Pseudo Oil Based Muds
Drilling Safety Issues
A Review

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PSEUDO OIL BASED MUDS
DRILLING SAFETY ISSUES
A REVIEW

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SUMMARY

The objective of this report is to review the existing and available information on the health and safety issues associated with the use of pseudo oil based mud (POBM). This objective has been achieved by contacting key personnel within operating and mud supply companies, surveying the open literature, and studying documented health and safety incidents involving POBM.

The development of POBM was driven by the desire to retain the technical performance of mineral oil based mud (OBM) whilst attempting to reduce environmental damage caused by the discharge of oil on cuttings (OOC). Environmental legislation has resulted in a decline in the use of OBM while the use of POBM has steadily increased. Recent investigations, however, suggest that the effects on the environment are not greatly alleviated by the use of POBM. Currently, there is debate within industry on the future levels of allowable discharge for POBM.

The primary advantage of POBM, and the reason for their development, is that current discharge limits do not apply. Other advantages include better performance for some applications and the perception that some health and safety aspects may be improved. The higher cost-of-POBM, however, is a distinct disadvantage to their use. Should the current legislation be extended to POBM, then it is widely believed in industry that the additional expense of POBM would lead to it being phased out. In response though, mud companies may be able to find ways to reduce POBM costs, in which case, the choice between POBM and OBM could become dependent on other factors, such as drilling performance and health and safety considerations.

The health and safety issues can be divided into two categories. The first are those that are clearly evident from known properties (i.e. there is a direct causal link between a particular property and a particular health and safety issue), and these are:

- Flammability
- Drilling equipment corrosion
- Spills on rig floor
- Toxicity to rig personnel

The second category consists of those health and safety issues that would not be intuitively evident from known properties (i.e. there is a complex causal link between a particular property, or set of properties, and a particular issue). These are:

- Human factors
- Well control

Rig personnel working on a well control operation will have certain perceptions or expectations as to how the event will unfold. If the well does not behave in the way anticipated then, over the many hours that well control operations can last, stress, fatigue and commerical pressures will increase. This situation represents a health and safety issue in itself, since it can lead to incorrect diagnoses and hasty actions which could escalate the problems.
Pseudo oils will generally have physical and chemical properties that differ from mineral oils. These differences in properties may manifest themselves as well control responses that are different from those expected from a mineral oil. The physical properties likely to affect well control are:

- Gas solubility
- Compressibility and expansivity (PVT) properties
- Rheology and gas slip

The health and safety issues stemming from the use of POBM ultimately result from their chemical and physical properties. POBM is not only expected to have different properties to OBM, but also a much wider range of properties, due to the large number of substances that can be used as pseudo oils or as additives. Any generalisations made about POBM properties and associated health and safety issues, therefore, must be treated with caution. The perception within industry, however, is that the health and safety issues surrounding the use of POBM are better, or at least no worse, than for OBM.

Whilst the health and safety issues associated with POBM are generally considered to be an improvement over OBM, this report highlights areas which could benefit from further investigation:

- Toxicity of possible downhole reaction products
- Toxicity of POBM aerosols
- Long term exposure to POBM
- Well control differences between POBM and OBM
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1. INTRODUCTION

Pseudo oil based muds (POBM) were first used on the United Kingdom Continental Shelf (UKCS) in 1991, and subsequently there has been a steady increase in their use. The development of POBM was a response to legislation limiting the amount of oil that could be discharged offshore on drill cuttings. It was originally claimed that POBM has less of a detrimental effect on the seabed environment than mineral oil based muds (OBM), and thus they were exempt from legislation imposing discharge limits. POBM was claimed to have a similar technical performance to OBM, but with none of the environmental drawbacks.

In this report, the use of the labels POBM and synthetic based mud (SBM) are synonymous. Some sources do make a distinction [1, 22], saying that the term 'synthetic oil' applies to those oils produced by a synthesis process, and presumably cannot be derived from fractional distillation of petroleum. Whereas the term pseudo oil presumably applies to those oils that can be produced either by a synthesis process or by fractional distillation of petroleum but have less of a detrimental effect to the environment than the originating mineral oil. Here, the label POBM is used to cover the full range of mud formulations described by both the labels POBM and SBM.

While the development and application of POBM was driven primarily by environmental concerns, a parallel concern is health and safety to human beings. The interest that has been expressed in the full range of OBM health and safety issues over previous years has lead to a knowledge of the OBM properties that have consequences for health and safety. As a result, these issues are now familiar to the Health and Safety Executive (HSE) and the wider offshore industry. It can be expected, therefore, that POBM will also have properties that may have consequences for health and safety, and that these will not necessarily be the same as those of OBM.

The objective of this report, which is to review the full range of health and safety issues of using POBM, has been achieved by three different approaches:

- Contact with key personnel within operating companies and mud supply companies to ascertain their concerns with regard to the use of POBM.

- A survey of the open literature, gathering relevant material on the use of POBM and related topics.

- A study of documented health and safety incidents involving POBM, and supplied by operating companies.

All the information contained in this report, regarding the health and safety issues of using POBM, originates from the above sources. The report aims to present a balanced view of all the information gathered. Where an interpretation of this information is presented, it is made clear that this is a subjective view.
A brief history of POBM is given which includes a discussion of the technical, environmental and legislative issues that drove their development. The current level of POBM use is examined and speculation as to their future popularity is reported.

The attention that OBM health and safety issues have received over recent years has lead to an examination of their chemical and physical properties. As a result, these issues should now be familiar to the HSE and to industry. All the health and safety issues associated with either OBM and POBM are derivable, or at least explainable, in terms of their chemical and physical properties. By understanding how OBM health and safety issues are related to their properties, a comparison of OBM and POBM properties lays the foundations for an understanding of POBM health and safety issues.

The report goes on to review those health and safety issues that are evident from an understanding of the chemical and physical properties i.e. where there is a direct causal link between the mud property and the health and safety issue. For instance, one property of a particular mud component may be that it is toxic to humans in some way. The health and safety issue, therefore, becomes one of degree of exposure to that component.

Next, the health and safety issues that would not immediately seem derivable from an understanding of the chemical and physical properties i.e. where there is a complex causal link between the mud property and the health and safety issue are examined. These include human factors and well control.

A number of documented well control incidents are studied to determine whether any of the symptoms point to a problem directly associated with the use of POBM. Interpretations and conclusions drawn from these studies are presented.

Finally, the report goes on to highlight areas of possible further work that would be useful in better understanding the health and safety aspects of using POBM.
2. HISTORY OF POBM

The first well on the UKCS to use POBM was drilled in May 1991, and since then it has been estimated that over 200 further wells have been drilled with various POBM formulations on the UKCS [10, 22]. In this section, a brief history of the circumstances that lead to the development of POBM is presented, together with information on their current use, and also speculation on their future use. The detrimental effects OBM have on the environment together with their particular benefits to the industry lead to numerous technical initiatives to eliminate the former while preserving the latter. The development of POBM was one of those initiatives and is the focus of this review document.

2.1 ADVANTAGES OF OBM OVER WBM

Traditionally, two types of base fluid have been used to formulate mud systems: oil and water. The base fluid constitutes the continuous phase of the mud. As used in the North Sea today, OBM's are formulated with low aromatic mineral oils (previous to this diesel was used). These muds offer numerous technical advantages over WBM which are directly attributable to the chemical and physical nature of the base fluids themselves. The prime benefits obtained from OBM are as follows [1, 2, 5]:

- **Borehole stability in clay shale formations:** Mineral oils are non-polar compounds and therefore are essentially non-reactive with clay shales thus providing formation stability. Moreover, if the dispersed water phase is formulated with a salt concentration, such that the water activity is lower than that of the shale, then dehydration will occur producing a slightly over-gauge hole allowing more drillstring clearance. Water is a polar substance, and if used as a base fluid can result in shale swelling and stuck pipe.

- **Reduced washout in salt formations:** Again, mineral oils are non-polar compounds and therefore do not react with the salt formations thus maintaining an in-gauge borehole. Water is a polar substance, and if used as a base fluid can result in salt dissolution and significant washout of the borehole, subsequently leading to cementing and casing problems.

- **Low filtration:** Mineral oils have a low filtration rate into drilled formations. Conversely, water has a higher filtration rate which can result in the deposition of a significant mud cake increasing the likelihood of stuck pipe.

- **Low formation damage:** Again, mineral oils have a low filtration rate and therefore have little effect on the hydrocarbon producing reservoir. Conversely, water has a higher filtration rate which can result in the deposition of mud solids in the reservoir, thus lowering the permeability in the region of the wellbore.

- **Good high temperature stability:** OBM tend to be more stable at high temperature than WBM.
• **High lubricity**: OBM have a high degree of natural lubricity and therefore exhibit lower frictional losses than those achievable with WBM.

• **High rates of penetration**: OBM tend to produce higher rates of penetration than achievable with WBM.

• **No corrosion**: OBM provide excellent corrosion protection.

These qualities result in reduced overall operating costs when using OBM. This is evident when the frequency of OBM use on the UKCS is examined. In 1981, 36% of UKCS wells were drilled using OBM. By 1983, this figure had reached 65% and continued to increase for the next several years with a figure of 76% being reported in 1989 [2].

### 2.2 Environmental Background

The increase in OBM usage resulting from their improved overall drilling performance also prompted questions to be asked about their effect on the environment. An average North Sea well may generate approximately 1,100 tonnes of cuttings which, prior to being restricted by legislation, contained roughly 15% by weight of oil. Therefore, 165 tonnes of oil were being introduced into the environment from each well which was drilled using OBM. It was estimated that oil discharges totalled up to 20,000 tonnes on the UKCS during 1985. The environmental impact of such large discharges of oily cuttings caused concern since it was estimated that [2]:

• Within a 500 m radius of a well location, all seabed and fauna are physically smothered with oily cuttings. The hydrocarbon concentration is approximately 1000 times the background level. These piles of cuttings were predicted to maintain their integrity for an indefinite period of time and have since been demonstrated to have remained intact for more than ten years.

• Up to 2 km from a well location, seabed and fauna are partially smothered. The hydrocarbon concentration is 10-700 times the background level.

• Between 2 km and 4 km from a well location, seabed and fauna are largely unaffected. The hydrocarbon concentration is approximately 10 times the background level.

• Beyond 4 km, the hydrocarbon concentration is at background level.

As a direct result of the large number of such wells being drilled using OBM in the North Sea and elsewhere, governments introduced environmental restrictions to limit oily discharges.
2.3 LEGISLATIVE BACKGROUND

The UK legislation relating to the use of OBM has largely been concerned with regulating the oil content of the drill cuttings discharged to sea. One exception to this was in November 1984 where a ban was announced on the use of diesel as a base fluid, only the 'low toxicity' mineral oils (LTMO) could be used. Up to this date there had been no restriction on the use of OBM. From 1984 to 1989 there was no change to the legislation although, since then, changes have occurred quite rapidly [3].

Currently, mineral OBM is subject to a discharge limit of oil on cuttings (OOC) of 10 g/kg for all wells drilled on the UKCS. POBM has to score 'E' on the Offshore Chemical Notification Scheme (OCNS) to avoid discharge limits being imposed, and is discussed further in Section 2.5. Candidate POBM formulations that score other than 'E', and therefore would become subject to discharge limits, are presumably considered non-commercial.

From January 1989, the limit of OOC from all wells was set at 150 g/kg and remained in force until 1st January 1992. On this date, an important division was made between exploration and appraisal wells, and development wells. As a result, the OOC limit for single well sites was reduced to 100 g/kg from 1 January 1992 with a further reduction to 10 g/kg effective from 1 January 1994. Development wells are treated more leniently, the 100 g/kg limit which came into effect as from 1 September 1992 remained in force until 1 January 1997 when the 10 g/kg limit applied [3].

While the legislative frameworks for the discharge of oily drill cuttings in other countries will have no direct bearing on the UKCS, the oil and gas industry is international in nature and legislature in other hydrocarbon plays will drive technical developments that are readily transferable to other regions. It is necessary, therefore, to understand something of the regulations in these oil producing countries.

In Norway, the current OOC limit for mineral oils is 10 g/kg for all wells [3, 5], in the Netherlands, no mineral oil discharge is allowed [5], and in Denmark, mineral oil based muds are not used by general industry consensus [5].

