Zechstein Supergroup
Drilling Safety Issues
A Review
ZECHSTEIN SUPERGROUP

DRILLING SAFETY ISSUES

A REVIEW

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Issue No: 2
Issue Date: October 1997
Client Ref: OSD-D.3486
SUMMARY

The objective of this report is to review the health and safety issues which may be encountered for wells whose trajectory passes through formations in the Zechstein Supergroup. This objective has been achieved by contacting key personnel within operating companies, surveying the open literature, and studying documented health and safety incidents.

Operational problems present some intrinsic hazard or safety risk to rig personnel. Additionally, the procedures applied to alleviate these problems also present a safety risk, as they usually are non-routine and unfamiliar, thus increasing the likelihood of errors of judgement or mis-application. It is clear, therefore, that both the problems encountered and the alleviation procedures applied in Zechstein formations are inextricably linked to health and safety.

Contact with industry clearly shows that problems are anticipated when conducting drilling operations through Zechstein. These problems can be grouped into the following five categories:

- Kicks and Wellbore Gains
- Wellbore Losses
- Stuck Pipe
- Casing Collapse
- H₂S

Each of these problems have their origin in the physical mechanisms that can occur in Zechstein formations. The operational problems, as recognised through well responses observed on the rig floor, can be caused by one or more of these mechanisms, or by the interaction of a number of them. The mechanisms believed to be responsible are:

- Salt Washout
- Salt Movement
- Brine and Gas Kicks
- Formation Fracture
- Formation Filtration
- Brine Flows from Zero Porosity Salt

In response, industry has developed a number of alleviation procedures to attempt to avoid or remedy these problems:

- Well Control Procedures
- Mud Type Selection
- Casing Setting Selection
- Casing Type Selection
- Bi-centre and Eccentric Drill Bits
- Fast Drilling
- LCM Operations
• Seismic Survey
• Cement Selection
• Variation of Annular Pressure
• Freshwater Spotting
• Simultaneous Underreaming and Drilling

There is at least one procedure that is applicable to each of the different operational problems. While these procedures have some success in avoiding or remedying the problems that occur, two areas of uncertainty remain.

Firstly, an operational problem manifests itself as a particular symptom or well response, however, its origin could be a number of the possible physical mechanisms that can occur in these formations. The selection of an alleviation procedure should be focused on the physical mechanism causing the problem rather than the problem itself. Once a particular well response occurs for which a number of mechanisms may be responsible, it is not immediately apparent which action is appropriate. Any selection of alleviation procedure based on a misinterpretation of well response could make matters worse.

Secondly, wellbore losses and gains observed in close succession are described as loss-gain situations and are the result of a number of interacting physical mechanisms. These situations are particularly troublesome because they may ultimately develop into underground blowouts. Reports from incidents of this nature show that they are confusing and attempts to apply alleviation procedures seem only to aggravate the situation.

Five Zechstein well control incidents have been analysed as part of this review. Information useful to help avoid or remedy similar future events has been generated. Three types of well control problem, that differ from what can be considered typical or textbook well control, have emerged:

• High pressure formation brine kicks
• Charged formation kicks
• Low 'Kh' formation kicks

Decision analysis has been applied to Zechstein problems and their alleviation procedures. Provisional decision tools, or trees, have been developed based on all the information gathered from the open literature, dialogue with industry personnel, and the interpretation of the five well incidents considered in this review. These decision trees are intended to be applied both at the well planning stage to help avoid problems and at the drill site to remedy problems that have already occurred. Comments from drilling engineers are encouraged to bring these analyses to the stage where they can be applied to produce the maximum benefit.

It is considered that further work or research in some areas may help improve the methods by which these operational problems are dealt with. The following areas of further work would be considered of benefit:
• Viability of decision tree analysis approach
• Improvement in well control modelling capabilities
• Further application of kick simulator technology
• Salt movement (Wellbore Ballooning) modelling
• Cement volume estimation
• Cement sweepage efficiency estimation

The health and safety aspects of both the operational problems and alleviation procedures stem from the uncertainty associated with how these events will unfold. The overall objective of further work is to reduce this uncertainty.
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1. INTRODUCTION

Various operational problems can occur during the drilling or production phase of a well that passes through Zechstein formations, such as brine or gas kicks, wellbore losses, stuck pipe, increased annular pressure, casing collapse and sour gas corrosion. These operational problems represent unscheduled events, the symptoms of which may be misinterpreted on the rig floor leading to inappropriate actions, or may require unfamiliar remedial actions to be carried out, both of which have implications for health and safety.

The objective of this report, which is to review the full-range of health and safety issues associated with drilling through Zechstein, has been achieved by three different approaches:

- Contact with key personnel within operating companies to ascertain their concerns.
- A survey of the open literature, gathering relevant material on related topics.
- A study of documented health and safety incidents supplied by operating companies.

All the information, regarding the health and safety issues of drilling through Zechstein, contained in this report originates from the above sources. This 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.

In the body of this report, detailed maps are reproduced of the UKCS showing the currently known extent of Zechstein. Imposed on these maps is the licensing block structure.

The structure and properties of these formations are summarised and presented. The physical mechanisms that can occur during the drilling and production phases are introduced to lay the foundation to understand the origin of operational problems and the current operational procedures applied to alleviate these.

A brief account is given on how an estimate was made of the total experience to date in drilling and the operational problems that occur in these formations.

Next, the operational problems, and associated health and safety implications, are considered and related to the physical mechanisms outlined earlier.

The report goes on to consider the current operational procedures that are applied to attempt to alleviate these problems. Explanations are put forward, based on an understanding of the physical mechanisms, as to the way in which these procedures are intended to be effective.
A number of documented incident data sets of operational problems are analysed to determine whether further insight can be gained into Zechstein phenomena. Interpretations and conclusions drawn from the study of incident data are presented.

