth.

Environmental tests were carried out on various base fluids and on complete drilling fluids with different internal phases. The fluids were technically evaluated and thoroughly tested for their drilling performance prior to environmental testing. The environmental evaluation were conducted at the University of Calgary[3] and included the following tests:

1. Alfalfa seed emergence and root elongation.
2. Earthworms (Eisenia fetida) toxicity
3. Springtail (Folsomia candida) toxicity.
4. Microtox toxicity
5. Biodegradability (Respiration rate and hydrocarbon loss in moist soil.)

Results & discussion

Biodegradation of base fluids

The initial tests were conducted on the base fluids in order to select the most benign fluid for soil disposition, the choice of candidates being based on extensive knowledge of the aerobic biodegradation of these fluids. Although diesel does not fall in this category, it was included as a reference, since it is still the base fluid of choice in most land drilling operations.

In order to assess the relative biodegradability of the base fluids, they were mixed with clean clay soil and incubated for three months. The respiration rate, measured as headspace CO2 production, was measured 12 times during the incubation period. Soil samples spiked with 2% base fluids were also analyzed for total extractable hydrocarbons by GC-FID at the start and after the respiration period stabilized. The biodegradation results of the six selected base fluid candidates are shown in Figure 1. The rates of biodegradation appear to be consistent for the two methods applied. Acceptable results were obtained for the straight linear paraffin (LP) containing C12-C17, followed by C12-13 linear paraffin, an ester, and an isomerised olefin (IO) C14. Diesel and a complex paraffin blend comprising of linear and branched molecules yielded unacceptable and very low levels of biodegradation respectively.

Ecotoxicity of base fluids

As the standard toxicity tests normally used to evaluate potential base fluids for discharge offshore are unlikely to predict the potential toxic effects of soil mixed with the candidate base fluids, four different terrestrial ecotoxicity tests were used to represent various trophic levels found on land.

All tests were conducted on biodegraded fluids and cuttings, i.e. after the 90-day biodegradation testing was completed in order to simulate the effects that would occur during a landfarming process. Seedling emergence and root growth were measured after four and five days respectively, after barley, canola and alfalfa seeds were put into the soils. The results obtained are shown in Figure 2 and Figure 3 and are shown as a percentage increase or decrease when compared to uncontaminated reference soil. When compared to the reference sample, the root elongation of all the plants was enhanced by the presence of three of the fluids: the two linear paraffins and the IO C14 when compared to the reference sample. The mixed paraffin fluid did not change root elongation, and the diesel and ester suppressed the elongation completely. A similar scenario was observed for the emergence of the plants, however no enhancements could be observed in this case. Diesel and ester fluids result in a very toxic soil. It is interesting to note that barley seem to be a more resilient plant than the canola and alfalfa, as diesel had no effect on the barley, but killed the growth of the two other plants.

The survival rate of earthworms (Eisenia fetida) and springtails (Folsomia candida) were also measured in the base fluid-exposed soils and compared to their survival in a clean

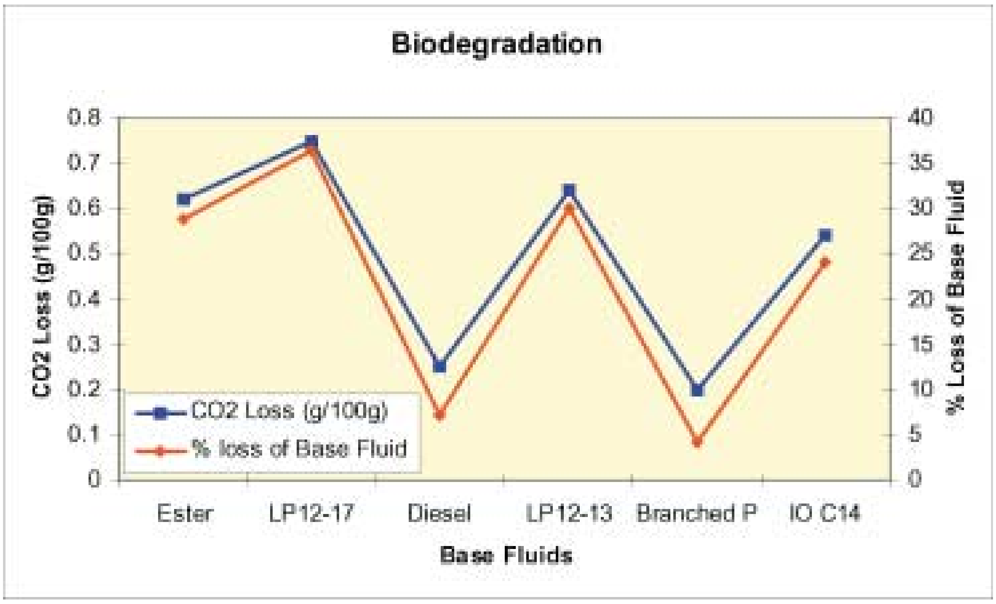

Figure 1: Biodegradation of base fluids.

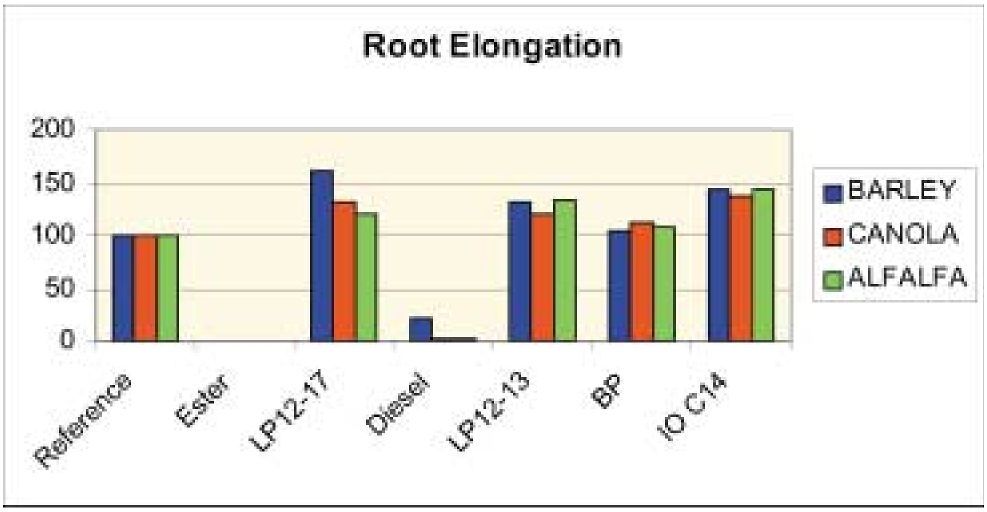

Figure 2: The influence of base fluid on root elongation.