In the Gulf of Mexico, discharge of diesel or mineral oil on cuttings has never been allowed [4]. The US Environmental Protection Agency (EPA) requires a mud to pass both the Sheen Test and the Mysid Shrimp Test before use on the Gulf of Mexico.

The Sheen Test requires injecting some mud into a bucket of water and viewing whether a surface sheen of oil develops [4].

For the Mysid Shrimp Test, the drilling mud is diluted with nine parts seawater and mixed well, the resulting suspension is left to settle for 1 hour, and the suspended particulate phase is decanted for testing. Mysid (Mysidopsis bahia) shrimp are exposed to a range of concentrations of the suspension and the lethal concentration to 50% of the shrimp, LC50, is calculated from observed shrimp mortality at the end of the 96 hours [12]. The lower the resulting LC50 concentration value, the higher the toxicity of the mud. The toxicity limit is set at 30,000 ppm of suspension. Operators
that discharge mud with $LC_{50}$ test result concentrations less than this are subject to penalty [4].

2.4 OPTIONS FOR COMPLIANCE

Technical developments have been driven by the need to comply with the above legislation while retaining the advantages of OBM systems. This has given rise to a number of possible solutions.

2.4.1 CUTTINGS TRANSPORTATION

One option is to continue to use OBM, but, instead of discharging the oily cuttings into the sea, barge the oily cuttings back to shore. This method is field proven but is expensive and dependent on weather and sea state [3]. This is a zero discharge option and would be insensitive to further legislation in this area.

2.4.2 CUTTINGS REINJECTION

Another option is to continue to use OBM, but, mix the oily cuttings into a slurry and reinject them into a suitable formation [3]. This method is field proven, but, is expensive. This is a zero discharge option and is insensitive to further legislation in this area.

2.4.3 CUTTINGS CLEANING

Again, continue to use OBM, but, clean the oil off the cuttings at the rig site to below 10 g/kg. The cuttings may then be discharged offshore [5]. Cleaning methods include solvent extraction, surfactant wash, enzymatic degradation and thermal distillation. The lowest OOC achieved to date is 5 g/kg [26] which complies with current legislation. This option would be sensitive to further tightening of legislation.

2.4.4 ALTERNATIVE MUDS

The development of a viable environmentally acceptable OBM equivalent must meet the following criteria [2]:

- The physical and chemical properties of the fluid should be similar to those of mineral oils.
- The fluid must have a very low toxic effect on the seabed environment.
- The fluid should be biodegradable and the decay products should have a very low toxicity and should not bioaccumulate.

There are two possible approaches:

- Modify WBM to achieve a drilling performance resembling that of OBM.
- Modify OBM to achieve a more environmentally acceptable product (i.e. POBM).
WBM is intrinsically of very low toxicity and highly biodegradable. Attempts have been made to modify WBM to better emulate OBM performance [11, 13, 14, 24]. Attempts have been made to design WBM with hole cleaning, lubrication and shale inhibition abilities approaching those of OBM's. Adding certain polymers to WBM can modify their rheological properties, and therefore hole cleaning and lubrication abilities, so that they approach those of OBM. The addition of certain salts to WBM can improve their shale inhibition and prevent salt formation washout. While WBM's can be modified so they go some way to emulate some of the properties of OBM, no generic modified WBM can replace all OBM under all circumstances. This option of compliance is sensitive to further tightening of legislation to reduce the toxicity of chemicals discharged with cuttings.

The alternative approach, which is the focus of this report, is to use a base fluid with similar characteristics to mineral oil while having a very low toxicity and high biodegradability. The advantages of OBM may be retained by using pseudo or synthetic oils as the continuous phase instead of mineral oils. Indeed, some claim [10] that POBM can offer improved lubricity, hole cleaning, rate of penetration and barite sag minimisation over OBM. These pseudo oils are claimed to be not strictly of petroleum origin and can be synthesised vegetable oils or other organic compounds. Pseudo oils used to formulate mud systems include ester, polyalphaolefin (PAO), ether, acetal, linear alphaolefin (LAO), internal olefins (IO) and linear paraflins (LP). These pseudo oils are claimed to be less toxic to the marine environment than low toxicity mineral oils (LTMO) and are more biodegradable. This option of compliance is also sensitive to further tightening of legislation to reduce the toxicity of chemicals discharged with cuttings.

All of these options may lead to changed, or new, worker exposures to hazardous materials. For example, in the case of solvent cleaning of cuttings, some of the solvents proposed have not only been very toxic but also highly flammable (e.g. n-hexane). Similarly, many POBM which may be environmentally more friendly than OBM may be potentially hazardous to the worker, thus presenting a greater health and safety risk for options such as cuttings transportation. This balance between environmental needs and worker protection has become generally more critical because of tightening environmental legislation [1]. The above options are intended to be applied singularly to achieve improved environmental performance with no loss of technical performance. The focus of this report is on health and safety implications of only one of these options, and that is the use of POBM. However, where the above options have been used together, as for example in the Netherlands where land wells were drilled using POBM and cuttings were transported away [10, 22], a health and safety consideration of the other options would be required.
2.5 DEFINITION OF POBM AND OBM

A definition of what does and does not constitute a POBM is needed to decide whether the discharges for a particular mud system have to conform to the current limits. The definition of POBM is considered to be a rather grey area [1]. Definitions have been attempted in terms of chemical and physical properties, method of production, and environmental affect.

A definition of a pseudo or synthetic oil made on the basis of chemical and physical properties is attempted by Growcock et al. [6]:

"the base fluids in POBM are synthesised organic compounds that act like petroleum-derived oils with respect to drilling but biodegrade readily in seawater"

A legal definition of POBM in terms of chemical and physical properties would be difficult to compose because of the wide range of potential chemicals that could be used.

A definition centred around the method of production is attempted by Friedheim et al. [22]:

"the definition of a synthetic material is something which is produced by chemical synthesis"

A legal definition of POBM based on the method of production would lead to contradictions. Synthesised linear parafins, for instance, which are similar to LTMO in many respects may be allowed, whereas linear parafins from fractional distillation may not [1].

Sawdon and Hodder [5] attempt a definition based around combining the above two approaches:

"POBM may be defined as a drilling fluid, the continuous liquid phase of which consists of a low toxicity, biodegradable 'oil' which is not of petroleum origin"

Another definition could be posed in terms of relative environmental effect. It seems sensible that, since environmental considerations were the driving force behind the development of POBM, the definition of a POBM would be related to the desire of reduced damage to the seabed environment on discharge. A test scheme could be proposed to evaluate the environmental effect and show that it is less than for OBM, thus offering a definition of POBM.

If a legal definition of POBM in terms of environmental effect could be composed, such a definition would reduce the term POBM to merely a label applied to mud systems that passed the chosen environmental test. Future research into the effect of discharged mud could result in a tightening or relaxing of the pass criteria, thus making the label POBM meaningless - a mud system would either pass or fail.
The above two paragraphs describe the current situation on the UKCS. No attempt is made to define a POBM, instead all muds have to undergo various environmental tests which they either pass or fail [1].

At present, all mud systems are evaluated according to the Offshore Chemicals Notification Scheme (OCNS), which has recently been revised. The OCNS is currently a voluntary scheme, though there has been some discussion about turning this into a statutory requirement. Mud systems are rated in terms of their effect on the environment. A score of ‘A’ (‘4’ on the previous OCNS scale) is the most harmful to the environment and a score of ‘E’ (‘0’ on the previous OCNS scale) is the least harmful to the environment. Mud systems must score an ‘E’ to avoid discharge being limited [1].

The mud is tested for toxicity to seabed life, biodegradation and bioaccumulation. The toxicity of the mud is tested against three different species as agreed by the Oslo-Paris Commission (OSPARCOM) 1995 protocol [1]. Biodegradation is tested according to the OECD Guideline for Testing of Chemicals [27], test numbers 301 and 306. Bioaccumulation is tested according to OECD test numbers 107 and 117. If a mud system passes all these tests then it is given a provisional category ‘E’ and discharge limits do not apply [1].

Immediately after drilling with a particular mud, and between six to twelve months later, grab samples of the seabed cuttings piles are made. Samples are tested against control results of OBM behaviour, and a decision is made on either maintaining or withdrawing OCNS category ‘E’ status for the particular mud formulation [1].

2.6 CURRENT POBM USAGE

The first well on the UKCS to use POBM was drilled May 1991, and since then it has been estimated that over 200 further wells have been drilled with various POBM formulations on the UKCS [10, 22].

A chart showing the use of OBM and POBM on the UKCS since this date is given by Friedheim and Conn [22], and is reproduced in Figure 2.1 (here the label SBM is applied). The 1996 figures are a projection for that year. It would appear that the use of OBM is on the decline while the use of POBM is on the increase.
**FIGURE 2.1 WELLS DRILLED ON UKCS WITH OBM AND POBM [22]**

The evident trend has undoubtedly been driven by tightening legislation restricting the discharge of oily cuttings into the sea. As the discharge limits were tightened, POBM began to take a larger share of the OBM market. The developments in the legislation described in Section 2.3 are summarised in Table 2.1.

**TABLE 2.1 LEGISLATION FOR MUD USAGE AND DISCHARGE ON UKCS**

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 84</td>
<td>Diesel use banned for all wells. LTMO introduced.</td>
</tr>
<tr>
<td>Jan 89</td>
<td>LTMO discharge on cuttings limited to 150 g/kg for all wells.</td>
</tr>
<tr>
<td>May 91</td>
<td>POBM first used to drill a well on UKCS.</td>
</tr>
<tr>
<td>Jan 92</td>
<td>LTMO discharge on cuttings limited to 100 g/kg for exploration and appraisal wells.</td>
</tr>
<tr>
<td>Sep 92</td>
<td>LTMO discharge on cuttings limited to 100 g/kg for development wells.</td>
</tr>
<tr>
<td>Jan 94</td>
<td>LTMO discharge on cuttings limited to 10 g/kg for exploration and appraisal wells.</td>
</tr>
<tr>
<td>Jan 97</td>
<td>LTMO discharge on cuttings limited to 10 g/kg for development wells.</td>
</tr>
</tbody>
</table>

Also shown in Table 2.1, is the date of the first well to be drilled on the UKCS using POBM. Subsequently, the use of the various pseudo base oils on the UKCS has increased. Table 2.2 shows the usage of POBM in the United Kingdom, Norwegian and Dutch sectors of the North Sea up to the 30th September 1994. LAB pseudo oil has now been withdrawn.
Table 2.2 POBM Usage in the North Sea to 30th September 1994 [22]

<table>
<thead>
<tr>
<th>United Kingdom</th>
<th>Norway</th>
<th>The Netherlands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of operators</td>
<td>Number of wells</td>
<td>Pseudo oil</td>
</tr>
<tr>
<td>6</td>
<td>26</td>
<td>Ester</td>
</tr>
<tr>
<td>9</td>
<td>33</td>
<td>LAB</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>Ether / Acetal</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>PAO</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>PAO / LP Blend</td>
</tr>
</tbody>
</table>

Linear alkyl benzene (LAB) saw some application on the UKCS, being used to drill 33 wells from June 1993 to September 1994. However, the basic chemistry of LAB was a cause of concern; the fear being that at high temperatures LAB would decompose to form free benzene. Attempts were made to measure benzene in air and benzene in pseudo base oil, however, no benzene was ever actually found [1]. LAB is no longer used as a pseudo base oil on the UKCS [22].

While OBM and POBM offer essentially the same performance, discharge restrictions apply to OBM that would be costly to comply with. This results in POBM becoming more attractive. However, this is not the whole story, as Figure 2.1 does not include the figures for wells drilled with WBM.

A snapshot of mud used in wells drilled on the UKCS in July 1993 and in July 1994 is given by Friedheim [10], and is reproduced in Figure 2.2.

Figure 2.2 Wells Drilled on UKCS for July 1993 and July 1994 [10]
While Figure 2.2 is only a snapshot comparing two months activity, it appears that POBM (labelled SBM here) has to some extent been used to replace both OBM and WBM. This view is also supported by some members of industry [1]. There are a number of possible explanations for this occurrence.