Finally, the report concludes by applying decision analysis to Zechstein drilling and highlights areas of further work that would be useful to better address the operational problems associated with wells drilled through Zechstein.
2. DISTRIBUTION OF ZECHSTEIN ON UKCS

The Zechstein Supergroup is a sequence of formations found, offshore, beneath the North Sea and, onshore beneath many coastal European countries notably the United Kingdom, the Netherlands, Denmark, Germany and Poland [7, 8]. These formations were laid down in the Palaeozoic period, about 250 million years ago, by successive flooding and evaporation of seawater within a large coastal basin. The evaporation process resulted in the deposition of carbonate, sulphate and salt sequences which now constitute the Zechstein. A sketch of Zechstein distribution throughout Europe is shown in Figure 2.1 [7].

Offshore, these formations underlie most of the UK sector of the North Sea, while onshore, they underlie much of East Yorkshire. In the west of the UK, there is a sequence equivalent to Zechstein known as the Cumbrian Coast Group (close to where the Bakevellia Sea in marked in Figure 2.1). Offshore, the Cumbrian Coast Group underlies parts of the East Irish Sea and, onshore, parts of the Cumbrian Coast. It is thought that, because of the similarities, the Zechstein Basin may be linked to the Cumbrian Coast Group, see Figure 2.1.

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Figure 2.1 Sketch of Approximate Extent of Zechstein in North Atlantic [7]
Over recent years, the British Geological Survey, BGS, has undertaken a number of surveys to map regions of the UKCS, in terms of lateral extent of formations and stratigraphy, where there has been significant exploration activity or where it is likely in the future. As part of these surveys, Zechstein location and stratigraphy maps have been created [4, 5, 6].

Distribution in the Southern North Sea is shown in Figure 2.2 [5]. This map has the UKCS licensing block grid structure overlain to help determine whether exploration or field development activities involve drilling through these formations. The extent to which Zechstein is currently known to underlie offshore UKCS in the Southern North Sea is shown in Figure 2.2 by the thick black lines. As can be seen, this area underlies much of the southern North Sea.

The distribution of Zechstein in the Northern North Sea is shown in Figure 2.3 [4]. The extent to which it is currently known to underlie offshore UKCS in the Northern North Sea is bounded by the thick black line and the UKCS sector boundary shown in Figure 2.3. The shaded regions within the designated area represent the absence of certain Zechstein component formations. As can be seen, this basin also underlies much of the northern North Sea.

In the offshore East Irish Sea Basin, strata equivalent to the Zechstein Group are assigned to the Cumbrian Coast Group. This group is in many ways similar to the Zechstein, dominantly consisting of mudstones, sandstones, halites, anhydrites and carbonates. It is thought that, because of the similarities, the Zechstein Basin may be linked to the Cumbrian Coast Group, see Figure 2.1. The distribution of the Cumbrian Coast Group in the East Irish Sea Basin is shown in Figure 2.4 [6]. The extent to which this group is currently known to underlie the UKCS in the East Irish Sea Basin is shown by the thick black line in Figure 2.4.

The distribution of Zechstein West of Shetland is poorly understood because many of the wells drilled in this area have targets that lie above the level at which it would be expected. Its distribution in the West of Shetland is shown in Figure 2.5. The extent to which it is currently known to underlie offshore UKCS in the West of Shetland is bounded by the thick black line in Figure 2.5.

The maps presented in this section [4, 5, 6] indicate the current state of knowledge on the distribution of Zechstein, and its equivalents, on the UKCS.
FIGURE 2.2 DISTRIBUTION OF ZECHSTEIN IN SOUTHERN NORTH SEA [5]
FIGURE 2.3 DISTRIBUTION OF ZECHSTEIN IN NORTHERN NORTH SEA [4]
FIGURE 2.4 DISTRIBUTION OF CUMBRIAN COAST GROUP IN EAST IRISH SEA [6]
Figure 2.5 Distribution of Zechstein in West of Shetland [6]
3. CHARACTERISTICS OF ZECHSTEIN

The previous section presents information on the distribution of Zechstein, and its equivalents, on the UKCS. The health and safety, and operational issues of drilling through these formations depend on their geology, and on their physical and chemical properties. In order to gain a better understanding of these issues, and ultimately be in a position to suggest possible remedies, this section focuses on their geological, physical and chemical properties.

3.1 GEOLOGY

Zechstein consists of carbonate and salt (sulphate and chloride) rocks and is considered as one of the world’s ‘Saline Greats’. It has similarities to other salt sequences worldwide such as the Guadalupian to Ochoan sequences of the Delaware Basin in the USA, Nova Scotia outcrops (to which Zechstein may be connected, see Figure 2.1), and others found in the Gulf of Suez, Egypt, and the Gulf of Mexico [7, 13].

![Diagram of geological time scale showing recoverable reserves](image)

**Figure 3.1 Sequence Age and Recoverable Reserves for North Sea [7]**
The Zechstein sequence makes up the Upper Permian, and is estimated to have been laid down during the late Palaeozoic period, about 250 million years ago. The relation between Upper Permian and other sequences within the North Sea is shown in Figure 3.1 [7], together with the expected recoverable oil and gas reserves from each sequence.

The time scale shown in Figure 3.1 is an estimate of the time of deposition and, therefore, is an indication of the depth and order in which the sequences will be encountered during drilling. The absolute depth and thickness at any location will be highly variable depending on whether the location is over the basin proper or basin edges. Typically, however, the upper level of Zechstein is about 1000 - 2000 m deep and formations are about 1000 m thick [4, 5, 11].