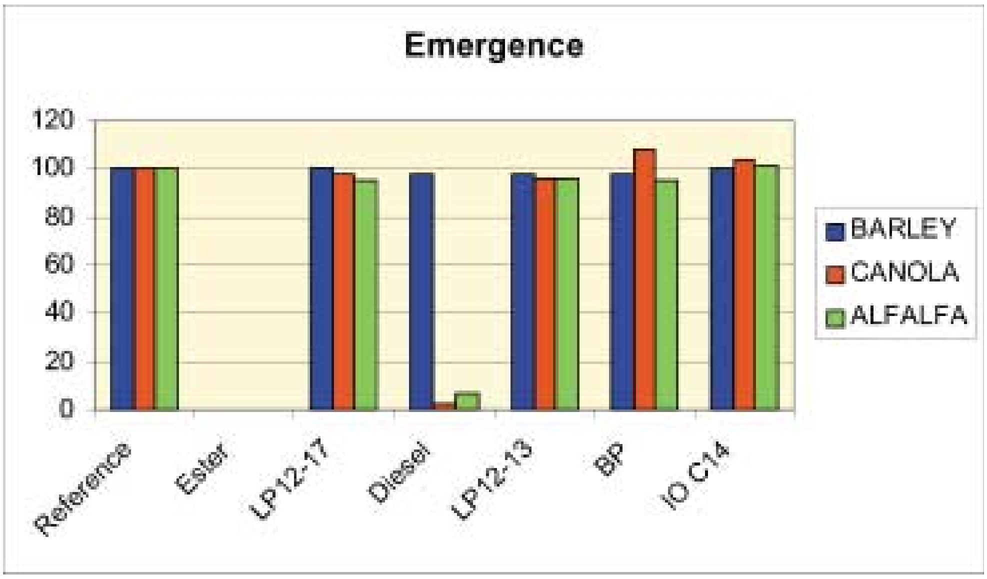

Figure 3: The influence of base fluid type on seed germination/plant emergence.

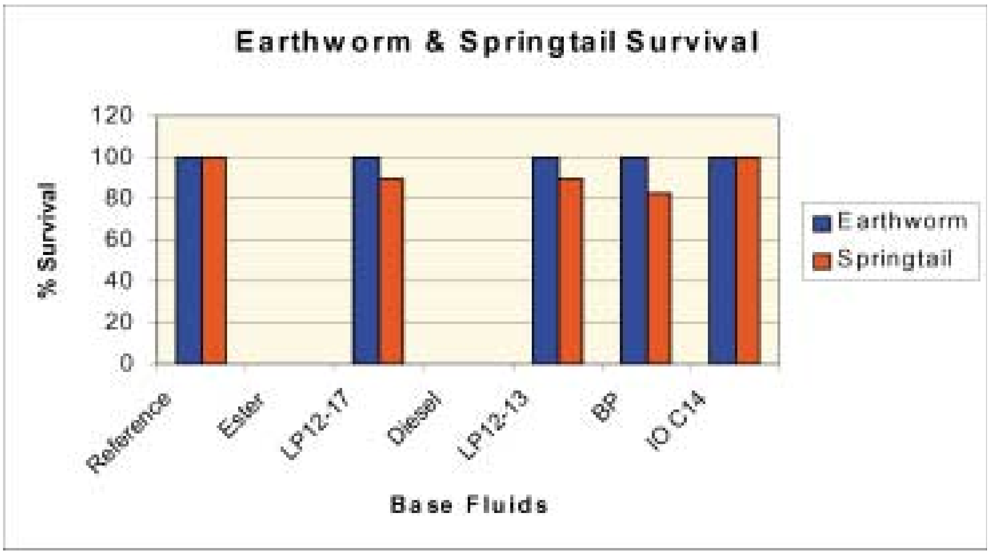

Figure 4: Survival rate of earthworms and springtails following exposure to base fluids.

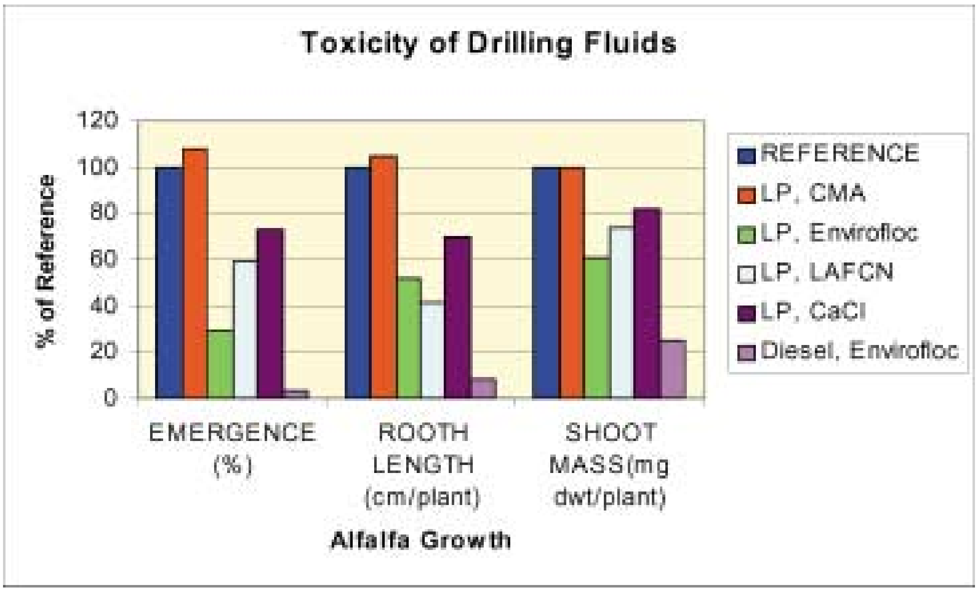

Figure 5: Effect of internal phase in drilling fluids on plant growth potential.