The first legislation limiting discharge was introduced in January 1989. To comply, industry turned to a mixture of solutions from those outlined in section 2.4. One of the solutions would have been to use WBM where OBM had previously been used. POBM was not one of the solutions immediately sought by industry because as Table 2.1 shows, the first well drilled with POBM on the UKCS was in May 1991, a period of 16 months from the introduction of the first legislation. There are a number of possible explanations for this delay:

- The technology may not have been sufficiently developed in time for the introduction of the new legislation.
- Operators may have been initially unconvinced about POBM performance being able to emulate that of OBM.
- Operators may have been initially unconvinced about POBM economics. Mud costs are typically US$30/bbl for WBM, US$60/bbl for OBM, and between US$100/bbl and US$400/bbl for POBM [1]. Operators may have weighed the reduced cost of WBM against the increased risk of drilling problems, and concluded that WBM would be more economical.

The most likely scenario then seems that operators partially turned to WBM to comply with the new legislation imposing discharge limits. Later, when POBM technology was sufficiently developed, or their performance and economics were understood, then some operators turned from WBM to POBM.

In January 1997, a further tightening of UK legislation came into force. The discharge limit for oil on cuttings for development wells was reduced from 100 g/kg to 10 g/kg to bring them into line with exploration and appraisal wells. This will probably result in a further increase in the use of POBM for this year [1].

### 2.7 Future POBM Usage

Efforts are being made to achieve pan-European harmonisation of the toxicity test limits, biodegradability limits, protocols and species used for both POBM and OBM assessment [5]. In 1994, the UK DTI began to prepare draft guidelines on the use of POBM's, including an 'ALARA' (As Low As Reasonably Achievable) principle on pseudo oil discharged on cuttings [5]. In Norway, operators have been requested to investigate means of reducing pseudo oil discharged on cuttings, however in the Netherlands, there are no limits at present for pseudo oil discharge [5].

A development which may affect the use of POBM in the longer term took place in December 1996. The Marine Laboratory of the Scottish Office Agriculture, Environment and Fisheries Department carried out a series of experiments in a
simulated seabed environment on POBM biodegradation and bioaccumulation. The results suggest that the effect of various pseudo oils on the environment is not significantly better than mineral oil. The ester oil performed best, although, its use is limited because of temperature restrictions. A consequence of this investigation might be that the current legislation is widened to cover POBM [1].

Whilst POBM and OBM have comparable performance, POBM is considerably more expensive. The advantage of POBM is there are no restrictions on its discharge. If POBM is given an equivalent legislative status to OBM then this advantage would disappear and, it is widely believed in industry that POBM would be phased out within 18 to 36 months [1].

On the other hand, it has been claimed that at least one operator would continue to use POBM for some specialist work where its performance is thought better than for OBM. Also on the plus side, it as been claimed that POBM can exhibit performance characteristics such as lubricity, hole cleaning, barite sag reduction and rate of penetration that are at least comparable to, or often better than, OBM.

Rate of penetration is claimed to be particularly high with POBM. For instance, a PAO fluid has set drilling records in the Ekofisk field and in the Gulf of Mexico, and other records have also been accomplished by both the ester and ether based systems in the North Sea. For a particular mud system, it is claimed that a more useful method of assessing well costs is feet-drilled per dollar (ft/$). Cost savings in utilising OBM as compared to WBM on many wells is readily realised by this method. Due to greater rates of penetration with POBM, many operators have seen additional savings over OBM [10].

Mud costs per barrel are typically US$30/bbl for WBM, US$60/bbl for OBM, and between US$100/bbl and US$400/bbl for POBM [1]. The earlier POBM systems to be used on the UKCS were the most expensive (Ester, Polyalphaolefin (PAO), Ether, Acetal), however subsequent systems to be developed (Linear alphaolefin (LAO), Internal olefin (IO), Linear paraflin (LP)) are cheaper, bringing them nearer to OBM cost. Also, a number of POBM systems can be reconditioned or reprocessed, thus allowing the operator to recover costs on the mud system [6, 22].

A number of wells have recently been drilled in the Netherlands using POBM where no discharge of oily cuttings took place. The primary criterion for using POBM could not, therefore, have been one of acceptability of discharge. POBM was used in nearly 15 wells by the end of 1995. Other than the first well, all operations have involved zero discharge or were land wells where the cuttings were hauled away. Performance played a major role in operators preferring to use POBM for these wells. The existing land rig sites were designed for use with WBM, however, no modifications were required to use POBM because of their good environmental performance. Additionally, occupational health and safety considerations of POBM as compared to LTOBM contributed to the approval by the State Supervision of Mines (SSM). Another factor in deciding the type of POBM to be used was the possibility for recycling [10, 22].
3. **CHEMICAL AND PHYSICAL PROPERTIES**

There has been an interest on the UKCS in the full range of OBM health and safety issues over recent years [29] and, as a result, these issues are now familiar to the HSE and industry. The issues themselves can be derived from, or at least explained in terms of, the chemical and physical properties of the OBM. By comparing the properties, an understanding can be reached as to how the health and safety issues may differ between OBM and POBM, see Figure 3.1.

![Diagram](image)

**Figure 3.1 Relation between Health & Safety Issues and Properties for OBM and POBM**

In this section, the physical and chemical properties of POBM and OBM are compared to lay the foundation for a consideration of their differing associated health and safety issues.
3.1 **Generic Mud Formulation**

All mud systems, no matter the constituent components, must perform similar tasks. How these tasks are related to mud properties is shown in Table 3.1.

<table>
<thead>
<tr>
<th>MUD TASKS</th>
<th>MUD PROPERTIES</th>
<th>MUD COMPONENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>control formation pressure</td>
<td>density</td>
<td>barite</td>
</tr>
<tr>
<td>carry cuttings out of the hole</td>
<td>low shear rheology - gel strength</td>
<td>lime, low end rheology modifier, base fluid</td>
</tr>
<tr>
<td>stabilise the wellbore to prevent it from caving in</td>
<td>mud water activity less than salt/clay sequence</td>
<td>dispersed water phase, emulsifier, salts (e.g. CaCl₂), clays (e.g. organophilic clays)</td>
</tr>
<tr>
<td>cool and lubricate the drill bit</td>
<td>high shear rheology - lubricity</td>
<td>Mineral oil base, pseudo/synthetic oil base, water base with polymer, viscofier</td>
</tr>
<tr>
<td>cool and lubricate the drill string</td>
<td>high shear rheology - lubricity</td>
<td>Mineral oil base, pseudo/synthetic oil base, water base with polymer, viscofier</td>
</tr>
<tr>
<td>help in the evaluation and interpretation of well logs</td>
<td>low filtration</td>
<td>fluid loss control additive</td>
</tr>
</tbody>
</table>

Mud systems, whether POBM or OBM, have very similar compositions in terms of the relative proportions of chemicals required to perform the necessary tasks expected of a mud. For different mud systems, different chemicals are chosen to perform these tasks. The composition of generic oil mud system is shown in Table 3.2.

In an oil mud system, the task of the base oil is to provide a continuous medium through which all the functions expected of the mud system can be achieved.

<table>
<thead>
<tr>
<th>TABLE 3.2 Generic Oil Mud Composition [2, 16, 23]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TYPICAL OIL MUD FORMULATION</strong></td>
</tr>
<tr>
<td><strong>CONSTITUENT</strong></td>
</tr>
<tr>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Base oil (pseudo/synthetic/mineral)</td>
</tr>
<tr>
<td>Primary emulsifier</td>
</tr>
<tr>
<td>Secondary emulsifier</td>
</tr>
<tr>
<td>Viscosifier</td>
</tr>
<tr>
<td>Fluid loss control additive</td>
</tr>
<tr>
<td>Low end rheology modifier</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>CaCl₂</td>
</tr>
<tr>
<td>Lime</td>
</tr>
<tr>
<td>Barite</td>
</tr>
<tr>
<td>Organophilic clay</td>
</tr>
</tbody>
</table>

Emulsifiers are selected from a wide group of chemicals known as surfactants, which act between the surfaces of substances. The emulsifiers in mud systems act between the oil and water maintaining the water in the dispersed droplet phase. One drawback
is that emulsifiers can also act between the oil and the surface of the cuttings, producing high OOC ratios and detrimental effects on the environment [19].

Viscosifiers and rheology modifiers are used to engineer the mud rheological properties regarding shear, temperature and pressure. For instance, low friction losses may be required at high shear, however, at low shear (e.g. shut-in) high viscosity is required to hold the cuttings in suspension, and thus avoiding stuck pipe through packing of cuttings around the bottomhole assembly (BHA).

Water is the dispersed phase, and is included as a medium to hold various salts (e.g. CaCl₂) and clays (e.g. Organophillic clays) whose function is to stabilise the drilled formations.

The chemical components of a mud are selected on their ability to perform the above tasks. A number of different chemical components could be used to achieve a specific task. The decision to use one component over another depends on efficacy and cost. Recently, however, other factors are being taken into consideration, such as environmental effects and health and safety consequences, in selecting mud components [1].

3.2 PSEUDO AND MINERAL BASE OIL TYPES

Various starting points for definitions of what constitutes a POBM were considered in Section 2.5. Chemical and physical properties, and method of production were shown to be unsatisfactory starting points for a legal definition that could be applied to discharge limits. A definition of POBM in terms of environmental effect seemed the most appropriate since, originally, environmental considerations drove the development of POBM. However, such a definition would ultimately make the label of POBM redundant. Future research into the effect of discharged mud could result in a tightening or relaxing of the pass criteria, thus making the label of POBM meaningless - a mud system would either pass or fail.

While no adequate definition of a POBM exists in terms of chemical and physical properties, when people in industry talk of POBM, or SBM, on the UKCS [1] they are referring to mud systems which have the following base fluids:

- Ester
- Ether
- Acetal
- Polyalphaolefin (PAO)
- Linear alpaolefin (LAO)
- Internal olefin (IO)
- Linear parafin (LP)
- Linear alkylbenzene (LAB)

Friedheim and Conn [22] separate the above base fluids in terms of when they were first applied as drilling base fluids: first and second generation fluids. First generation fluids were first introduced around 1991. Second generation fluids were first introduced around 1994, and tend to be cheaper and less viscous than first generation fluids. The chemical structure of the first generation fluids are shown in Figure 3.2 below:

**Ester**

\[
\text{CH}_3 \rightarrow (\text{CH}_2)_n \rightarrow \text{C} = \text{O} \\
\text{O} \rightarrow (\text{CH}_2)_m \rightarrow \text{CH}_3
\]

**PAO**

\[
\text{CH}_3 \rightarrow (\text{CH}_2)_n \rightarrow \text{C} = \text{CH} \rightarrow (\text{CH}_2)_m \rightarrow \text{CH}_3 \\
(\text{CH}_2)_p \rightarrow \text{CH}_3
\]

**Ether**

\[
\text{CH}_3 \rightarrow (\text{CH}_2)_n \rightarrow \text{O} \rightarrow (\text{CH}_2)_m \rightarrow \text{CH}_3
\]

**Acetal**

\[
\text{CH}_3 \rightarrow (\text{CH}_2)_n \rightarrow \text{O} \rightarrow (\text{CH}_2)_m \rightarrow \text{CH}_3 \\
\text{CH} \rightarrow (\text{CH}_2)_p \rightarrow \text{CH}_3
\]

**Figure 3.2 First Generation Pseudo Base Oils [22]**

The chemical structure of second generation fluids are shown in Figure 3.2.

**LAO**

\[
\text{CH}_3 \rightarrow (\text{CH}_2)_n \rightarrow \text{CH} = \text{CH}_2
\]

**IO**

\[
\text{CH}_3 \rightarrow (\text{CH}_2)_n \rightarrow \text{CH} = \text{CH} \rightarrow (\text{CH}_2)_m \rightarrow \text{CH}_3
\]

**LP**

\[
\text{CH}_3 \rightarrow (\text{CH}_2)_n \rightarrow \text{CH}_3
\]

**Figure 3.3 Second Generation Pseudo Base Oils [22]**
The above chemical formulae show that the functionality of pseudo base oils is
determined by saturated carbon-carbon single bonds, carbon-carbon double bonds or
by the presence of oxygen. Thus pseudo oils can exhibit a wide range of physical and
chemical properties. The letters n, m and p refer to integers representing the number
of carbon atoms. Pseudo oils in the marketplace are all the size range of C_{18} - C_{24}.