In locations where Zechstein is present, drilling through it is necessary to reach target reservoirs in the Permian, Carboniferous and Devonian sequences. The recoverable reserves expected from these sequences are predicted to be: Devonian, 0.25 billion bbl oil; Carboniferous 1 billion bbl oil-equivalent gas; Permian, 0.5 billion bbl oil and 8.5 billion bbl oil-equivalent gas [7].

The Permian, in particular the Lower Permian (Rotliegend) sandstone, contains by far the largest accumulation of hydrocarbon reserves and these are predominantly gas. These accumulations are the most desirable reservoir targets for wells drilled through Zechstein, and constitute many of the Southern North Sea gas fields now in production.

Only a small number of reservoirs have been produced on the UKCS from within the Zechstein itself (Auk, Argyll, Claymore, Ettrick, Hewett, Montrose, Morag) [7, 12]. Typically, these formations have poor permeability and porosity and, subsequently, good sealing qualities. Indeed, the Rotliegend gas fields of the Southern North Sea depend for their existence on the Zechstein sealing efficiency.

During the Palaeozoic period, around 250 million years ago, what is now the Zechstein basin was a large coastal basin. Each sequence corresponds to a change in sea level which allowed a major influx of seawater into this large coastal basin. The precipitation of salts during the evaporation of these influxes resulted in the deposition of a sequence within the group [7, 11, 15]. Evaporation caused the least soluble salts to precipitate first. The order of precipitation, and therefore deposition, is carbonates (calcite and dolomite), sulphates (anhdyrite and gypsum), chlorides (halite - 'rock salt'), and finally a mixture of chlorides and sulphates (carnalite, sylvite, kieserite and bischofite - 'squeezing salts') [11]. Table 3.1 lists these minerals in order of decreasing solubility, and therefore increasing depth. Their chemical formula is also shown which is useful to appreciate the geochemical processes that have taken place within the Zechstein [11].
### Table 3.1 Zechstein Mineral Composition [11]

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chemical Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bischofite</td>
<td>$2\text{[MgCl}_2\cdot6\text{H}_2\text{O]}$</td>
</tr>
<tr>
<td>Carnalite</td>
<td>$12\text{[KMgCl}_3\cdot6\text{H}_2\text{O]}$</td>
</tr>
<tr>
<td>Kieserite</td>
<td>$4\text{[MgSO}_4\cdot\text{H}_2\text{O]}$</td>
</tr>
<tr>
<td>Sylville</td>
<td>$4\text{[KCl]}$</td>
</tr>
<tr>
<td>Halite</td>
<td>$4\text{[NaCl]}$</td>
</tr>
<tr>
<td>Gypsum</td>
<td>$4\text{[CaSO}_4\cdot2\text{H}_2\text{O]}$</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>$4\text{[CaSO}_4$</td>
</tr>
<tr>
<td>Calcite</td>
<td>$\text{CaCO}_3$</td>
</tr>
<tr>
<td>Dolomite</td>
<td>$\text{MgCO}_3$</td>
</tr>
</tbody>
</table>

The Zechstein Supergroup consists of about five, essentially identical, sub-sequences Z1 to Z5 [4, 5, 7, 11], as shown in Figure 3.2.

![Idealised Cycle Diagram](image)

**Figure 3.2 Zechstein Supergroup**

Whilst this idealised cycle is useful as a framework, there are many omissions and reversals of stages in these sequences [11].

#### 3.2 Zechstein Carbonates

The carbonates, calcite and dolomite, are the least soluble and, therefore, were the first to precipitate for any cycle [11]. Dolomite forms the reservoir rock for fields within the Zechstein because of its favourable porosity and permeability. Encountered dolomite accumulations can either be overpressured or underpressured, which may lead to kicks or losses, respectively [7]. The accumulations can contain brine, oil, gas, $\text{H}_2\text{S}$, previously lost mud or mixtures of these.
Typical envelopes of dolomite permeability, porosity and density are shown in Figures 3.3 and 3.4 [15], and refer to two sets of samples taken from the Z2 (Hauptdolomite) carbonate formation. Dolomite permeability lies in a range of between zero and about 10 mD. Porosity lies in a range between zero and about 8%, and density lies in a range between 2.78 and 2.88 kg/m³. These are typical values for dolomite found within Zechstein [10, 14].

**Figure 3.3 Zechstein Dolomite (Z2) Permeability & Porosity Sample Set #1 [15]**

**Figure 3.4 Zechstein Dolomite (Z2) Permeability & Porosity Sample Set #2 [15]**
A number of geochemical processes can occur in the dolomite which affect its petrophysical properties, such as leaching, calcitisation and redolomitisation, and are shown in Figures 3.3 and 3.4.

Leaching was probably the main porosity creating agent within the dolomite. Pore water with a salt content low in magnesium (Mg) compared to the in situ dolomite (MgCO₃) allowed dolomite to be dissolved and carried away, thus generating increased porosity through increased intercrystal porosity and the creation of microvugs (~μm) and vugs (~cm) [9, 15]. The resulting porous dolomite may have permeabilities of up to about 100 mD and porosities of up to about 22%, see Figure 3.3.

Another process that can occur is calcitisation, whereby dolomite (MgCO₃) is converted to calcite (CaCO₃). The reverse process is redolomitisation. Calcitisation occurs when the pore water magnesium/calcium ratio (Mg/Ca) is low, thus favouring the dissolution of dolomite and the precipitation of calcite. This process does not greatly effect permeability or porosity [15].

3.3 ZECHSTEIN SULPHATES

The overlying sulphates, anhydrite and gypsum, have poor permeability and porosity, however, they have efficient sealing properties and act as cap rock for the Zechstein dolomite and Rotliegens fields. These efficient sealing properties are also responsible for the absence of economically viable hydrocarbon deposits within these formations. The anhydrite acts as a cement that not only seals the upper sections of the dolomite but seeps down into the dolomite pore spaces (Anhydritisation) reducing permeability and porosity, and compartmentalising the dolomite (sections or rafts) into commercially non-viable deposits [15].