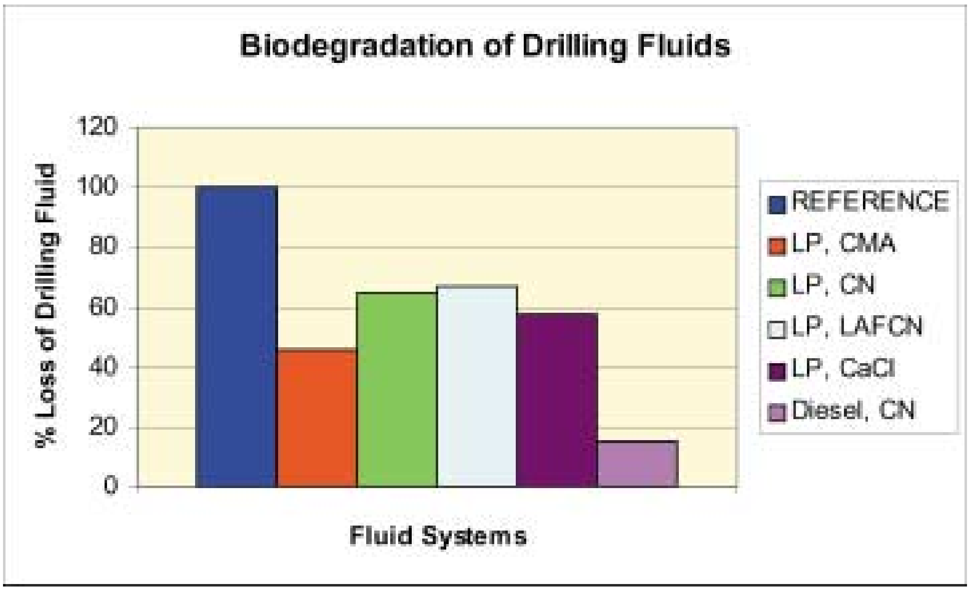

Figure 6: Effect of internal phase on biodegradation of drilling fluids.

reference soil. The number of live worms was counted after seven days, and the results are shown in Figure 4. All the earthworms survived in the soils and were assumed to be utilizing the linear paraffins and the IO for growth and food. None of the worms survived in soil containing the biodegraded diesel and ester fluids. The survival rate of the springtails was highest for the IO C14, with a 100% survival rate. Some 80-90% of the springtails survived the paraffin soil, whereas none survived the ester and the diesel fluids.

The combined toxicity results clearly indicate that neither diesel nor ester is suitable candidates for base fluids in land-based drilling fluid systems. Although the ester biodegrade rapidly, the degradation products were found to be toxic to soil organisms and plants. Similar results have been observed when simulating environmental conditions for species in the sea using marine mesocosm studies.[4]

Of all the base fluids studied, diesel is the worst option as it poorly degrades and yields toxic byproducts that kill naturally occurring soil animals and, with the exception of the barley seeds studied, inhibits plant growth. This is thought to be due to the biodegraded residues of complex hydrocarbon structures and the aromatic compounds present in diesel. Although the branched paraffin was non-toxic, it degraded poorly and was therefore unsuitable for this type of drilling fluid. The remaining three base fluids can all be utilized as the main component of a land-based drilling fluid system, as they are non-toxic and degrade well. At the end of the study, it was decided to use the C_{12-17} linear paraffin as it displayed a somewhat higher rate of biodegradation than the C_{12-13} linear paraffin and the IO C_{14}.

Environmental evaluation of drilling fluid systems

Similar environmental tests and test conditions to those used on soils laden with base fluids were used also on soils containing remnants of drilling fluids. The results of the seed germination/emergence, root elongation and shoot mass production of alfalfa (after 65 days of biodegradation testing.) is shown in Figure 5. All the fluids represented contained barite.

The selection of an appropriate internal phase is critical for an environmentally benign land-based drilling fluid system. The internal phases used in this study included: calcium chloride (the standard internal phase for most invert emulsion drilling fluids), calcium magnesium acetate (CMA), liquid ammonium-free calcium nitrate, and a standard calcium nitrate.

From Fig, 5, it can be seen that diesel has a detrimental effect on the growth of alfalfa plants, even if the internal phase is a Ca Nitrate, which can also be used as a fertilizer. Adverse effects were also obtained for linear paraffin-based drilling fluid systems with CaCl and other nitrate variations as internal phase, although the negative effect for the linear paraffin/nitrate blend was not as bad as those obtained for the diesel fluid. The LP-based drilling fluid system containing CMA as the internal phase had no effect on the growth of alfalfa.

In contrast to the plant bioassay, none of the earthworms died as a result of exposure to any of the linear paraffin drilling fluid systems. The diesel system killed all the worms after 7 days.

The springtails showed a behavior similar to that experienced with the earthworms. In this case, more than 80% survived the paraffin fluid systems. On the other hand, there was 100% mortality of springtails exposed to bioremediated diesel fluid. The effect of different internal phases of a linear paraffin-based drilling fluid system on the aerobic biodegradation is shown in Figure 6. A diesel fluid system with standard nitrate as the internal phase is included for comparison.