Equally, no rigorous definition exists of what constitutes a mineral oil, however, when
the term ‘mineral oil’ is used it is generally accepted within industry what type of oil
is being described, i.e. one that can be derived from crude oils, and is a mixture that
can contain several thousands of different components. Carbon compounds within a
typical mineral oil can contain a single carbon atom (methane) and anything up to 100
carbon atoms. These carbon compounds can also contain small amounts of oxygen,
nitrogen and sulphur, and trace amounts of heavy metals may be present. The carbon
compounds that go to make up a mineral oil can be placed in five categories [31]:

- **Parafin**: straight-chain or branched saturated hydrocarbons, similar to LP in Figure
  3.2.
- **Naphthene**: cyclic saturated hydrocarbons.
- **Aromatic**: contains one or more benzene rings.
and to a lesser extent,
- **Olefin**: hydrocarbon containing a double bond, similar to LAO in Figure 3.2.
- **Diolefin**: olefin with two double bonds.

Different mineral oils will have different proportions of the chemicals from each of
these categories, however, the chemical functionality of mineral oils is dominated by
saturated carbon-carbon single bonds, so their chemical and physical properties are
usually similar.

### 3.3 Pseudo and Mineral Base Oil Properties

Mineral oils are typically composed of thousands of different types of carbon
compounds, and different mineral oils will contain different proportions of these
compounds. However, the mineral oils used to formulate drilling muds exhibit similar
chemical properties because, for the majority of molecules the chemical functionality
is determined by the saturated carbon-carbon bond. They also exhibit similar physical
properties because the range and quantity of molecular structures within each mineral
oil is broadly the same.

It is understood that only eight different types of pseudo oil have been used on the
UKCS to date. These have been used either individually or within blends of pseudo
oil. However, despite the reduced number of components, pseudo oils exhibit a much
wider variation in chemical and physical properties than is the case for mineral oils.
This is because pseudo oils display a wider range of chemical functionality and chemical structures as can be seen from an inspection of Figures 3.2 and 3.3.

The physical properties of the various pseudo base oils, mineral base oils of diesel and low toxicity mineral oil (LTMO), and what would be considered an 'ideal' base oil are shown in Table 3.3. These are the chemical and physical properties that have a bearing on health and safety.

**Table 3.3 Base Oil Physical Properties [2, 5, 17, 18, 22, 23]**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td></td>
<td>ALAP</td>
<td>No</td>
<td>0</td>
<td>0</td>
<td>AHAP (≥120)</td>
<td>High (≥250)</td>
<td>0</td>
</tr>
<tr>
<td>Mineral Oils</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td>0.85</td>
<td>3.3</td>
<td>Yes</td>
<td>?</td>
<td>?</td>
<td>66</td>
<td>?</td>
<td>25</td>
</tr>
<tr>
<td>LTMO</td>
<td>0.79</td>
<td>3</td>
<td>Yes</td>
<td>0.99</td>
<td>0.97</td>
<td>95+</td>
<td>High</td>
<td>5</td>
</tr>
<tr>
<td>Pseudo Oils</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ester</td>
<td>0.85</td>
<td>5.6</td>
<td>?</td>
<td>1.27</td>
<td>1.49</td>
<td>&gt;150</td>
<td>150</td>
<td>0</td>
</tr>
<tr>
<td>PAO</td>
<td>0.80</td>
<td>6.7</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>160</td>
<td>High</td>
<td>0</td>
</tr>
<tr>
<td>Ether</td>
<td>0.83</td>
<td>6</td>
<td>?</td>
<td>1.87</td>
<td>1.66</td>
<td>&gt;120</td>
<td>180-200</td>
<td>0</td>
</tr>
<tr>
<td>Acetel</td>
<td>0.84</td>
<td>3.5</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>&gt;120</td>
<td>180-200</td>
<td>0</td>
</tr>
<tr>
<td>LAB</td>
<td>0.86</td>
<td>4.0</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>126</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>LAO</td>
<td>0.78</td>
<td>2.1-2.7</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>113-135</td>
<td>?</td>
<td>0</td>
</tr>
<tr>
<td>IO</td>
<td>0.78</td>
<td>3.1</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>137</td>
<td>?</td>
<td>0</td>
</tr>
<tr>
<td>LP</td>
<td>0.77</td>
<td>2.5</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>&gt;100</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>Rape Seed Oil</td>
<td>0.90</td>
<td>32.5</td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>High</td>
<td>125</td>
<td></td>
</tr>
</tbody>
</table>

The viscosity values in Table 3.3 are shown to convey a feeling for the rheology of each base fluid. Ideally, the viscosity of the base oil should be as low as possible (ALAP). The desired rheology profile can then be constructed by adding viscosifying agents. The viscosity of the first generation pseudo oils (ester, PAO, ether, acetel) is much higher than for the mineral oils and second generation pseudo oils (LAO, IO, LP). The rheology of pseudo oils, particularly the earlier ones, is such that they tend to be more viscous than mineral oils at low shear and usually less viscous at high shear, and their rheology tends to have a greater temperature dependence, resulting in greater thinning at higher temperatures [6, 9].

The solubility of hydrocarbon kick gas within mineral oil has received at great deal of attention over recent years. Gas entering the wellbore downhole will displace a volume of mud from the well capsizing an increase in the mud pit level observable on the rig floor, this is known as a ‘pit gain’ and is one method of detecting gas kicks. The net volume downhole of mud and dissolved gas will be less than the volume of the separate mud and free gas, therefore, gas solubility tends to mask the presence of the gas kick, reducing the pit gain observed at surface, and thus making kicks more difficult to detect. Gas solubility in mineral oils affects the efficacy of well control
attempts and therefore has implications for health and safety. Gas solubility may be an issue for pseudo oils, particularly in high pressure high temperature (HPHT) wells [10]. It has been reported that gas solubility data has been measured for at least one commercial POBM system [1]. It is generally accepted that the solubility of gas in pseudo oil is similar to, or less than for, mineral oil [1]. This has been corroborated somewhat in one simulation study [28] where gas solubility in pseudo oil was assumed to be 25% less than for a typical mineral oil.

The compressibility and expansivity of a fluid are measures of the change in density with changes in pressure and temperature, respectively. It is claimed that there are small, but not insignificant, differences between mineral oil and pseudo oil compressibility and expansivity [1, 10]. These differences can be explained in terms of the structure of the molecules in each of these type of oil. The degree of linearity of a molecule is proportional to the degree of compressibility and expansivity. Molecules within some pseudo oils tend to be fairly linear (see Figures 3.2 and 3.3), therefore, some pseudo oils can be expected to exhibit a relatively high degree of compressibility and expansivity. Molecules within mineral oils vary in size and shape (small or large, or linear, branched or cyclic), therefore, changes in pressure and temperature cannot result in significant movement of the molecules past each other to occupy a different volume. Mineral oils can be expected to exhibit a relatively low degree of compressibility and expansivity.

The flash point of a substance is the temperature (at atmospheric pressure) at which a liquid will flash over to become a vapour. As the temperature is increased towards the flash point, increasing amounts of vapour will be given off, until at the flash point the entire liquid vaporises. At a particular ambient temperature, a lower flash point liquid will produce more vapour than a higher flash point liquid. Ideally, the flash point of the base oil should be as high as possible (AHAP). Pseudo oils tend to have higher flash points than mineral oils [8, 22], thus implying that fewer vapours are given off and, consequently, vapour build up and subsequent flammability are less likely.

The hydrolytic stability of a base oil refers to its tendency to react in the presence of water. The hydrolytic thermal stability of a substance can be expressed as a temperature above which it will react with any water present. For example, of all the possible base oils, ester has the lowest hydrolytic thermal stability of 150°C, see Table 3.3. Above this temperature, the ester and water react to form a vegetable oil fatty acid and an alcohol. The hydrolytic stability of a base oil can be important since, during reaction with water, other derivatives may be formed which are toxic to rig personnel.

Some aromatic compounds (e.g. benzene and polycyclic aromatic hydrocarbons) are carcinogenic. The high percentage of aromatic in diesel contributed to this base fluid being banned on the UKCS in 1984. Low toxicity mineral oil (LTMO) contain far less, but still significant amounts of, aromatic. Linear alkylbenzene (LAB) based mud was used to drill 33 wells on the UKCS before being withdrawn. The question surrounding LAB was how can a fluid having an aromatic content be regarded as environmentally acceptable. The initial reason for their approval was based on the old
UK OCNS rather than the present one. When subject to the new criteria, LAB were not approved as Category ‘E’. LAB is aromatic in the sense that it is a dodecylbenzene. In another sense, however, this categorisation is less clear since it does not contain any simple aromatic compounds like benzene, xylene and toluene. These are characteristically found in diesel and, albeit at low levels, in low toxicity mineral oils (LTMO). Attempts were made to measure benzene in air and benzene in the pseudo oil, however, no benzene was ever actually found [1]. Linear paraffin can be produced by two means, synthesis which is expensive but produces a pure product, or fractional distillation which is cheaper, however, the product may become contaminated with aromatic somewhat.

3.4 ADDITIVE PROPERTIES

In Section 3.1, the tasks a mud system has to perform were related to the mud properties and to the mud components. For oil mud systems the primary function of the base oil, whether mineral or pseudo, is to provide a continuous medium through which all the tasks of the mud system can be achieved. The additives give the mud system its properties.

The primary property of any additive is directly related to its particular task. For example, the first requirement of an emulsifier is that it should hold water in the dispersed phase, the first requirement of a rheology modifier is that it should modify the mud rheology in the intended way. Different additives will be better than others e.g. operate at higher temperatures, higher pressures, greater brine concentrations etc. In the context of this report, however, the interest in additives lies in any secondary chemical and physical properties (as it did for base oils) that raise health and safety issues.

Additives can be separated into two groups: those that are common to almost all mud systems and those specific to a particular mud system. Additives common to almost all mud systems are water, barite, lime, various salts (e.g. CaCl₂), and various clays (e.g. organophilic clay) the function of these additives and any side-effects regarding health and safety are largely known [2, 1, 16, 23]. Additives specific to particular mud systems are the emulsifiers, viscosifiers and rheology modifiers, loss control additives, and other specialist agents. These additives largely determine how well the mud system performs. The exact chemical composition and physical properties of the additives are commercially sensitive and mud companies have naturally been reluctant to provide specific compositions and formulae [1]. However, a number of mud companies have been prepared to offer some information on whole mud properties such as volatility and toxicity.

Additives used in the formulation of POBM, can be the same as those used in OBM. However, certain OBM additives required the presence of aromatic hydrocarbons to function efficiently (e.g. organophilic clays). Additionally, since the toxicity of the continuous phase was reduced substantially, both in terms of the effect on rig personnel and the seabed environment, the toxicity of the additives become more evident and improvements in this respect become an important issue [2].
As outlined in the previous section, the hydrolytic thermal stability of pseudo oils are generally comparable to those of mineral oils. However, POBM has generally been limited to lower temperatures (250-350°F) than OBM’s (400-500°F). The reasons for this have not been clear, but apparently arise from the chemical composition of the POBM. To determine which constituents are responsible for the low thermal stability of these muds, chemical degradation tests were carried out on the individual mud components. Thermal degradation experiments clearly demonstrate that the pseudo oils themselves are stable to at least 425°F. Of all the other constituents present in POBM’s, the emulsifiers (surfactants) and low-shear rheology modifiers (oligomers of fatty acid emulsifiers) are probably the most susceptible to thermal degradation. The emulsifiers used degrade at around 200-300°F [6]. It could be possible that within the whole mud, especially if there are any oxidants present, quite toxic materials could be produced [1].
4. DIRECT HEALTH AND SAFETY ISSUES

The health and safety issues associated with the use of POBM can be divided into two categories. In the first category are those health and safety issues that are clearly derivable from known properties (i.e. there is a direct causal link between a particular property and a particular health and safety issue). The second category consists of those health and safety issues that would not immediately seem derivable from known properties (i.e. there is a complex causal link between a particular property, or set of properties, and a particular health and safety issue).