Salt sequences are usually less dense than the formations immediately above them which can result in the creation of salt domes and thus significant vertical displacements. Rafts of dolomite may break away from the main dolomite sections and be displaced along with the salt. These dolomite rafts are effectively volumes of various sizes with high permeability and porosity that are surrounded by low permeability and porosity anhydrite. Dolomite rafts that undergo vertical displacement will, therefore, take their original pore pressure with them. This can result in overpressured zones with the potential to kick or underpressured zones with the potential to cause losses.

In addition, depending on the size of the loss zone, they can become charged with pressure from heavy muds or high equivalent circulating densities (ECD) only later to kick with returned lost mud when the wellbore pressure is reduced.

3.4 ROCK SALT AND SQUEEZING SALTS

Above the anhydrite and gypsum are a sequence of sulphates and chlorides (halite, sylvite, kieserite, carnalite and bischofite) [11]. These salts have two physical properties which are of consequence to drilling:
- They have a high solubility which results in large wellbore cavities when using water-based muds [11, 13].

- They can behave like highly viscous fluids and flow into the wellbore under differential overburden stress [11, 13].

The solubilities of the various Zechstein salts are shown in Table 3.2 below. The superscript refers to the temperature at which the solubility was measured. Where no temperature is shown, no value could be found from the original source [11]. As can be seen, a number of these salts are highly soluble, for example, bischofite, which is about ten times more soluble in hot water than is halite (NaCl, common table salt).

One reason for problems when drilling through salt layers is their ability to flow under very low differential pressures (i.e. they tend to behave like very viscous fluids). The rate at which they will move is dependent on the depth of burial, formation temperature, the mineralogical composition, the water content, and the presence of impurities such as clay. The minerals containing water (e.g. bischofite and carnallite) are the most mobile, and anhydrite and the carbonates are essentially immobile.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Solubility in Water [g/100cc]</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Cold</td>
</tr>
<tr>
<td>Bischofite</td>
<td>167.0</td>
</tr>
<tr>
<td>Carnallite</td>
<td>64.5°C</td>
</tr>
<tr>
<td>Kieserite</td>
<td>68.4°C</td>
</tr>
<tr>
<td>Sylvite</td>
<td>23.8°C</td>
</tr>
<tr>
<td>Halite</td>
<td>35.7°C</td>
</tr>
<tr>
<td>Gypsum</td>
<td>0.24</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>0.21°C</td>
</tr>
</tbody>
</table>

In addition, a further behavioural mechanism has been suggested [1] to explain the reported occurrence of a brine flow from an adjacent salt section. Salt has, by definition, zero porosity and, it is claimed, that no local porous formations could be attributable. One possible explanation is that the water saturation in the salt was higher than in the mud, thus causing the flow. This explanation seems plausible considering the water content of salts at the top of a sequence, see Table 3.1.

### 3.5 Consequential Properties

The characteristics discussed in the above passages result in Zechstein formations being able to exhibit the following behaviour which is also illustrated in Figures 3.5a and 3.5b:

- **Salt washout**: The salt in a number of sequences is highly soluble in water, therefore, salt sections drilled with some mud systems can significantly washout producing out-of-gauge holes.
- **Salt movement**: Salts can behave as highly viscous fluids, and can flow into and away from the wellbore depending on the wellbore pressure.

- **Kicks**: Dolomite sections or rafts that are overpressured may kick once penetrated due to their permeability and porosity.

- **Fractures losses and charging**: Fractured underpressured dolomites may be the cause of sudden losses during drilling. Charging may occur depending on the size and connectivity of the dolomite section.

- **Filtration losses and charging**: Underpressured dolomites may be the cause of gradual losses during drilling due to their permeability and porosity. Charging may occur depending on the size and connectivity of the dolomite section.

- **Zero porosity salt brine flows**: It has been proposed [1] that salt sections with water saturations greater than the mud may flow brine into the wellbore.
Salt washout

Salt movement

Kicks

Brine/oil/gas H₂S/return mud

FIGURE 3.5A ILLUSTRATIONS OF ZECHSTEIN BEHAVIOURAL MECHANISMS
FIGURE 3.5B ILLUSTRATIONS OF ZECHSTEIN BEHAVIOURAL MECHANISMS
4. EXPERIENCE OF ZECHSTEIN DRILLING ON UKCS

In order to fully assess all the health and safety implications of Zechstein drilling, it is necessary to gain an appreciation of past experiences. This can be achieved by identifying which fields lie in or beneath Zechstein formations, and therefore, identifying the past requirements for drilling through them.

Zechstein extends beneath much of the Southern, Central and Northern North Sea, and parts of the West of Shetlands and East Irish Sea Basin. In Section 2, maps of Zechstein distribution on parts of the UKCS are presented. These maps have the UKCS licensing block grid structure overlain to help determine which fields are in their location.

In an area where these formations are present, a target field, may lie above, within or below Zechstein. Experience will have only been gained for fields that lie within or beneath the strata.

In Figure 3.1, the timescale shown is an estimate of the time of deposition and, therefore, is an indication of the depth and order in which the sequences will be encountered during drilling. For locations where Zechstein is present, their drilling is necessary to reach target reservoirs in the Permian, Carboniferous and Devonian sequences.

Thus, two criteria emerge in the search for fields for which Zechstein drilling experience has been gained:

- Field in a location where Zechstein is currently known to be present, as determined from Figures 2.2 to 2.5, and

- Target reservoir of field lies in either within or beneath the Zechstein.