The two nitrate-based fluids yielded the best biodegradation rates, approximately 60%, over the test period. While calcium chloride as the internal phase results in a similar biodegradation rate, a marked difference was obtained for

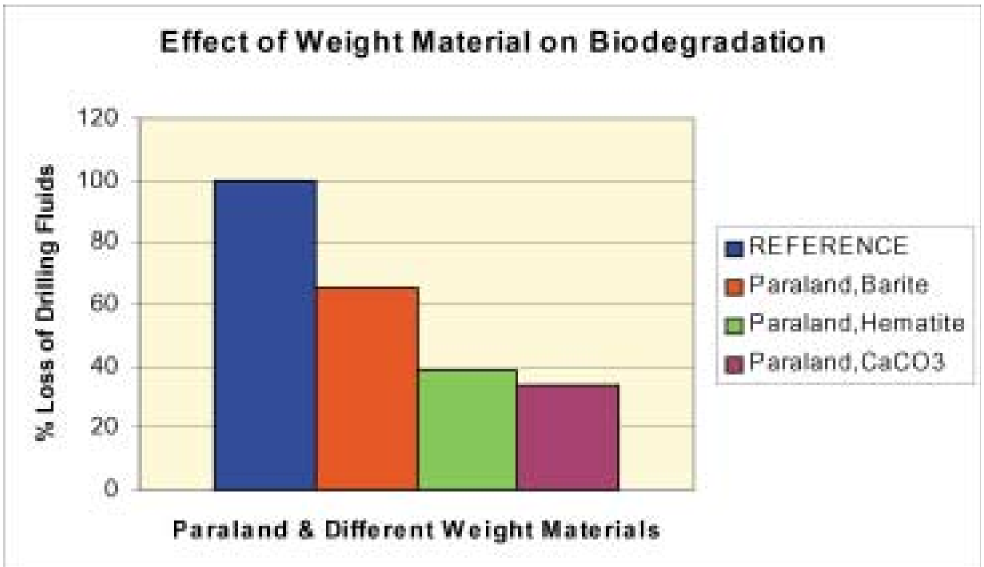

Figure 7: Effect of weight material on the biodegradation of base fluids.

the acetate, with less than 50% biodegradation. The reason for the good nitrate results may be due to the nitrogen acting as an additional nitrogen source for the biodegradation process.[5] As expected, the diesel fluid showed a poor biodegradation rate - only 17%.

Weight material selection

Potential weight materials for use in drilling fluid systems are: barite, hematite, illmenite, and $CaCO_3$. As barite is commonly associated with heavy metals (it can however be argued whether or not these actually leach out of the lattice and if they are really bioavailable) and $CaCO_3$ may effect the fluid rheology at higher mud weights, the primary choice for weight material was either hematite or illmenite.

Hematite was chosen during the course of the fluid development, because of its better availability than illmenite and its potential for providing additional iron to soils, a critical characteristic as many soils naturally have low iron content.

It is also interesting to note that the respiratory carbon loss from drilling fluids containing C12-17 linear paraffins and three types of internal phases, showed that fluid systems containing barite had a more rapid degradation than those containing hematite (Figure 7). Calcium carbonate resulted in the slowest rate of degradation.

The reason for the observed differences in the rate of biodegradation as an effect of weight material is probably due to different absorption characteristics of the weight materials. The effects of the different weight materials on toxicity appear to be negligent, apart from the root lengths. Both hematite and $CaCO_3$ promotes the growth compared to reference soil. The difference was significant compared to barite and reference.

Internal phase selection

The results from the electrical conductivity measurements on drilling fluid systems containing LP_{12-17} and barite, but different internal phases are shown in Figure 8. A diesel fluid system with a standard calcium nitrate as internal phase is included as reference. Electrical conductivity (EC) is used to measure the salinity of agricultural soil. An EC level below 2 is considered benign, but detrimental effects may occur at levels >2. The calcium magnesium acetate is clearly superior as an internal phase in that it only has an EC of 0.5 dS/m. However, it was subsequently found that a 100% internal phase consisting of CMA would not yield a technically usable drilling fluid system. Thus a compromise was reached with a 50/50 mix of acetate and nitrate. Further work is in progress to obtain a more EC friendly internal phase.

Emulsifier selection

The environmental impact of different emulsifiers was not analyzed in this study. As the available range of emulsifiers already has a large amount of environmental test data, it was decided to choose the most environmentally friendly emulsifiers that would result in a technically competent drilling fluid system. Nonetheless, several emulsifiers were investigated in the studies.

Technical performance of drilling fluid during field trials

Selection criteria

- The primary selection criteria for the drilling fluid was enhancement of production from tight gas sands. Water-based drilling fluids impair permeability of the sandstone by saturating the pore space of the invaded zone with water thus reducing the relative permeability to gas. Oil or synthetic-based drilling fluid may damage

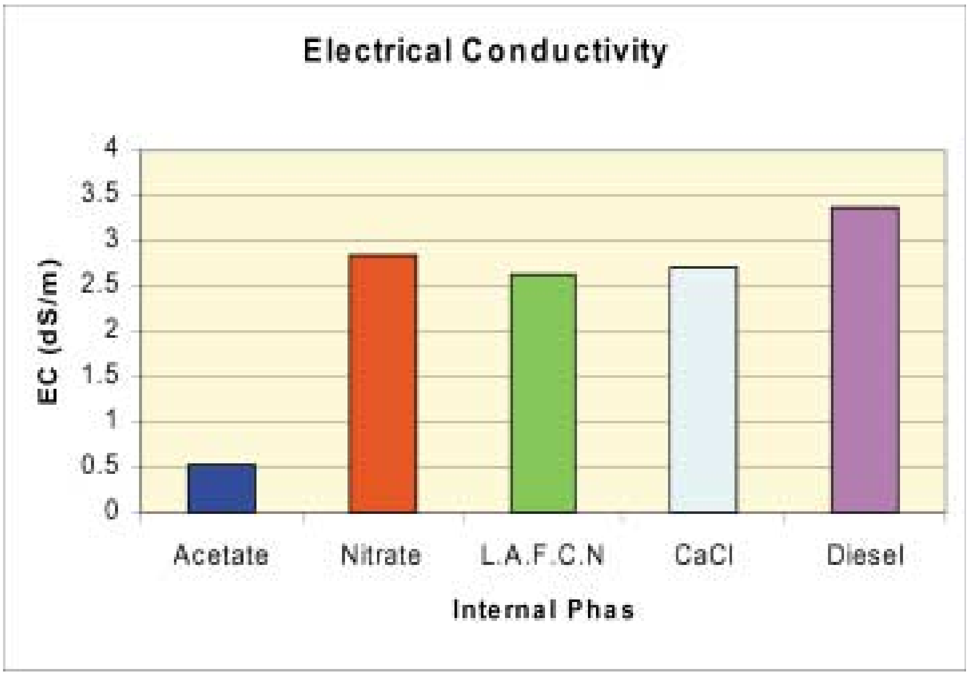

Figure 8: Effect of internal phase on electrical conductivity.