This section is concerned with the health and safety issues in the first of these two categories. Events such as divers encountering skin problems around the seals of their dry suits when working near seabed cuttings piles [1] are examples. There is a direct link between the POBM property (the fact it can cause skin problems) and the health and safety issue (what is an acceptable level of exposure?). Other health and safety issues directly related to POBM properties, considered in this section, are flammability, drilling equipment corrosion, spills on the rig floor, and toxicity to rig personnel.

4.1 FLAMMABILITY

All oils, whether pseudo or mineral, are flammable to some extent. The main risk of fire stems from the build up of flammable vapours in enclosures such as the mud room. The flammability of a mud system will depend on the amount of water present which is usually between 5% - 45%, and therefore, a lot of the vapour in the mud room can be expected to be water vapour which reduces the flammability of the vapour mixture.

Pseudo oils tend to have higher flash points than mineral oils (see Table 3.3), implying that less vapour is given off, and therefore, that the risk of ignition would be less with pseudo oils than with mineral oils [8, 25]. The total vapours emitted for various pseudo oils and low toxicity mineral oil (LTMO) for various temperatures are shown in Table 4.1. As can be seen, pseudo base oils tend to be much less volatile than mineral oils.

**Table 4.1 Vapours Released for Base Oils at Various Temperature [22]**

<table>
<thead>
<tr>
<th>Base Oil Category and Type</th>
<th>Total Vapours [ppm]</th>
<th>Aromatic Content [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>@ 40°C</td>
<td>@ 65°C</td>
</tr>
<tr>
<td>Mineral Oil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LTMO</td>
<td>2.7</td>
<td>14</td>
</tr>
<tr>
<td>Pseudo Oil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ester</td>
<td>&lt; 1.0</td>
<td>2.3</td>
</tr>
<tr>
<td>PAO</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>LAO</td>
<td>3.9</td>
<td>37.0</td>
</tr>
<tr>
<td>IO</td>
<td>2.1</td>
<td>7.3</td>
</tr>
</tbody>
</table>
4.2 DRILLING EQUIPMENT CORROSION

Drilling fluids can chemically alter the properties of elastomers used in drilling equipment, severely affecting operational lifetime and function. The products affected include blowout preventers (BOP), pulsation dampeners, downhole mud motors, drill bits, pump seals and rig cabling [1, 7, 15]. Elastomers are developed and selected for mechanical performance. The emergence of POBM has caused tool manufacturers and operators to examine the effect of drilling fluids on their equipment.

A series of tests have been conducted on the effect of a number POBM systems on a range of seal components [15]. Changes in hardness were recorded in the range -26 Shore A points to +8 Shore A points. These recorded changes are equilibrium values and took around 50 hours to achieve. Changes in volume were recorded in the range of -10% to +30%. These recorded changes are equilibrium values and took around 150 hours to achieve. Changes in tensile strength were recorded in the range of -50% to +25%. Changes in elongation were recorded in the range of -80% to +60%. Despite these apparently large changes, only one of the pseudo oils examined, an ester based mud, was reported to cause elastomer property changes that would materially affect its operation.

All elastomeric and rubber components will be affected to some extent on exposure to oils, however the degree varies with the type of product. It is generally considered that oils with a low aniline point (<150°F) have the greatest effect on rubber parts. The aniline point is the temperature at which a mixture of aniline and an equal volume of petroleum throws down a second liquid phase as the temperature is lowered. Mineral oils have low aniline points (~150°F) because aromatic content suppresses them. Oils with a high relative aromatic content have a low aniline point, and vice versa. Pseudo oils usually have higher aniline points. Mineral oils are expected to have a greater detrimental effect than most pseudo oils. An exception is natural, esters, which have aniline points around 46°F and would therefore be expected to be most detrimental to rubber components [1].

4.3 SPILLS ON RIG FLOOR

Accidental spillages of pseudo oil or POBM on the rig floor must be avoided for two reasons, their effect on the insulation of electrical cables and the slip hazards posed to rig personnel.

As discussed above, POBM can effect rubber and plastic components to some degree. Spillages of POBM on electrical cable may corrode the insulation of the cable thus exposing potential ignition sources [1].

The high lubriucity of the POBM systems means that care must be taken to contain any accidental spills to avoid injury caused by rig personnel slipping. The emphasis should be on spill avoidance where possible and immediate containment should a spill occur to minimise the risk. The use of non-slip paints and non-slip mats on the rig floor has proved successful [16].
4.4 TOXICITY TO RIG PERSONNEL

A consideration of the toxic effects of POBM and OBM to rig personnel can be divided into three categories: vapour contact, aerosol contact, and direct contact.

4.4.1 VAPOUR CONTACT

During drilling, mud circulated through the wellbore becomes hotter due to the geothermal temperature downhole. At surface, the mud is returned at temperatures that can be significantly above ambient. The mud is directed to the mud room, housing the mud pits and the shale shakers, where vapours build up. The toxic effect these vapours have on the rig personnel working in the mud room will depend on the volatility of the mud components and on their intrinsic toxicity. The vapours released for pseudo oils at various temperatures are shown in Table 4.1. As can be seen pseudo oils release fewer vapours than mineral oils and the aromatic content of the pseudo oils is lower than for mineral oils. This would suggest that exposure to pseudo oil vapour poses less of a health and safety risk than exposure to mineral oil vapour.

Additives present in POBM may possibly be volatile and toxic to rig personnel, however, surveys on vapour concentrations show an improvement over OBM use [1], suggesting the effect of additives can be no worse than for OBM.

In recent years, there has been an improvement in the conditions within mud rooms. Before the use of diesel was banned for all wells on the UKCS in November 1984, reports of personnel working in mud rooms filled with 'impenetrable white fog' were recorded [1]. The introduction of LTMO muds with lower aromatic contents, and therefore lower toxicities, and subsequently POBM with their very low aromatic content is partly responsible for this improvement. The second reason for improvement is probably due to the introduction offshore of The Control of Substances Hazardous to Health Regulation (COSHH) [1] which lead directly to improved ventilation in the mud rooms.

4.4.2 AEROSOL CONTACT

With low volatility liquids such as POBM, exposure to aerosols is likely to be of more significance than exposure to vapours, so the comparison of vapour levels may not be paramount when considering toxicity to rig personnel. Any comparison of the toxic effects of POBM and OBM and the ease of exposure control, would rely on a comparison of operational exposure limits (OEL) for aerosols. For example, Appendix 6 of EH/40/96 [30] sets an OEL of 5 mg/m³ (8-hour time average weighted (TWA)) for oil mist from mineral oils. No OEL values are presently available for any of the pseudo oils.
4.4.3 **Skin Contact**

The label of pseudo oil covers a group of substances with a far wider range of chemical and physical properties than is the case for mineral oil. Pseudo oils can be selected from chemical groups such as ester, ether, acetal, polyalphaolefin (PAO), linear alphaolefin (LAO), internal olefins (IO) and linear paraffins (LP). Within each of these groups there is a wide selection of variants to choose from. For example, when setting out to design one particular mud system, 21 different base esters were evaluated before a fish oil based ester was finally chosen [23]. Therefore, any generalisations made about pseudo oil properties must be treated cautiously. However, on the whole, pseudo oils are considered to be less toxic to rig personnel than mineral oil because they have a much reduced, or zero, aromatic content [1].

The toxicity of the additives becomes more evident as the toxicity of the continuous phase is reduced. Additives utilised in the formulation of POBM may well be similar to those used in OBM. However, certain OBM additives require the presence of aromatic hydrocarbons to function efficiently e.g. organophillic clay (see Table 3.2). It is not clear whether such additives are used in POBM or whether less toxic equivalents are being used.

Information on the toxicity of other, less specialised, mud components in Table 3.2 has been obtained. Calcium chloride and lime can be detrimental to the skin-by causing severe dehydration [1, 23]. Also, organophillic clays contain aromatic hydrocarbons, the toxicity of which become more evident when the toxicity of the continuous phase is reduced substantially [2].

The exact chemical composition of the specialist additives are commercially sensitive and companies are naturally reluctant to divulge specific compositions and chemical formulae. Also, it appears that the range of chemicals that can be considered as suitable additives is potentially very large [6, 23]. Continuing with the above example, once a suitable fish based ester was decided upon, it was then evaluated with a total of 74 emulsifiers from different suppliers before the final selection of emulsifier was made.

Since knowledge of specialised mud additives is limited and there is such a wide range of potential additives, the approach has been to focus on pseudo base oil and whole-mud toxicity rather than on the toxicity of all the individual POBM components. The results of a series of toxicity tests conducted on an ester pseudo base oil and whole mud system are given in Table 4.2.
In Table 4.2, the numbers refer to arbitrary toxicity scales. The OECD 404 protocol [27] for skin irritation describes tests for both erythema (redness) and oedema (swelling). The higher the number, the greater the toxic affect. For erythema, the scale ranges from ‘0’ which is no erythema to ‘4’ which is sufficiently severe to prevent grading of erythema. Values of 1.2 and 1.4, as shown in Table 4.2, lie between ‘1’ which is very slight erythema (barely perceptible) and ‘2’ which is well defined erythema. For oedema, there is a similar scale that ranges from ‘0’ which is no oedema to ‘4’ which is severe oedema (raised more than 1 mm and extending beyond area of exposure). Values of 0.3 and 0.5, as shown in Table 4.2, lie between ‘1’ which
represents a very slight oedema (barely perceptible) and '0' which represents no oedema. Rig workers handling POBM and encountering direct skin contact have reported problems [1].

The OECD 405 protocol [27] for eye irritation tests for cornea opacity, iris lesion, oedema of conjunctiva, and redness of conjunctiva. Again, the higher the number, the greater the toxic effect. A value of '0' represents normality or no reaction for all tests. A value of '1' for the oedema of conjunctiva test indicates any swelling above normal (includes nicating membranes).

It should be kept in mind that these tests are direct animal tests, and the potential effects may be different for handling by human beings at the rig site. The introduction of POBM has been associated with some reports of dermatitis, whether this was due to the pseudo oil or an additive is not always known, although in one case the pseudo oil itself seems to be the cause [1].

Another possible source of potentially toxic chemicals, apart from the pseudo oils and additives, could be downhole reaction products. It has already been discussed in Section 3.3 that above the hydrolytic stability temperature a base oil will react with water forming a multitude of reaction products, some of which may be quite toxic. For ester muds, it has been suggested that aldehydes, which could be toxic to rig personnel when they are circulated to the surface, might be formed downhole [1]. The presence of additives complicates matters further since they will also have limiting temperatures above which they will decompose. The resulting chemical products could be toxic themselves or react with the pseudo oil to produce toxic by-products [1].
5. COMPLEX HEALTH & SAFETY ISSUES

This section is concerned with the health and safety issues in the second of the two categories defined at the beginning of Section 4. These are the health and safety issues that would not immediately be apparent from known properties (i.e. there is a complex causal link between a particular property, or set of properties, and a particular health and safety issue). Human factors and well control are complex health and safety issues.

5.1 HUMAN FACTORS

Perception of the safety risk posed by POBM is an important part of the overall safety picture surrounding their use. For example, rig personnel may assume that since POBM is described as ‘safer’ than OBM then it is entirely ‘safe’, and stop using gloves and barrier creams, thus, resulting in skin problems [1].

While in general, the health and safety issues associated with POBM are considered to be at least the same as, or less severe than, for OBM, a mis-perception of POBM properties may in itself generate safety problems.

5.2 WELL CONTROL

Well control texts describe the behaviour of an idealised gas kick, whereby the gas is assumed to behave as a single bubble rising up the wellbore. This model can attempt explanations and predictions for initiation, detection and development of the gas kick together with the subsequent application of well control. Despite being an idealised description this model has had some success in describing gas kicks in WBM.

In the 1980’s, there was some confusion about the interpretation of well responses for gas kicks in OBM. The single bubble model seemed unable to account for well behaviour. Typically, little or no pit gain would be seen, and thus, the rig crew would detect the kick only during the later stages of its development and thus have less time to implement well control procedures.

The different well responses are due to the difference in kick gas solubility in WBM and OBM. At high pressure, hydrocarbon gas will dissolve in the base oil of OBM. On dissolution, the oil and dissolved gas occupy a volume smaller than would be occupied by the oil and free gas, therefore, the pit gain is reduced and the kick is more difficult to detect. Solubility tends to mask the presence of a gas kick.