Detailed information on the target reservoirs of fields within the UKCS is given in the Energy Report Vol. II Oil & Gas Resource UK (Brown Book), DTI, April 1996 [3] and in the FT Guide to North Sea Operations, 1995 [2]. The Brown Book [3] supplies information on the target reservoir for each field only for what are considered to be significant discoveries. The description “significant” refers generally to flow rates achieved or achievable in well tests rather than the commercial potential of a discovery. The FT Guide [2] supplies information on the reservoir for each field, however, this tends to be patchy.

Applying these criteria to fields within the UKCS yields the following insights:

- Zechstein has been drilled in the North Sea ever since the earliest years of exploration in this region.

- Zechstein drilling is reasonably common, particularly to reach the gas fields in the Southern North Sea.
- A large number of operators have experience in drilling Zechstein.

Information on relevant fields, and hence their operators, was used as a starting point for contacting key industry personnel to ascertain their concerns and the operational procedures they undertake to alleviate any problems [1].
5. HEALTH AND SAFETY ISSUES OF ZECHSTEIN DRILLING

A number of problems can occur when drilling Zechstein, and information on these has been sourced in the literature (see references) and through dialogue with industry personnel [1]. In this section, the problems that have direct or indirect health and safety implications are reviewed. These problems have been categorised in terms of the well responses observable on the drill floor:

- Wellbore losses
- Wellbore gains
- Stuck pipe
- Casing collapse

Wellbore losses can have implications for subsequent wellbore gains and are, therefore, considered first. Below, attempts are made to explain these problems in terms of the physical mechanisms introduced earlier.

5.1 WELLBORE LOSSES

A wellbore loss is the term used to describe a sudden decrease in pit level, and is the opposite of a wellbore gain.

There are a number of obvious situations that can result in apparent wellbore losses which have no connection to Zechstein drilling. Running the drillpipe out of the wellbore can cause a reduction in pit level if a compensating volume of mud is not added to the system. Also, the drilling process itself will, over time, cause the pit level to fall because the volume of the wellbore will increase with time, therefore requiring a compensating volume of mud to be added to the system [24].

The standard interpretation of an unexpected wellbore loss is that a volume of the mud has been absorbed by the formation. Mud loss to the formation can lower the hydrostatic head of mud in the wellbore and, thus, reduce the bottomhole pressure. The reduction in bottomhole pressure may be sufficient to initiate a kick. This is just one mechanism by which a loss-gain situation can arise.

Wellbore losses experienced while drilling through Zechstein may be interpreted in a number of ways.

5.1.1 FRACTURE LOSSES, FILTRATION LOSSES, AND CHARGING

Mud losses to the formation can occur if the formation is underbalanced with respect to the pressure exerted downhole by the mud column.

The rate at which losses occur depends on the flow characteristics of the formation. Penetration of a naturally fractured formation or fractures resulting from excessive mud pressure can cause severe mud losses with many barrels or tens of barrels being
lost suddenly [1]. Where there are no fractures, mud can be lost by filtering into the formation driven by the underbalanced pressure gradient. The rate at which mud is lost to the formation is a function of the underbalance, the height of loss zone penetrated, and the formation permeability and porosity.

Losses to a large accumulation will probably continue until some loss prevention action is taken. A smaller accumulation, however, will become charged, over time, until its pressure becomes that exerted by the hydrostatic head of mud plus any ECD pressure. Once circulation ceases, for example during a flowcheck, then the accumulation appears to have a overpressure less than or equal to the ECD pressure, and thus the accumulation flow back into the wellbore, resulting in a loss-gain situation, see Figure 5.1.

5.1.2 SALT WASHOUT

Zechstein salts, particularly those at the top of a sequence, are highly soluble. Bischofite, for instance, is about ten times more soluble than sodium chloride in water at downhole temperatures, see Table 3.2. When a well is drilled using WBM, these salts can dissolve in the mud causing an enlargement of the wellbore. Washouts beyond the range of calliper logs (22") have been experienced downhole [1, 13]. Wellbore enlargement does not occur for oil based mud (OBM), however, environmental regulations tend to discourage their use.

Fresh mud will continually circulate past the face of the cavity dissolving and carrying away salt thus causing the size of the cavity to increase. A critical cavity size will be reached where the lateral extent of the cavity is such that the mud circulation is no longer sufficient to refresh the mud at the cavity face. This mud eventually becomes saturated with salt, at downhole conditions, and an equilibrium cavity size will be reached.

As the mud with dissolved salt is circulated up the wellbore, the temperature of the circulating mud will decrease. A point will be reached where the mud is supersaturated and, thus, solid salt crystals will begin to nucleate within the mud. At surface the salt will be partially removed by the shale shaker. Salt washout will have caused the volume of the wellbore to increase, however, the mud system volume will have remained approximately the same. If the rate of dissolution is large enough then this could give the impression of a wellbore loss.

Salt dissolution and removal at the shale shaker could cause the mud level in the wellbore to fall, thus reducing the margin between the bottomhole pressure (BHP) exerted by the mud column and the formation pressure sufficiently to either cause a direct kick or to allow surge movements of the drillpipe to cause a kick.

5.1.3 SALT MOVEMENT

As stated previously, salts can behave as highly viscous fluids, and can flow into and away from the wellbore depending on the surrounding rock stresses and the pressure within the wellbore. Field measurements have shown that salt can move by as much as
one inch per hour [13], however, other sources have indicated that rates could be even higher [1]. If the stress within the surrounding rock is lower than the pressure exerted by the mud column then salt may flow away from the wellbore [1]. If the rate of salt movement away from the wellbore is large enough then this could give the impression of a wellbore loss.

Salt movement away from the wellbore could cause the mud level to fall, thus reducing the margin between the BHP exerted by the mud column and the formation pressure sufficiently to either cause a direct kick or to allow surge movements of the drillpipe to cause a kick.

5.2 WELLBORE GAINS

A wellbore gain is the term used to describe a sudden increase in pit level, and is the opposite to a wellbore loss.