permeability due to filtrate invasion, but is less damaging than water-based drilling fluids (WBM).

- The second selection criteria was based on increased shale inhibition of synthetic fluids as compared to water-based. This reduces the risk of hole problems experienced in previous wells, including excessive chunky cavings "popping" off the wellbore, hole ballooning, lost circulation due to induced fractures, stuck pipe, well abandonment and sidetracks. Additional benefits include increased rates of penetration and the provision of fluid stability for high-pressure formations and subsequent high-weight requirements. This system must be designed with 17 – 18 lb/gal (2.04 – 2.16 sg) fluid weight in order to achieve stability. Water-based drilling fluids at this weight are relatively unstable with little margin of error as slightly elevated gel strengths will destabilize the rheology.
- The third selection criteria was derived from the New Zealand environmental legislation. Since this is the first application of a synthetic-based drilling fluid in New Zealand, it was expected that the operator not only meets, but also exceeds, the environmental objectives.

Field trial 1

The synthetic-based PARALAND system used in New Zealand employed a linear paraffin as the base fluid, calcium ammonium nitrate as the internal phase and barite as the weight material. The technical performance of the new fluid system was assessed in the laboratory prior to the field trial. The results obtained in the laboratory tests have been reported previously.[6]

The PARALAND system was introduced in a field where high weight WBM's from 16 – 19 lb/gal were traditionally used at depths from around 1000 m with hole problems experienced, including but not limited to:

- extremely reactive plasticene clays, squeezing up the inside of the casing,
- formation of "mud rings"
- significant borehole ballooning
- high background gas and gas kicks
- numerous hole packoffs due to tectonics, e.g. 3 – 4-in. pieces of wellbore popping off into the annulus
- minimal hole tolerance to formation pressure balance, i.e. a fine line between gains and losses
- fluid rheology problems at high weights
- induced fractures due to ECD's
- water flows
- no logs successfully run
- difficulty in running casing
- resultant fluid cost contributed to 30% of the AFE Total well budget.

Eleven wells had been drilled in the area with WBM and all experienced extensive hole problems. Alternative systems were considered and the newly engineered SBM was chosen based on the selection criteria discussed previously.

Well 1 was drilled using a silicate-based system and resulted in three stuck pipe incidents, two sidetracks, significant torque and overpull, ballooning from plastic clays, numerous packoffs, high rheologies due to excessive MBTs, and difficult wiper trips. The well never reached TD and had to be plugged and abandoned due to poor hole conditions. It took 28 days to drill to 1150 m.

Well 2 was drilled with the new synthetic-PARALAND system. The cuttings were transported to a hazardous waste facility, as this was the first well of its kind to be drilled in New Zealand. A mobile liquid mud plant was subsequently moved onto the location and all synthetic fluid mixing was performed on site, as shown in Figure 9.

Figure 9: Mobile liquid mud plant.

The results surpassed expectations. A depth of 2544 m was achieved in only 34 days. No drilling problems were experienced and torque and drag was reduced. The hole was successfully logged with the caliper indicating gauge hole, and the hole integrity was maintained during a five-day, open-hole testing program, This had not been achieved in previous wells.

Additional wells using the system have since been drilled in this area with minimal hole problems and cheaper drilling fluid costs compared to the previous WBM wells. The paleontology results are the best the operator has seen and all holes have reached TD with efficient casing runs and logging. Hole conditions are still difficult but the combination of experience, good drilling practice and the PARALAND system has contributed to a successful ongoing drilling program. Skin irritation levels are very low by comparison with other synthetic and oil-based systems that have been used in other countries – the first incidence of skin irritation was reported 22 days into the program. Strict adherence to a PPE program of barrier cream, nitrile gloves and disposable coveralls greatly reduces the chances of irritations.

Field trial 2

Field Trial 2 incorporated the waste management project with PARALAND cuttings being transported to the worm farm for further investigations. An advantage of this field trial was the fact that PARALAND was used in an 8½-in.