A number of initiatives were taken to minimise the effect this physical phenomena has on the safety risk to rig personnel and operations. Experiments were carried out to determine the solubility of gas in various mineral oils at elevated pressures and temperatures. Algorithms have been developed using correlations derived from these experimental results. Simulation tools have been developed which incorporate these algorithms and which predict the well responses from gas kicks in OBM. Some of these simulators have been validated against field data and full scale kick experiments.
Advanced gas kick simulators contain not only detailed algorithms on gas solubility, but also frictional losses, two-phase flow, rheology and most other physical phenomena and operational procedures relevant to gas kicks and well control. While the safety implications of gas solubility in OBM were the initial driving force behind the development of kick simulators, they are now a valued tool used to interpret all kinds of well control events.

After over a decade of investigation and research into OBM well control issues, it would be expected that these are now familiar to the HSE and industry. In this section, the differences between POBM and OBM that may affect well responses for the development of gas kicks and the application of well control are discussed. The most significant differences are considered to be gas solubility, compressibility and expansivity, and rheology. Information from the literature and industry dialogue is assessed on the basis of the differences in chemical and physical properties between POBM and OBM.

5.2.1 GAS SOLUBILITY

Over the preceding decade, a large amount of work has been done to better understand the phenomenon of gas solubility in OBM. Hamilton [29] provides a good starting point from which to trace references covering the results of this work.

Friedheim [10], in February 1995, raised the prospect of kick gas solubility within pseudo base oil being a possible issue, particularly for high temperature high pressure (HTHP), drilling. It is known that at least one mud supply company has made gas solubility measurements for one of their mud systems [1].

It is generally accepted that the solubility of gas in pseudo base oil is similar or less than for mineral oil [1]. This has been corroborated somewhat in one simulation study [28] where gas solubility in pseudo oil was assumed to be 25% less than for a typical mineral oil.

Despite mineral oils being made up of a multitude of components, the variation in the proportion of these components is not particularly large across different mineral oils used in mud formulations. The variation of gas solubility, therefore, across the various mineral oils would not be expected to be too large.

On the other hand, the pseudo oils used on the UKCS make up a much smaller grouping of chemicals. They exhibit, however, a much wider range of chemical functionality and display a wider range of physical properties. It would be expected, therefore, that gas solubility could vary significantly across the pseudo oils. The gas solubility in LP, for instance, could be expected to resemble that of mineral oil [1], whereas, the gas solubility for an ester might be very different.

Opinion expressed on the differences in gas solubility between POBM and OBM [1] is generally based on experience with only a limited number of systems. Extrapolating such opinion to all pseudo oil muds is unwise.
Some sources state that there is only a slight difference in gas solubility between POBM and OBM. Such opinions may have developed from experience with LP pseudo oil muds where the properties resemble those of mineral oil. Other sources state that the gas solubility can be significantly less with pseudo rather than mineral oil. These opinions may have developed from experience with pseudo oils very different to mineral oil, such as ester for example [1].

If, in general, the solubility of gas in pseudo oils is comparable to that in mineral oils, then this safety aspect is no worse. If the solubility is lower, then less of the gas influx, and thus pit gain, is masked and detection may be made earlier and well control applied sooner, thus reducing the safety risk.

5.2.2 COMRESSIBILITY AND EXPANSIVITY

Downhole, the volume occupied by a quantity of mud will depend on the local pressure and temperature. The pressure downhole can be many thousands of psi because of the weight of the mud column, and the temperature can be many hundreds of degrees Fahrenheit because of the geothermal temperature gradient. Strictly, the mud compressibility is a measure of the change in mud volume resulting from a change in pressure, and the mud expansivity is a measure of the change in mud volume resulting from a change in temperature. The mud volume will be determined by the combined effect of compressibility and expansivity. It is difficult to separate their effects because of the combined pressure and temperature gradients along the wellbore. Most sources do not make a distinction between compressibility and expansivity properties, and consider only their combination which is usually described as a compressibility property. It is generally accepted that the compressibility properties of pseudo base oil are similar or greater than those for mineral oil [1].

For one particular pseudo oil system, the compressibility was estimated to result in a density increase downhole of 0.1–0.2 PPG for a 16,000 ft well [1]. This results in a bottomhole pressure (BHP) increase of ~150 psi above the estimated value if compressibility effects had not been taken into account. An error of this size in calculating the BHP can easily represent the difference between pore pressure and fracture pressure. One consequence of this can be losses and subsequent kicks. Misunderstanding the compressibility of a particular pseudo oil may increase the safety risk.

A further consequence of compressibility affects can occur during leak-off tests. The calculated leak-off pressure will be inaccurate because the surface density, instead of effective downhole density, of the mud may have been used [10]. This will result in the calculation of leak-off pressures that are less than their true values, leading to fracture pressures being assumed lower than their actual values.

It is likely that opinion expressed about compressibility has been gained for only a limited number of pseudo oil systems, and then through the act of labelling the mud system as a pseudo oil system, this opinion may have been associated with all such systems whether it strictly applies or not.
Some sources state that there is only a slight difference in compressibility between POBM and OBM. Such opinions may have developed from experience with LP pseudo oil muds where the properties resemble those of mineral oil. In conventional depth wells, compressibility effects of mineral oils and some pseudo oils may not be apparent, however, in deep HPHT wells compressibility effects can become noticeable. Other sources state that the compressibility can be significantly higher with pseudo rather than mineral oil. These opinions may have developed from experience with pseudo oils very different to mineral oil [1].

From a consideration of the molecular structure of the various pseudo oils, those oils and blends which predominantly consist of linear molecules are expected to exhibit higher compressibilities. The degree of linearity of the molecule is proportional to the degree of compressibility, and expansivity, of the oil. The theory is that, being linear, the molecules can react to changes in pressure, and temperature, by sliding against one another thus changing the volume they occupy. Pseudo oils which consist of branched molecules, and mineral oils which consist of irregular shaped molecules, cannot react to changes in pressure, and temperature, in this way. These oils are expected to exhibit lower compressibilities, and expansivities.

5.2.3 RHEOLOGY

The rheology of pseudo oils, particularly those described as the first generation, is such that they tend to be more viscous than mineral oils at low shear and usually-less viscous at high shear, and their rheology tends to have a greater temperature dependence, exhibiting greater thinning at higher temperatures [5, 6, 9]. Second generation pseudo oils are claimed to be thinner and tend to have rheologies similar to those of mineral oils.

Ester muds, as an example of a first generation mud, are particularly viscous. The equivalent circulating density (ECD) can be high enough to cause losses. One reaction is to lower the mud weight, however, once circulation stops kicks have been known to occur [1].

An additional consideration for ester based muds is the ester's low hydrolytic thermal stability of around 150°C, see Table 3.3. Ester systems have to be limited to conventional depths where the geothermal temperature is below this value. For deeper wells the ester will hydrolyse forming a fatty vegetable oil semi-solid. This increases the viscosity considerably, thus, decreasing pumpability and increasing ECD, leading to possible losses and kicks [1].

Pump-pressure calculations with POBM can be in error by as much as 35% [20]. Unreliable ECD values can lead to kicks and losses, both resulting in additional costs because of drilling delays while implementing well control procedure or losses of POBM at high costs per barrel. Current API equations [21] seriously underestimate drillstring losses, which account for the pump-pressure differences. Conversely, annular pressure losses were much lower than predicted. An incident has been reported in the Gulf of Mexico where mud losses to the formation occurred during
circulation of a pseudo oil mud [1]. The mud losses would only occur during circulation and were ascribed to the high ECD of the mud.

As well as determining the frictional pressure losses on circulation, the rheology of the mud will also determine the rate of gas migration, or gas slip, up the wellbore. Gas slip determines how quickly gas is seen at surface after the start of the influx, and how quickly pressures, caused by gas migration, rise on shut-in. The gas slip and the fraction of gas that is held stationary in the mud is dependent on the mud rheology, the mud-gas interfacial tension, and the difference between mud and gas densities. The viscosity of drilling mud hinders the break-up of gas bubbles allowing gas to migrate as larger bubbles, which can travel faster than smaller bubbles in less viscous muds [34]. The yield stress of drilling mud can hold low concentrations of gas in suspension with no migration [34].

It is likely that opinion expressed about rheology has been gained for one or a limited number of pseudo oils systems, and then through the act of labelling the mud system as a pseudo oil system, this opinion may have been associated with all such systems whether it strictly applies or not.

Some sources state that mud rheology additive packages (viscosifiers, low end rheology modifiers, thinners, gel agents etc.) have reached such a stage that a required rheology can be specified within reasonable tolerances at different shear, pressure and temperature conditions. In this case, the rheology of the base oil becomes less significant [1].
6. ANALYSIS OF DOCUMENTED INCIDENT DATA

In this section, a number of actual incidents involving POBM, where safety issues were raised, are analysed in an attempt to gain insight that may be useful in similar future events.

Events such as rig personnel encountering skin problems because they neglected to use barrier cream and gloves, or divers encountering similar problems working near seabed cuttings piles coated with POBM, are examples of operational experience. With events such as these, the cause and methods of possible prevention are well understood.

The type of event considered in this section are complex, where neither the cause nor the method of prevention are clear. Well control events fit into this category.

Well control events are the result of the interaction of a number of physical phenomena and can have significant safety consequences. In response, a number of kick simulators have been developed to provide insight into these well control events. This section describes how kick simulators have been used to conduct a preliminary analysis to reconstruct and analyse two incidents involving POBM, each supplied by a different operator. The objective is to determine whether the incidents are attributable to or modified significantly by to use of POBM, and then to provide insight into these problems, their alleviation procedures, and the resulting safety issues, that may prove useful in similar future events.

6.1 WELL INCIDENT #1

The objective of analysing this well incident is to:

- Attempt an explanation for the occurrence of a kick from a well that has remained uncirculated for 48 hours.
- Identify any discrepancies between field data and simulation results.
- Provide help to assess a difficult situation and generate information that may be useful to speed up well control operations in similar future events.

The initial kick detection phase of a well control incident is analysed using the RMODEL (Research Model) kick simulator.

The key events immediately before and during this well incident are summarised below:
TABLE 5.1. SEQUENCE OF WELL CONTROL ACTIONS FOR WELL INCIDENT #1

<table>
<thead>
<tr>
<th>Start Time [hrs]</th>
<th>Duration [hrs]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>48 00</td>
<td>No circulation 1.47 SG mud in well.</td>
</tr>
<tr>
<td>10 33</td>
<td>00 05</td>
<td>Circulate through annulus 1.47 SG 470 GPM</td>
</tr>
<tr>
<td>10 38</td>
<td></td>
<td>Shut-in SIDPP 0 psi, SICP 140 psi at 1200 hrs. Final pit gain 5 bbl. Final SIDPP 200 psi, SICP 440 psi.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Driller’s method One circulation. 1.47 SG</td>
</tr>
</tbody>
</table>

There are two main features of this well incident. Firstly, a kick occurred shortly after circulation resumed on a well that had been previously uncirculated for 48 hours. Secondly, there is a clear delay in the build-up of shut-in drillpipe pressure relative to casing pressure.

The well was uncirculated for 48 hours in order to perform logging operations. Once circulation resumed, a pit gain of 5 bbl was observed and the well was shut-in. Around ninety minutes later SICP read 140 psi and SIDPP read 0 psi. At an unspecified time later, the final stabilised values read SICP 440 psi and SIDPP 200 psi. The well was killed using the Driller’s method with one circulation and the original mud weight of 1.47 SG.

The explanation proposed for this well incident, and which forms the basis of simulations attempting to reproduce recorded events, is that an overpressured low permeability formation was encountered. It may be the case that during normal drilling the low gas rate into the wellbore is circulated without consequence or, alternatively, that the equivalent circulating density (ECD) is sufficient to restrain the formation.