There are a number of obvious situations that have no connection to Zechstein drilling which can result in apparent wellbore gains. Mud moved from a reserve pit to the main pit will increase the pit level. Also, running the drillpipe back into the wellbore can cause an increase in pit level if a compensating volume of mud is not removed from the system [24].

The standard interpretation of an unexpected wellbore gain is that a formation fluid (either brine, oil, gas, H₂S, return mud or a mixture of these) has entered the wellbore. On detection of the supposed kick, the wellbore can be shut-in and once the pressures have stabilised, the formation overpressure can be determined. A well control procedure can be selected and executed to remove the influx and regain pressure control of the well. In the extreme, if well control intervention fails or is not applied then the kick could ultimately develop into a blowout. [23, 24].

Wellbore gains experienced while drilling through Zechstein may be interpreted in a number of ways.

5.2.1 BRINE KICKS

Brine kicks are one possible explanation for a wellbore gain while drilling through Zechstein. These will be considered first because the majority of influxes from the Zechstein are reported as consisting of predominately brine with lesser quantities of oil and gas. Brine kicks commonly originate from the Plattendolomite formation (Z3 dolomite, see Figure 3.2) and from the Hauptdolomite formation (Z2 dolomite, see Figure 3.2) [1].

Brine kicks have a density which is closer to that of drilling mud rather than of gas, therefore, they do not rise up the wellbore as quickly as a gas kick, they do not expand, and at surface are not flammable. Brine kicks pose less of a threat than gas kicks, however, they do represent unscheduled events that can lead to the implementation of non-routine, and therefore unfamiliar operations, which in themselves raise safety issues.
Brine kicks can behave in a non-conventional manner. Once a brine kick is detected, the well is shut-in and the pressures are allowed to stabilise. Using the stabilised shut-in drillpipe pressure (SIDPP) reading, a mud density necessary to kill the well can be calculated. Once the brine has been circulated out with the kill mud, the SIDPP reading should have fallen to zero, however, some residual shut-in pressure can remain [1]. One explanation is that gradual salt movement into the wellbore squeezes the wellbore fluids thus increasing the pressure on shut-in. Another explanation could be that the wellbore charging is taking place and that the SIDPP reading is due to the ECD pressure.

A brine kick can be problematic for the following reasons:

- Brine has a lower density than mud, and therefore, may lower the wellbore pressure sufficiently to initiate a further kick from a candidate formation. This results in a loss-gain situation, which ultimately could lead to an underground or surface blowout [1].

- A large brine kick can destroy the emulsion of an oil based mud (OBM) resulting in a change in the rheology [1]. The pumpability of the mud will increase raising the frictional pressures along the well. This may cause wellbore losses via the fracture, filtration, or salt movement mechanisms, again resulting in a loss-gain situation.

- A brine kick circulated up the annulus and past open salt formations is likely to cause washout. The brine will probably be saturated with a salt (e.g. MgCl₂ for brine kicks from the Plattendolomit Z3 [1]) which is different to the salts it is circulating past, so a washout is possible [1].

5.2.2 GAS KICKS

Gas kicks pose a far greater threat to safety because they can rise and expand quickly within the wellbore and are flammable if released at surface. Where Zechstein dolomites are buried deeply enough for gas generation, local vuggy porosity and fractures can give rise to gas accumulations [7]. These are reported to be accompanied by brine flows or kicks [1].

Gas kicks can behave in a non-conventional manner, as can brine kicks, because charging can still be an issue.

Another non-conventional aspect of gas kick behaviour can be caused by high pressure low permeability formations [16]. During drilling, there can be clearly observable gas in the mud indicating an influx downhole. On shut-in, however, there is little or no build-up in SIDPP. If it is suspected that the gas bearing formation has very low permeability and the shut-in period extended then once pressures do begin to rise it is difficult to distinguish the formation overpressure from the gas migration effects as no clear stabilisation is reached, see Figure 5.2. Without a clearly stabilised value of SIDPP, no kill mud weight can be determined. This may result in extended periods of circulating successively heavier weighted muds, until the well is finally under control and gas shows ceased. This process can last for days, adding to the
stress levels experienced by the rig crew, resulting in fatigue and an increased likelihood of errors.

5.2.3 H₂S Kicks

While there is no direct correlation between the occurrence of Zechstein and the occurrence of H₂S, a number of wells drilled through Zechstein in the Southern North Sea have encountered H₂S [1].

As described above, Zechstein well control operations involving gas can be difficult to resolve perhaps taking many days to complete. The presence of H₂S makes the problem worse because it is extremely toxic to personnel and can corrode pipework and rubber seals particularly over the extended periods required to conduct these type well control operations.

A sour condition exists when either H₂S or CO₂ are present in the formation. H₂S and CO₂ are corrosive individually only in the presence of water, and are severely corrosive in the presence of each other and water [25].

Attack on steel casing strings by H₂S causes the formation of iron sulphide, and the adherence of the iron sulphide to steel surfaces creates an electrolytic cell. The iron sulphide is cathodic to the steel and accelerates local corrosion. Hydrogen sulphide also causes hydrogen embrittlement by releasing hydrogen into the steel grain structure to reduce ductility and cause extreme brittleness [25].

Sour gas corrosion is certainly not unique to Zechstein formations but one incident where this phenomenon could have been a factor has been reported [11].

5.2.4 Return Lost Mud Kicks

Mud can be lost to the formation either through fractures or filtration. Mud lost to large underbalanced dolomite sections will probably never return to the wellbore. Smaller underbalanced accumulations may, however, charge-up with mud filtering in from the wellbore. Once circulation ceases, for example during a flowcheck, the pressure exerted by the mud column is reduced, however, the accumulation is still charged with ECD pressure. The charged mud will flow back into the wellbore giving the impression of a wellbore gain.