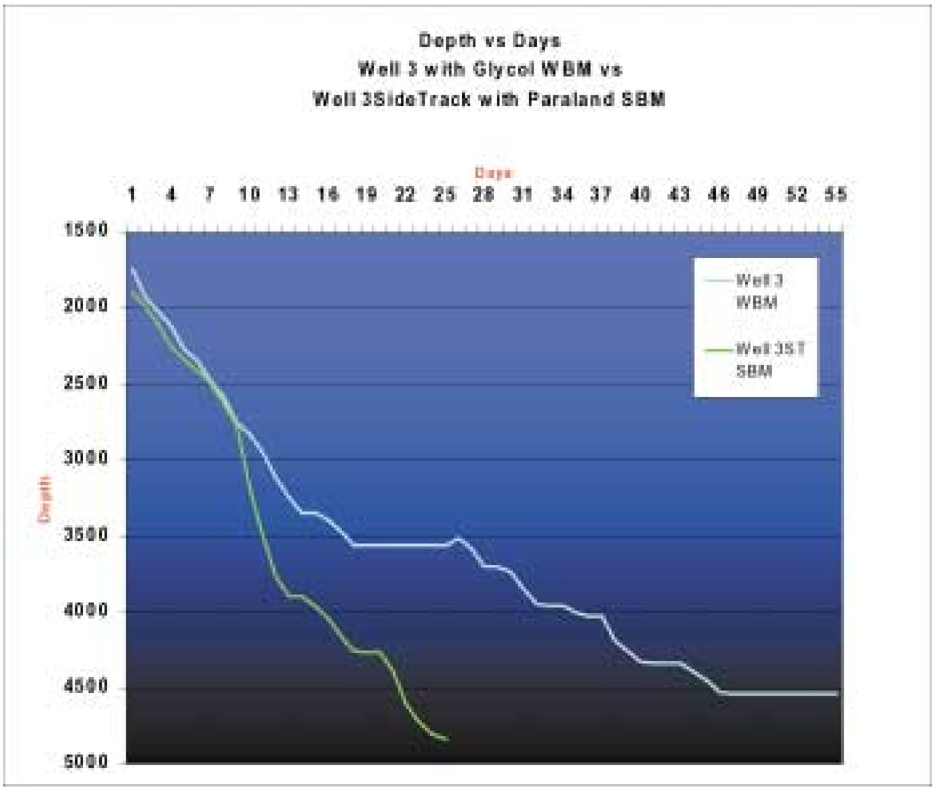

Figure 10 - Sidetrack drilling history of PARALAND vs glycol-based WBM.

sidetrack of a wellbore, originally drilled with a KCl/Glycol water-based mud, thus conditions for comparison were ideal.

Traditional drilling fluid weights for wells in this area are 9.2 – 11 lb/gal using highly inhibitive WBMs. Although hole problems are generally less in this area compared to the area drilled in the first Field Trial, there were still a few challenges such as:

- Highly reactive, tectonically stressed shale bands, causing excessive cavings.
- Interbedded clays dispersing into the system and creating concerns with rheology
- Slow ROPs through the lower section of the hole
- Considerable borehole breakout due to openhole exposure time.
- Seepage losses to limestone
- Coal stringers
- Excessive trip times due to reaming and back reaming of open hole sectioning

The 8½-in. hole was drilled in 47 days using a WBM, including a four-day fishing run, with a section length of 3005 m. Average ROPs through the lower section of the hole were 2 – 4 m/hr. Hole washout was extensive and difficult trips were experienced. The logs could not be run to the bottom. The high MBT of the system required increased dilution requirements.

After plugging back and displacing to PARALAND, the hole was drilled ahead with cuttings transported to the worm farm. Drilling was fast and 22 days into drilling, the depth was greater than that of the original well, reducing 26 days off the previous time curve. By day 25, the well had reached a depth of 4800 m with no hole problems experienced, minimal overpull and drag, and no logging or tripping incidents. The logs revealed an in-gauge hole. The system was stable and only one incidence of skin irritation was reported. Figure 10 illustrates the reduced drilling days obtained from the use of the PARALAND system, in a sidetrack, as compared to the drilling history of a water-base fluid.

The cuttings were collected in a direct collection bin at the base of the auger outlet and transferred to a tip truck after blending with bulking material (sawdust) to facilitate transport. The operation is depicted in Figure 11.

Although the drilling fluid and the handling of cuttings associated with the running of SBM were costly, the resultant reduction in rig downtime considerably offset these costs. The only negative aspect, noted to date, of the PARALAND system is the ammonia smell generated by the calcium nitrate, which contains a small concentration of ammonia. This results in an uncomfortable emission of ammonia as it dissipates at the shakers. Other internal phase salts are being considered at this time to eliminate this effect.

Figure 11: Collection and transportation of cuttings to worm farm.

Figure 12: a) Drill cuttings and sawdust; b) Paunch material and grass clippings and c) Mixing of the paunch material with the drill cuttings in the tank of the feed-out wagon.

Figure 13: a) and b); Feed out of the blended cuttings and Paunch material onto the worm beds; c) windrow worm beds showing the felt and polypropylene backed covers.

Experimental design of worm remediation

Drill cuttings

Drill cuttings were mixed with sawdust (Figure 12; 45% w/w) to facilitate transport and then delivered to the vermiculture site near New Plymouth, New Zealand where they were blended with paunch waste (undigested grass) from a slaughterhouse before being fed to the worm beds using an agricultural feed-out wagon of the sort used for feeding silage to livestock (Figure 13).

Preparation of the mixture - blending and feed balancing

Successful degradation of organic materials by worms is dependent upon maintaining optimum environmental conditions for the worms, the most important parameters being the carbon nitrogen ratio (25:1) and moisture content (75%).

The drill cuttings were blended and mixed with the paunch material at a 20% w/w ratio of cuttings to paunch and then combined with water giving a 50:50 v/v water:solids slurry that could be evenly distributed from the feedout wagon. Blending and mixing of the drill cuttings, paunch wastes, green wastes and water was performed on a bunded concrete pad that is approximately 30 m by 15 m in diameter, giving 450 m^2 for controlled waste mixing and was carried out in a Marmix combined mixing and feedout wagon, the three internal augers of the trailer being used to ensure thorough mixing.

This blending step is a critical precursory step in the vermicast production as the quality of the “feedstock” ultimately impacts upon the potential for optimal conditions to exist during the resultant vermicasting process.

Application of the cuttings and paunch mixture to the worm beds

Once the blended material has been prepared it is loaded into a watertight “feed out” wagon for application as “feedstock” for the worms to process in mounds referred to as “windrows”. The research windrows were 88 m in length by 3 m wide. There are two meter-wide access tracks between each of the windrows for access of the feed-out wagon to apply the mixed material, and also to allow for ongoing maintenance of the windrows and the subsequent vermiculture production processes.

The blended material is applied to the center/top of the windrows, typically at an average depth of 15-30 mm on a weekly basis. The exact application rate is depending upon climatic conditions and is higher in summer than winter. The worms work the top 100 mm of each windrow, consuming the applied material over a five to seven-day period.