Once circulation is stopped to perform logging operations, the gas entering the well begins to dissolve in the paraffin base oil (Figure 5.1). The mud directly adjacent the formation will become saturated with dissolved gas. Subsequent gas will be unable to dissolve in the saturated mud and will, therefore, rise due to buoyancy until unsaturated mud is encountered where it will begin to dissolve. Over a period of 48 hrs, the mud will become ever more loaded with dissolved gas (Figure 5.2). Also, the amount of free gas will increase as the bubbles have to rise increasingly higher up the wellbore to reach unsaturated mud (Figure 5.3, the stepping behaviour is probably a function of the numerical solution scheme rather than a real physical phenomenon). During the 48 hour period, there will be little in the way of a surface well response to indicate that an influx is occurring.
**Figure 5.1. Schematic of Well Behaviour**

As the gas saturated mud is circulated up the wellbore, the pressure will be reduced until the bubble point is reached and free gas will begin to evolve from the mud. Evolution of free gas will produce a pit gain thus making the influx detectable.

**Figure 5.2. Build-up of Dissolved Gas in Well over 48 Hours**
This well incident has been modelled, and simulations produced, using the Health & Safety Executive Gas Kick Simulator (RMODELER). All steps in the well control operation shown in Table 5.1 have been modelled, however, the timing of some events is unclear and, therefore, emphasis has been placed on matching the two available data points during the shut-in pressure rise in order to gain a possible insight into the well control differences between mineral oil and pseudo oil based muds. The following data was made available:

- Well control incident report.
- Well geometry information.

When attempting to reconstruct a well control incident, the two main uncertainties are the formation pressure and the fluid flowrate into the wellbore. To allow simulations to proceed, the formation pressure was estimated from the pressure exerted by the mud column plus the final shut-in drillpipe pressure.

The fluid flowrate into the wellbore depends on the permeability of the kicking formation and the height of the formation drilled. From a radial flow analysis of a wellbore, which is reproduced in most petroleum engineering texts, the fluid flowrate into the wellbore is proportional to the product of permeability, $K$, and height drilled into the kicking formation, $h$.

$$Q_{\text{fluid}} = f(Kh)$$
Therefore, it is the product Kh that is important rather than the individual values of K and h. The actual Kh, as determined by the far-field formation permeability and actual depth drilled into the kicking formation, will be greater than the effective Kh because of formation damage in the vicinity of the wellbore and the effect of mud cake build-up.

Correspondence with rig observations

As mentioned previously, the entire well incident has been modelled, however, emphasis has been placed on matching the rise in shut-in pressures to gain a possible insight into the well control differences between mineral oil and pseudo oil based muds.

The simulation results have been optimised against the available data for SIDPP and SICP. Unfortunately, only two spot readings for each are available. We have attempted to reconstruct the incident against this sparse data set and the additional requirement that there should be no detectable well response after 48 hours but there should be sufficient gas concentration to produce a 5 bbl pit gain. The kick zone properties to give the best match are:

- 200 psi static kick zone overpressure.
- 0.03 mD kick zone permeability and 2.5 ft zone penetration (Kh ~ 0.03 mD m).
- POBM gas solubility is 75% of typical mineral OBM.
- Kick fluid is gas.

A match of SIDPP readings and simulation results is shown in Figure 5.4 for various assumed POBM gas solubilities. The pseudo oil gas solubility is given in terms of a percentage of typical mineral oil gas solubility. Both readings, giving a SIDPP of 0 psi at shut-in and after 80 min. later, match the simulation results. Depending on the assumed gas solubility, the simulations predict that SIDPP remains zero for between 140 min. and 230 min.

The delayed rise of SIDPP has been successfully modelled within the RMODEL, but at this stage no tests have been carried out to determine the exact mechanism. There are a number of possibilities:

- **U-tubing effects:** The net fluid density in the annulus is lower than in the drillpipe and, therefore, the mud in the drillpipe could flow through the bit into the annulus thus helping to mask any SIDPP.

- **Thermal effects:** Once circulation ceases, the mud in the drillpipe will cool and its density will increase which may help mask any SIDPP.

- **Pressure wave effects:** When the well is first shut-in, a pressure wave travels down the drillpipe, up the annulus, is reflected at the closed blowout preventer (BOP),
travels back down the annulus and up the drillpipe to register a shut-in pressure. The presence of gas can significantly reduce the speed of the pressure wave possibly causing a delay in the build-up of SIDPP.

An additional mechanism is:

- **Drillpipe mud gelling effects:** The mud gels within the drillpipe thus shielding the build-up in bottomhole pressure (BHP) until the differential pressure is great enough to break the gel.

The above mechanism has been used on a number of occasions to explain the delayed build-up in SIDPP. This mechanism is not believed to be responsible here, however, because the RMODEL reproduces the observed behaviour without this mechanism actually being modelled within the RMODEL.

A match of SICP readings and simulation results is shown in Figure 5.5 for various assumed POBM gas solubilities. The pseudo oil gas solubility is given in terms of a percentage of typical mineral oil gas solubility. Both readings, SICP of 0 psi at shut-in and 140 psi at 80 min. later, match the simulation results assuming the pseudo oil has a gas solubility which is about 75% that of a typical mineral oil.

![Percentage of mineral oil gas solubility vs. Time](image-url)

**Figure 5.4. SIDPP Match comparing driller's gauge readings against simulation results**
Figure 5.5. SICP Match Comparing Driller’s Gauge Readings Against Simulation Results

6.2 WELL INCIDENT #2

A thorough investigation of this well control incident has been conducted elsewhere [33]. Here, a summary of the findings from this investigation is presented that have a bearing on POBM usage. This incident involved a condensate kick and wellbore fracture during shut-in while drilling with a POBM. While the initial kick and subsequent fracture are not blamed on the use of a parafinic POBM, reconstruction and analysis of the event using a kick simulator may provide some insight into how kick behaviour and well control differ between OBM and POBM. The objective of analysing this well incident is to:

- Attempt an explanation for the occurrence of a kick and subsequent fracture and losses.
- Identify any discrepancies between field data and simulation results.
- Provide help to assess a difficult situation and generate information that may be useful to speed up well control operations in similar future events.

The kick initiation, detection, and initial shut-in phase were simulated using SideKick v3.0 which includes a fracture loss and a gas-oil mixture kick modelling capability.

A large amount of detailed data was made available for this study including rig log information. The key events immediately before and during this well incident are summarised below:
### TABLE 5.2. SEQUENCE OF WELL CONTROL ACTIONS

<table>
<thead>
<tr>
<th>Start Time [hrs]</th>
<th>Duration [hrs]</th>
<th>Description</th>
</tr>
</thead>
</table>
| 00 00            | 10 00          | Drill ahead to 13809.75'.  
Av. ROP 7.5 ft/hr.  
Pump at 541 gpm.  
No influxes or losses. |
| 10 00            | 00 10          | Drill ahead to 13811'.  
ROP 7.5 ft/hr.  
Pump at 541 gpm.  
No influxes or losses. |
| 10 10            | 00 13          | Stop drilling at 13811'.  
Pump at 541 gpm.  
No influxes or losses. |
| 10 23            | 04 37          | Drill ahead to 13842'.  
ROP 6.67 ft/hr.  
Pump at 541 gpm.  
No influxes or losses. |
| 15 00            | 00 26          | Stop drilling at 13842'.  
Pump at 541 gpm.  
No influxes or losses. |
| 15 26            | 00 53          | Drill ahead to 13850'.  
ROP 8.89 ft/hr.  
Pump at 541 gpm.  
Pit levels start to rise at 16.06 hours. Initially gains at 8.5 bbl/hr. |
| 16 19            | 00 34          | Stop drilling  
Pump at 541 gpm.  
Pit gain continues to rise, at approx. 19 bbl/hr. Eventually gains to 10 bbl - but detection of this was delayed due to stopping and starting pumps for survey. |
| 16 53            | 00 01          | Drill ahead 2.6' to 13852.6'.  
ROP 156 ft/hr.  
Pump at 541 gpm.  
Influx continues. |
| 16 54            | 00 16          | Stop drilling at 13852.6'.  
Pump at 541 gpm.  
Influx continues. |
| 17 10            | 00 01          | Drill ahead 2.3' to 13854.9'.  
ROP 138 ft/hr.  
Pump at 541 gpm.  
Influx continues. |
| 17 11            | 00 15          | Stop drilling at 13854.9'.  
Pump at 541 gpm.  
Although the daily drilling report indicate that the kick was detected with a pit gain of 10 bbl, the rig log data indicates a pit gain of some 20-22 bbl at the time of detection. |
| 17 26            | 00 15          | Flow check  
3.5 bbl gain |
| 17 41            | 00 21          | Shut-in  
Initially SIDPP 104 psi; SICP 50 psi - the shut-in pressures on the log discs are slightly higher than those quoted in the drilling report. |
| 18 02            | 00 65          | Continued shut-in  
Pressures increase, reaching peak values of: SIDPP 1193 psi; SICP 1019 psi. |
There are two main features of this well incident. Firstly, a kick occurred, which was later discovered to be a condensate kick. Secondly, the pressure rise during shut-in was sufficient to fracture the openhole section causing losses.

At a depth of around 13,850 ft, pit level start to rise. The well is shut-in with a final pit gain of 22 bbl recorded on the rig log. Out of this 22 bbl influx, a net fluid gain of 10 bbl was recorded. The other 10 bbl was claimed to be lost due to gas evaporation, thus indicating a gas-condensate influx. The density of the condensate influx at bottomhole conditions was estimated to be 210 ppg (4.0 ppg) from logs of a nearby well. On detection, the well was shut-in and pressures increased reaching peak values of SIDP 1193 psi and SICP 1019 psi before the formation fractured. Subsequent losses to the formation were estimated to be ~0.15-0.16 bbl/min.

Correspondence with rig observations

The simulation results were optimised against the continuous rig logs of SIDPP and SICP. The well parameters to give the best match were reported as being:

- 1550 psi static kick zone overpressure.
- 5.7 mD kick zone permeability and 6.3 ft kick zone penetration (Kh ~ 11 mD m).
- POBM gas solubility is 75% of typical mineral OBM.
- Kick fluid is condensate with a bottomhole density of 210 ppg (4.0 ppg), and was modelled.
- Loss zone was assumed to be 2,325 ft off bottom with a loss rate of ~0.15-0.16 bbl/min.
A match of the SICP readings and simulation results is shown Figure 5.5, and a match of SIDPP readings and simulation results is shown in Figure 5.6.

Usually, SICP is greater than SIDPP because there is a reduced hydrostatic head in the annulus to restrain the formation due to influx fluids mixing with the mud. Here, however, SIDPP is greater than SICP. The proposed explanation is that condensate fluid entered the drillpipe through the bit nozzles thus lowering the hydrostatic head [33]. Within SideKick v3.0, influx in the drillpipe cannot be modelled, therefore, the simulation was optimised against the SICP readings.

As with the previous well incident, there is some delay in the build-up of shut-in pressures. For this well incident, however, there is a delay in both the build-up of SICP and SIDPP, and this delay is not successfully modelled. For the previous well incident, there was only a delay in SIDPP build-up, and this was successfully modelled (within the sparse data available), which would suggest a different mud behavioural mechanism is responsible and that this mechanism is not modelled within SideKick v3.0. The proposed explanation is that the greater compressibility of the POBM (relative to OBM which SideKick v3.0 assumes) helps absorb the increase in pressure in both the drillpipe and annulus.

![Figure 5.5 SICP Match Comparing Rig Log Against Simulation Results](image-url)
FIGURE 5.6 SIDPP MATCH COMPARING RIG LOG AGAINST SIMULATION RESULTS

6.3 DISCUSSION

There are two main features of well incident #1. Firstly, an overpressured-low permeability formation was encountered which kicked during circulation after previously being uncirculated for 48 hrs to enable logging operations. Secondly, there is a clear delay in the build-up of SIDPP relative to SICP.

An explanation has been proposed in terms of the build-up of dissolved gas within the wellbore over the 48 hour period in which the well was uncirculated. A good match between observed and simulated SIDPP and SICP was obtained by modelling the paraffinic pseudo oil gas solubility as 75% that of a typical mineral oil. This value for paraffinic pseudo oils has been corroborated elsewhere [28, 33]. Assuming full mineral oil gas solubility would not have produced the observed pressure build-up, while assuming an effective zero solubility (as for WBM) would have caused a blowout within the 48 hour period. The effect of pseudo oil gas solubility appears to be the underlying mechanism behind the incident; however, it is unclear how the other pseudo oil properties such as compressibility and rheology through gas slip, that may differ from typical mineral oil values, also affect the results.