Hazards can arise if the existing formation fluid is gas. Initially, the formation is no threat because the mud weight has been selected to exert a pressure greater than the pore pressure. Once drilling ahead and circulating, the ECD pressure causes mud to filter into the formation and, thus, charge the existing pore gas to the pressure exerted by the circulating mud column. When circulation ceases, the formation has an overpressure equal to the ECD pressure and, therefore, charged mud and gas flow into the wellbore causing a kick.
5.2.5 **Brine Flows from Zero Porosity Salt**

Conventionally, brine kicks are thought to originate from formations, such as dolomite, with reasonable porosity and permeability. It has been reported, however, [1] that a brine flow whose origin could not be attributable to any local porous formation appeared to emanate from a salt formation. One possible explanation suggested that the salt water saturation could have been such that the water activity of the salt was higher than for the mud (presumably the mud was oil/synthetic/pseudo based), resulting in brine flow from the salt into the mud.

This explanation may have some merit if an analogy can be drawn with shale dehydration. A mud can be formulated to have a water activity either higher or lower than that of the shale. Muds with higher water activities cause the shale to hydrate, and thereby swell possibly causing stuck pipe. Muds with lower water activities cause the shale to dehydrate, increasing its strength, stabilising the wellbore, and producing a slightly over-gauge hole [24].

5.2.6 **Salt Movement**

Salts can behave as highly viscous fluids, and can flow into or away from the wellbore depending on the surrounding rock stresses and the pressure within the wellbore. If the stress within the surrounding rock is greater than the pressure exerted by the mud column then salt will flow into the wellbore. Field measurements have shown that salt can move by as much as one inch per hour [13], however, other sources have indicated that rates could be even higher [1]. It could be the case that for particularly
high rates of salt flow, sufficient mud is displaced from the wellbore and into the mud pits to produce a noticeable wellbore gain.

5.3 STUCK PIPE

During the drilling process, it is often necessary to run the drillpipe either out of or into the well. On some occasions, it can be difficult, or impossible, to run the drillpipe past certain formations. This phenomenon is termed ‘stuck pipe’.

There are a number of situations that can result in stuck pipe and that have no connection to Zechstein drilling. Stuck pipe can occur when there is significant differential pressure between the wellbore and the formation, by cuttings packing off the drillpipe, or when a drillpipe is run too quickly and hits a bridge, a tight spot or the bottomhole [24].

In Zechstein formations, salt can be considered to behave as an extremely viscous fluid. Before a borehole is drilled, the overburden stresses that act on the salt are in equilibrium. Once a borehole is opened, these stresses no longer balance and the salt can flow back into the wellbore tightening the bore around the drillpipe [1].

When drilling with WBM in Zechstein salt, stuck pipe is not usually a problem because, for the duration of the drilling process, the salt washout mechanism tending to increase the bore is more dominant than the salt movement mechanism tending to decrease the bore.

When drilling with OBM, stuck pipe can be a problem because there is no salt washout to compensate for any inward salt movement. Salt movement is claimed to be greatest during drilling, and field measurements have shown that salt can move by as much as one inch per hour [13], however, other sources have indicated that rates can be much higher [1]. Operators have experienced tight spots when pulling the bottomhole assembly and then found themselves unable to run the casing to total depth due to wellbore reduction.

5.4 CASING COLLAPSE

Casing collapse can occur during drilling or even after as much as twelve years into production [11, 17, 18, 19, 20, 21]. During drilling, casing collapse will manifest itself on the rig floor as an inability to run pipe, or as lost circulation, or both. Two explanations have been proposed to explain casing collapse in Zechstein wells.

5.4.1 SALT WASHOUT

The points where collapse occur are often preceded by large washout. The washout leaves a less dissolvable salt, forming a ledge which exerts a point load on the casing, eventually causing failure [1,13].
5.4.2 **SALT WASHOUT AND SALT MOVEMENT**

During drilling, significant uneven salt washout may have occurred, either because a WBM was used or because a large brine kick occurred using a OBM. During the casing operation, it is possible that an inaccurate cement volume is calculated because the washout may extend beyond the range of calliper logs (22"). The salts are, thus, ineffectively sealed. Even if the required cement volume could be accurately found, then there may be inefficient cement sweepage leading to a weak cement seal [17]. In either case, as time progresses the salt may flow back towards the wellbore at a uniform rate, forcing old mud between the strings. It is estimated that salt movement is greatest during drilling, slowing down during casing and cementing, and speeding up again when production begins [13]. Thus, over a period of time, one point on the circumference of the casing is subjected to the salt loading prior to the rest. The casing then bends, supported by wall contact at either end, such that casing failure is caused by non-uniform loading [1, 11].
6. CURRENT OPERATIONAL PROCEDURES

In the previous section, the operational problems that can occur when drilling through Zechstein were introduced together with their associated health and safety implications. This section introduces the operational procedures that are prescribed at the well planning stage, to avoid anticipated problems, and those applied at the rig site to remedy a problem that has already occurred.

6.1 WELL CONTROL

According to traditional well control procedure, when a kick is detected the well is shut-in and pressures are allowed to stabilise. From the stabilised SIDPP, it is possible to calculate a value for the required mud density to kill the well. The kick is then circulated out of the well in a controlled manner while the kill mud is circulated into the well. Once the kick is removed, and the well is full of kill mud, there should be no shut-in surface pressures and the well is said to be killed.

As stated in the previous section, both brine and gas kicks from the Zechstein can exhibit pressure behaviour that does not fit with traditional well control techniques.

Kicks have been reported [1, 16] where there has been little or no pressure build-up on shut-in, thus making any determination of kill mud weight impossible. While the mud clearly contains gas, no pressure build-up is observed except possibly due to gas migration, and thus the required mud weight cannot be found. Under these circumstances [1, 16], the mud weight is usually incremented and circulated until the gas shows cease, however, it is not uncommon for this process to last for many days until the kill mud weight is found.