Maintenance of the worm beds

Each of the windrows is covered completely by a polypropylene-backed felt mat which excludes light from the worm bed and, although semi permeable to water, the polypropylene backing deflects heavy rainfall away from the surface of the bed and prevents the windrow from becoming waterlogged, thus maintaining an optimum aerobic environment the worms to work in. As this trial was performed during the New Zealand summer, a controlled irrigation system was periodically used on the windrows to keep the covers moist and maintain the correct moisture content, i.e. a damp but not “wet” environment. Each side of the polypropylene/felt matting is fitted with a D12 steel rod to act as a weight to stop wind lifting the covers off the bed.

As the use of worms for degradation of the mixture is an aerobic process the windrows are aerated prior to each feeding procedure to ensure aerobic conditions within all of the beds and maintain optimum conditions for the worms and their associated microbial processes. This aerator is attached to the power take-off linkage on the tractor and side arms guide any material (vermicast) back onto the beds, ensuring no windrow exceeds the width to be covered by the covers themselves.

Harvesting the “Vermicast”

Once the “worm-driven windrows” convert the applied material into vermicastings (worm castings), the vermicast organic fertiliser is harvested using an industrial digger and is then packaged for distribution and use on agricultural and horticultural land as a beneficial fertiliser and soil conditioner.

Sampling and Analytical Procedures

50-cc Grab samples were taken at time zero and then at approximately weekly intervals. Samples were transported by overnight courier to the analytical laboratory in Hamilton, New Zealand where they analyzed for TPH content according to the New Zealand Oil Industries Environmental Working Group (OIEWG) guidelines and recommendations.[7] A sample of the cuttings and sawdust (as received) was also taken and analysed for hydrocarbon content (Column 2 of Table 1).

Worm remediation results

There was no detectable excess mortality amongst the worms that the drill cuttings were fed to and although the numbers were not quantified, there appeared to be a definite preference among the worms for the area where the cuttings and paunch feed had been applied although it is not clear if this was due to the hydrocarbons themselves attracting the worms or the increased carbon content/microbial biomass that would be associated with the highly biodegradable linear paraffins of the drill cuttings. It was also noted that there was complete physical degradation of the cuttings by the vermidigestion process and none of the original intact cuttings could be found, the original cuttings size being 5 –10 mm in diameter.

TPH

The blend of cuttings and sawdust contained 41,000 mg/kg (dry wt) hydrocarbons (4.1%) which given the amount of sawdust added to the cuttings for transportation, is in good general agreement with typical oil on cuttings retention values for these types of drilling fluids. Looking at the carbon-chain-length distribution of the hydrocarbons in the samples shown in Table 1, it can be seen that the bulk of the hydrocarbons comprised $C_{10} – C_{14}$ aliphatic hydrocarbons. This is to be expected from the knowledge of the chemistry and carbon chain length distribution of the $C_{12} – C_{17}$ linear paraffin blend used in this drilling fluid. It can also be seen from the results in Table 1 and the graph of total hydrocarbon concentrations shown in Figure 14 that the hydrocarbon concentrations decreased from 4600 mg /kg (dry wt) to less than 100 mg/kg (dry wt) in under 28 days with less than 200 mg/kg (dry wt) remaining after 10 days in what appears to be a fairly typical exponential type degradation curve.

Discussion

Optimum benefit is obtained from the synergistic use of PARALAND drilling fluids and Vermiculture technology, the worms being used to add value to the cleaned cuttings and further reducing disposal costs.

The results shown above indicate a substantial degradation of the hydrocarbons within the worm bed, although at this point it is not clear exactly what the method of degradation is, possibly microbial degradation within the worm beds, favourable aerobic conditions being generated by the burrowing and mixing activities of the worms, metabolism of the hydrocarbons by the worms or a symbiotic relationship

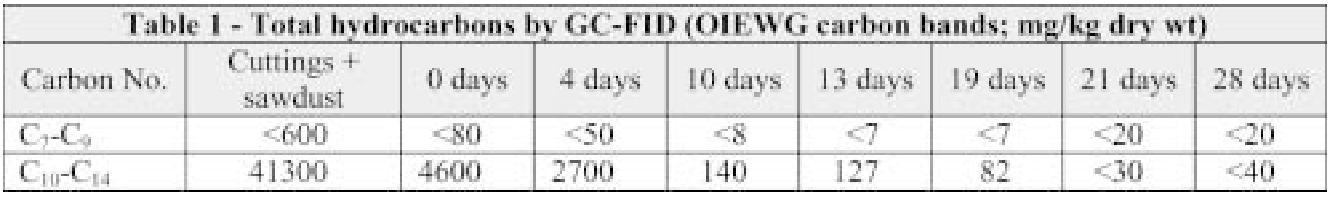

Table 1 - Total hydrocarbons by GC-FID (OIEWG carbon bands; mg/kg dry wt)

Carbon No.	Cuttings + sawdust	0 days	4 days	10 days	13 days	19 days	21 days	28 days
C_7-C_9	<600	<80	<50	<8	<7	<7	<20	<20
C_{10}-C_{14}	41300	4600	2700	140	127	82	<30	<40