The delay in the rise of SIDPP has been successfully modelled, however, without further investigation it is unclear which mechanism is responsible.

There are number of features to well incident #2. Firstly, a condensate kick originated from a high pressure formation which during pressure build-up on shut-in caused the formation to fracture and loose mud. Secondly, there is a clear delay in the build-up of
both SIDPP and SICP which is not modelled by the simulator. Thirdly, SIDPP is
greater than SICP.

The objective of the original study of this incident was to explain the occurrence of a
condensate kick that lead the formation to fracture and thus causing mud losses. Here,
this study has been reviewed in an attempt to extract any information on how POBM
behaviour differs from OBM. Two features appear of relevance. Firstly, this incident
was modelled assuming the parafinic pseudo oil gas solubility to be 75% of that for a
typical mineral oil, which has been corroborated from an analysis of well incident #1
and elsewhere [28]. Secondly, there is a clear delay in the build-up of both SIDPP and
SICP which was attributed to pseudo oil compressibility initially masking the
downhole pressure increase.

The objective of conducting analyses of documented POBM incident data was to
determine how POBM behaviour differs from that of OBM and how this affects the
success of well control attempts. The initial phase of the POBM incidents (kick
initiation, kick detection, and shut-in) were analysed using either the RMODEL or
SideKick kick simulators. These simulators assume the mud base oil to have typical
mineral oil behaviour: gas solubility, rheology pressure and temperature dependence,
gas slip, compressibility and expansivity (PVT) properties. Any differences between
the reported incident data and the simulation results may be attributable, within the
tolerances set by the simulator, to the differing physical properties between OBM and
POBM. While differences have been observed that can be attributable to POBM, it is
difficult to determine which physical property is responsible. For example in well
incident #1, the measured rise in SICP was matched to a pseudo oil gas solubility of
75% of that for a typical mineral oil, however from well incident #2, it is suspected
that pseudo oil compressibility also affects the pressure rise profile. In addition,
rheology through gas slip will also affect the pressure rise profile because of the
pressure of migrating gas in a shut-in well.

The approach adopted here, while indicating that there are differences in POBM and
OBM that affect well control, cannot readily determine which pseudo oil properties
are responsible. This issue is discussed further in the next section.
7. DISCUSSION

Any discussion of the health and safety issues raised by drilling with POBM, and how these compare with OBM, needs to be seen in the context of the current and future levels of POBM usage. In this discussion, the current usage of POBM is estimated, and then the developments that will determine their future use are considered. Once the context of usage is set, the findings regarding each health and safety issue are discussed. Further work or research is highlighted where it could be considered beneficial in gaining a greater understanding of these issues, or would go some way to help eliminate them.

In January 1997, the discharge limit for oil on cuttings for development wells was reduced from 100 g/kg to 10 g/kg to bring them into line with exploration and appraisal wells. This will probably result in an increase in the use of POBM for this year.

A development that may affect the use of POBM over the longer term are the results from a series of experiments carried out in December 1996 by the Marine Laboratory of the Scottish Office Agriculture, Environment and Fisheries Department. A seabed environment was physically simulated to investigate pseudo-oil biodegradation and bioaccumulation. The results suggest that the effect of various pseudo oils on the environment is not significantly better than mineral oil. A consequence of this investigation might be that the current legislation is widened to cover POBM [1].

Whilst POBM and OBM have comparable performance, POBM is considerably more expensive. The advantage of POBM is there are no restrictions, at the moment, on its discharge. If POBM is given an equivalent legislative status to OBM then this advantage would disappear and, it is widely believed in industry that POBM would be phased out within 18 to 36 months [1].

On the plus side, it has been claimed that POBM can exhibit some superior aspects of performance over OBM, resulting in lower well costs [1, 10, 22]. At least one operator is known to have claimed they would continue to use POBM for some specialist work should the current legislation be extended to POBM [1]. Also, in the Netherlands, it is known that POBM has been used in a number of situations simply on the grounds of improved performance and health and safety considerations [10, 22].

A summary of the advantages and disadvantages of POBM over OBM is given in Table 6.1. The perceived primary advantage of POBM is that current discharge limits of OOC do not apply. It is generally accepted that the cost savings of drilling with POBM (cost savings from POBM performance being similar to OBM and thus fewer well problems, and cost savings from not having to implement expensive barging, reinjection or cleaning options) usually outweigh the high cost-per-barrel.
### TABLE 6.1 ADVANTAGES AND DISADVANTAGES OF POBM OVER OBM

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current discharge limits do not apply</td>
<td>Higher cost-per-barrel</td>
</tr>
<tr>
<td>Generally better health and safety</td>
<td></td>
</tr>
<tr>
<td>Better performance in some applications resulting in lower costs-per-foot-drilled</td>
<td></td>
</tr>
</tbody>
</table>

Should the current legislation be extended to include POBM, then the first advantage in Table 6.1 would disappear and the balance of advantages and disadvantages would tip towards a reduction in their use. In attempts to address this possible future imbalance, the most recent POBM formulations have costs-per-barrel that, while still higher than OBM, are much reduced. Most mud companies now also offer to recycle POBM formulations, thus further reducing costs-per-barrel.

While it is widely believed in industry that a tightening of the legislation would result in the phasing out of POBM [1], further technical developments, reductions in cost and greater appreciation of health and safety issues may result in their continued use for some applications. Mud companies continually strive to improve the technical performance of their mud systems, and in the light of possible future legislation may attempt to reduce mud costs, both through unit cost reductions and reprocessing, bringing them more in-line with OBM. Greater awareness of possible health and safety advantages associated with POBM may also play a part in any continued use of pseudo oils.

All the data pertaining to health and safety have been categorised into the various issues associated with the use of POBM, and compared to those for OBM. These health and safety issues have themselves been grouped into two categories. The first are those that are clearly evident from known properties (i.e. there is a direct causal link between a particular property and a particular health and safety issue), and these are:

- **Flammability**: Pseudo oils generally have higher flash points than mineral oils, therefore, fewer vapours are given off and subsequent ignition in enclosed spaces such as the mud room is less likely.

- **Drilling equipment corrosion**: It is generally considered that oils with low aniline points (<150°F) have the greatest effect on rubber parts. Mineral oils have low aniline points because of their high aromatic content, and therefore are expected to have a greater detrimental effect than most pseudo oils. The exception is ester which has an aniline point around 46°F, and therefore would be expected to be most detrimental to rubber.

- **Spills on rig floor**: Pseudo oils can have higher lubricities than mineral oil, and therefore spills of the rig floor can cause hazards because of rig personnel slipping.
The oil may also corrode the insulation of electrical cables thus exposing potential ignition sources.

- **Toxicity to rig personnel:** In general, toxicity is considered to be less for POBM than OBM in terms of direct contact and vapour contact largely because of the absence of aromatics. Questions remain, however, over aerosol contact and exposure to the possible products that may be formed from pseudo oil and additive reaction at downhole conditions.

Whilst the health and safety issues associated with POBM are generally considered to be an improvement over OBM, a few areas of possible work can be envisaged:

- Reaction products formed at downhole conditions from pseudo oil, additives and possibly formation fluids, may be both toxic to rig personnel and also volatile.

- Toxic effect of POBM aerosols, possibly containing reaction products mentioned above, on rig personnel.

- Long term exposure for workers when combinations of compliance options are used, such as using POBM and transportation of cuttings.

It may be entirely possible that, at the pressures and temperatures downhole, the conditions exist for the POBM components, and possibly formation fluids, to react to form products which are toxic to rig personnel and possibly volatile. When circulated to surface these would pose a hazard to workers. Earlier, the limiting hydrolytic thermal stability temperatures for pseudo oils and the decomposition temperatures for additives were discussed, together with the concern of the types of product formed. Indeed, for ester based muds, it has been suggested that among the products formed downhole are aldehydes which can be very toxic to rig personnel when they are circulated to the surface.

The exposure limit for oil aerosol (mists) is currently under review by the Health and Safety Executive [1, 30]. Until the review is complete, the current occupational exposure standards of $5 \text{ mg m}^{-3}$ (8-hour time weighted average (TWA)) and $10 \text{ mg m}^{-3}$ (15 min. reference period) are only applicable to highly refined mineral oils. This limit does not apply to unrefined or mildly refined mineral oils, catalytically cracked petroleum oils with final boiling points above $320^\circ\text{C}$, or used engine oils. With low volatility liquids such as POBM, exposure to aerosols is likely to be of more significance than exposure to vapours, so the comparison of vapour levels is not especially useful. Because of the significance of aerosols over vapours, any comparison with existing occupational exposure standards should consider those which have been set for oil aerosol exposures. It might be worth considering extending this review to cover pseudo oil and POBM mists.

The second category consists of those health and safety issues that would not be intuitively evident from known properties (i.e. there is a complex causal link between a particular property, or set of properties, and a particular health and safety issue), and these are:
- **Human factors**: Perception of the safety risk posed by POBM is an important part of the overall safety picture surrounding their use, and underlies the full range of health and safety issues, including well control.

- **Well control**: Well control is a complex health and safety issue in its own right due to the number of interacting physical and chemical mechanisms that take place during a well control event. The differences in chemical and physical properties between POBM and OBM may manifest themselves in differences in well responses for kick detection, kick development and the application of well control procedures. This, therefore, poses a different set of safety risks.

Pseudo oils are not only expected to have different properties to mineral oils, but are also expected to have a wider range of properties. It is difficult, therefore, to make generalisations about how pseudo oil will behave during well control. The most significant properties to affect well control are considered to be gas solubility, mud compressibility and expansivity, and mud rheology. Gas solubility is expected to be similar or less than for mineral oil [1]. Compressibility and expansivity are expected to be similar or greater than for mineral oil [1]. Rheologies can result in calculation errors off as much as 35% for pressure loss analysis techniques based on conventional OBM [20, 21], and effect the rate of gas slip. The rig personnel working on the well control procedure will have certain perceptions or expectations on how the event will unfold. If the well does not behave in the way anticipated then, over the many hours that well control procedures can last, the levels of stress and fatigue that rig personnel experience will increase possibly leading to incorrect diagnosis and incorrect actions which further increase the safety risk.

Two well control incidents involving POBM have been analysed as part of this review. The initial phase of the incidents (kick initiation, kick detection, and shut-in) were analysed using the RMODEL and SideKick well control simulators. These simulators both assume typical mineral oil behaviour: gas solubility, rheology pressure and temperature dependence, gas slip, compressibility and expansivity (PVT) properties. Any differences between the reported incident data and the simulation results may be attributable, within the tolerances set by the simulator, to the differing physical properties between POBM and OBM. While differences have been observed that can be attributable to POBM, it is difficult to determine which physical property is responsible. For example during shut-in, the pressure rise is a function of gas solubility, compressibility, and rheology through gas slip, and for any discrepancy between measured and simulated values it is not readily discernible which property or properties are responsible.

The objective of analysing this incident data has been to gain insight directly into properties differences between OBM and POBM, and how these may affect well control. The consequences, however, associated with all these property differences are felt simultaneously at all points in the mud system and at all times and, therefore while differences can be observed through simulation, it is unclear which property is responsible and to what extent.
Another possible approach, which would be likely to yield greater certainty, could be to directly measure the physical properties of pseudo oils and POBM formulations over downhole pressure and temperature ranges, and to incorporate these into kick simulator codes as add-on modules which can be changed depending on the mud system. This would produce a tool capable of predicting the behaviour of POBM during well control and of determining which physical properties are responsible in causing a divergence from OBM behaviour.

The health and safety issues of using POBM ultimately result from their chemical and physical properties. POBM is not only expected to have different properties to OBM, but also a much wider range of properties due to the large number of substances that can be used as pseudo oils or as additives. Any generalisations made about POBM properties and associated health and safety issues, therefore, must be treated with caution. The perception within industry, however, is that the health and safety issues surrounding the use of POBM are better, or at least no worse, than for OBM.
8. REFERENCES

1. Personal Communications with industry representatives from operating, service and mud supply companies, 9/96-3/97.