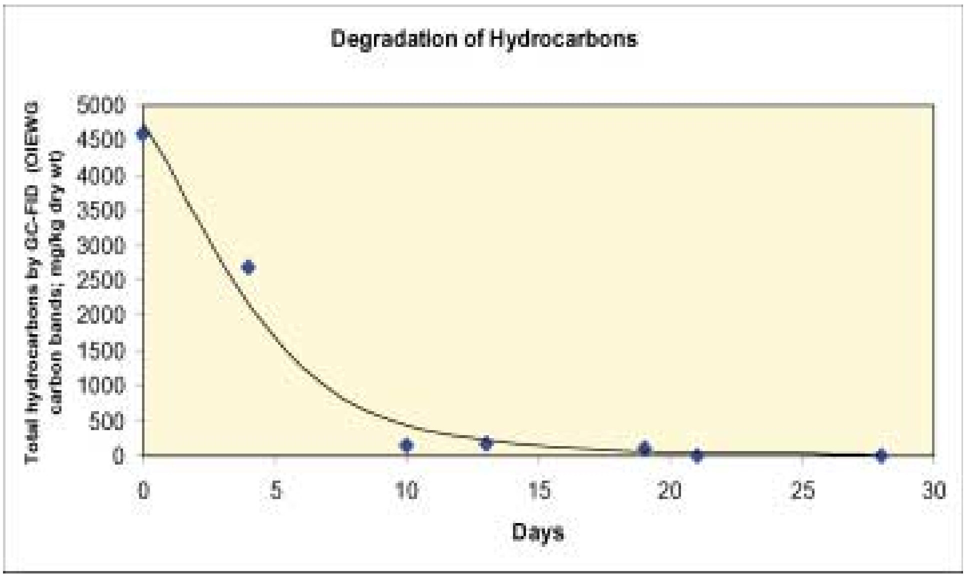

Figure 14: Degradation of hydrocarbons by worm driven waste management.

between the bacteria in the earth worms gut degrading the hydrocarbons on the cutting particles ingested by the earth worms, or perhaps a combination of all three. Following the success of this feasibility study, additional tests have been commissioned to investigate the effects of different loading rates on the process and the effects of different climatic conditions (New Zealand summer and winter) as well as to gain more information on the effects of nutrients such as nitrogen and phosphorous on the process and to study the fate of the barium sulphate associated with the drilling fluid. As worm cast has been shown to have beneficial properties as an agricultural fertilizer,[8] we also propose to perform further studies to determine whether or not the clays and minerals present in the now clean drill cuttings have any negative or beneficial effects on the horticultural properties of the worm cast

Conclusions

From a technical standpoint, the newly engineered synthetic-based (PARALAND) system delivered in all facets of design, maximizing drillability of the well, minimizing the environmental impact, and protecting the health and safety of the rig crew.

The system offers operators a now proven drilling fluid alternative for difficult wells and enhanced production of tight gas sands in environmentally sensitive areas.

The specially designed, environmentally compatible, PARALAND fluid system, utilized components, the choice of which, was based on results from ecotoxicological studies, and also proved to be very amenable to subsequent bioremediation utilizing worms.

The initial studies have shown that the combination of PARALAND and worm remediation decreased the hydrocarbon concentrations from 4600 mg/kg (dry wt) to less than 100 mg/kg (dry wt) in under 28 days.

This is a considerable improvement to landfarming of diesel cuttings, which has been reported to take up to one year,9 although it is not unknown for it to take even longer for the aromatic compounds present in diesel to degrade.

Acknowledgements

The authors wish to thank the management of M-I L.L.C. for permission to publish this paper. Additional thanks to Mary Dimataris for her help in preparing the paper.

References

1. Edwards, C.A and Neuhausen, E.F. 1998. Earthworms in waste and environmental management. SPB Academic Publishing, The Hague.
2. Canadian Association of Petroleum Producers. 2000. Report on Drilling Waste Management Review. St. Johns. Newfoundland. Canada. Aug 29, 2000.
3. Visser, S. 2000. Biodegradability and ecotoxicity of six base fluids being considered for drilling mud production. Confidential Report.
4. Norman M. 1997. Esters- The only synthetic option for the next millennium? IBC. 5th Int. Conf. on Minimizing Environmental Effects of Drilling Operations. Aberdeen.
5. Alexander, M. 1994. Biodegradation and Bioremediation, Academic Press.
6. Curtis, G.W., Growcock, F.B., Candler, J.E., Rabke, S.P., and Getliffe, J. 2001. Can synthetic-based muds be designed to enhance soil quality? AADE National Drilling Conference, Houston. AADE-01-NC-HO-11.

12. Draft Sampling Protocols and Analytical Methods for Determining Petroleum Products in Soil and Water, Prepared by the Oil Industry Environmental Working Group May 1999. New Zealand Ministry for the Environment.
13. Buchanan, M.A. 1988. Chemical characterisation and nitrogen mineralisation potentials of vermicomposts. In: C.A. Edwards and E.F. Neuhaser. 1998. Earthworms in Waste and Environmental Management, The Hague, SPB Academic Publishing.
14. Chaineau, C.H., Morel, J. Land, and Oudot, J. 1995, Environ. Sci. Technol. 29., 1615-1621.

Authors

MONICA NORMAN is Vice President, R&E for M-I L.L.C. Prior to Dr. Norman's current position in M-I, she has been Director of R&E for M-I's Eastern Hemisphere, V.P.-Technical/Environmental Services for Anchor Drilling Fluids, and Research Manager for Rogaland Research Institute in Norway. Dr. Norman received her Ph.D. and M.S. from University of Salford, England.

SONYA ROSS is Manager, New Zealand Operations for M-I. In addition to her current position, Ms. Ross has worked as a Drilling Fluids Engineer, Project Engineer and Senior Engineer, and Manager New Technology Operations in New Zealand and Australia. Ms. Ross' education includes studies in the NZ Diploma in Geology.

GREG MCEWEN is a Technical Engineer for M-I/Swaco Asia Pacific where he is currently researching the toxicity/bioremediation rates of synthetic base fluids. Prior to joining M-I, Mr. McEwen was employed by Global Vermiculture Ltd. utilizing worms to convert organic matter into viable fertilizer and the remediation of synthetic mud/cuttings via vermiculture. Mr. McEwen received a B.S. in Microbiology and Zoology from Massey University, Palmerston, North New Zealand.

JONATHAN GETLIFF is a Research Scientist with M-I/Swaco leading the Waste Management and Environmental Testing Group at the M-I Aberdeen Research and Technology Centre, Aberdeen Scotland. Prior to joining M-I, Dr. Getliff worked for Dowell Drilling Fluids as a Microbiologist/Ecotoxicologist and as a Research Associate at the University of Bristol studying the role of bacteria in the preservation of fossil biomarkers. Dr. Getliff has a B. Sc. (Hons) in Applied Biology and a Ph.D. in Microbial Ecology.