Kicks have been reported [1, 27] where a shut-in pressure is measured and kill mud weight is determined, however, after circulation a residual shut-in pressure remains. Sometimes under such circumstances, the drill crew assume that an error as been made in calculating the kill mud weight or there is a problem with the pressure gauge [1] and attempt to re-calculate the kill mud weight. This process can be carried out a number of times before a realisation is made that ECD pressure charging of the formation is occurring, and that the best way to proceed would deplete the charged zone and drill ahead controlling the well by ECD.

There are other techniques which can applied in an attempt to remedy Zechstein kicks and losses [1, 27].

Bullhead kill technique involves increasing the wellbore pressure by continuing to pump on shut-in in an attempt to force the influx back into the formation. Shoe strength should be considered before this method is employed.

If the kick zone is thought to have a small volume then depletion can be attempted through the mud-gas separator, for gas kicks, or directly into the mud pits for brine kicks.
For a larger volume brine zone with low productivity, it may be possible to drill ahead with the well flowing. For a higher productivity brine zone, it has been suggested that the influx could be used to make up a temporary mud system.

Mud cap drilling is a method which has been used to alleviate underground flow situations. Formation fluids will flow from the overpressured kick zone to the underpressured loss zone, any losses from the mud column above can be topped up by pumping mud down the annulus. This method can allow drilling to continue during underground flow situations.

It has been suggested that one way to cure a loss or kick zone is to set casing over the zone. This technique may be useful if all else fails and the original shoe setting depth is still some depth away.

Additional precautions are required if H$_2$S is thought likely. Breathing apparatus (BA) capable of being plugged into a permanent cascade air supply system would be necessary to protect crew during the well control operation. Also, the vented H$_2$S should be burnt, if possible, to avoid the possibility of pockets rising into the path of helicopters.

6.2 Mud Type Selection

The type of mud used to drill a well will be chosen during the well planning stage, however, some of its properties can be changed at the rig site in response to well developments. There are two basic mud parameters which have a bearing on Zechstein drilling problems: base fluid and mud weight.

6.2.1 Base Fluid

Large salt washouts can, to some extent, be blamed on the type of mud used. The advantage of OBM is that it does not dissolve salts and, as a result, only the salt directly contacted by the bit is removed, giving a gauge hole. However, large brine kicks can destroy the emulsion of OBM. When the brine/mud mixture is circulated passed a salt section it is likely that the brine is not saturated with precisely the same salt resulting in possible washout.

Environmental legislation has caused a reduction in the use of OBM by limiting the amount of oil that can be dumped overboard with the cuttings. At present, the use of pseudo oil base mud (POBM) through the Zechstein sequence is yielding good results [1, 11, 13].

Operators have had varying degrees of success using salt saturated WBM in salt sections. The main problem experienced is due to the WBM being designed to be saturated at surface conditions, and with respect to the more dominant NaCl type salt. Field results have shown that large washouts were observed due to the dissolution of salt at the high downhole temperatures [1, 13].
Mixed salt mud has been used to deal with the problem of complex salt sections (potassium/magnesium - so called polyhalites). Proponents of the mixed salt mud claim that it can be saturated to all types of salt that could be encountered downhole. However, there is still the problem of saturation at downhole temperatures and large hole washouts have been reported [13].

The use of heated, salt saturated mud, has met with some success [11]. The mud is heated at surface to temperatures that approximate those across the salt section and is saturated with salts at these temperatures. However, solids control problems at the shakers have been experienced, as large salt particles crystallise due to supersaturation at surface temperatures [13].

6.2.2 MUD WEIGHT

The density of a mud system is engineered to give a bottomhole pressure greater than the pore pressure, thus avoiding brine and gas kicks, but lower than the fracture pressure, thus avoiding losses and associated well control problems. The margin between pore and fracture pressure can be small for the Zechstein and, along extended sections of open hole, the pore pressure at one point can exceed the leak-off pressure at another, thus leading to a loss-gain situation and possibly an underground blowout [1].

In open hole sections drilled through Zechstein, an ideal mud system would meet the following criteria:

- Pore pressure would be lower than pressure exerted by mud column.
- Fracture pressure would be higher than the pressure exerted by the mud column.
- Pressure required to stop salt flow into the wellbore would be lower than the pressure exerted by the mud column.

Salt flow into the wellbore is driven by the overburden rock stress, which is typically around 1.0 psi/ft (19 PPG). The salt may be able to sustain some part of this stress.

There are currently two views regarding the best mud to drill the Zechstein salts [1, 11, 13]:

- Use salt saturated WBM if a brine kick, typically coming from the Platten dolomite at 17-18.5 PPG, could be expected from seismic or previous drilling experience in the area. A brine kick will destroy the emulsion if OBM is used.
- Use OBM or POBM at a mud weight not below 14 PPG if no brine kicks are expected.

Mud weights around 14 PPG appear to have beneficial effects on the stability of holes in the Zechstein. Holes drilled with mud weights below 14 PPG have consistently
shown problems with stuck pipe and casing collapse. Wells drilled with mud weights greater than 14 PPG have been, on the whole, stable across the salt section [1, 13].

It would seem that the pressure required to hold the salt back (14 PPG) is less than the pressure of brine kicks expected from the Platten dolomite (17-18.5 PPG). If a brine kick were taken from an open hole section at this pressure, and a salt section was also open, then the mobile salt may be forced away from the wellbore, thus producing a loss-gain situation.

6.3 Casing Setting Selection

Two general rules or suggestions have been made concerning casing setting selection.

It is claimed that there is far less likelihood of casing collapse when the top of the cement (TOC) is set above the top of the squeezing salts (TOS) [1, 11]. This can be understood with the aid of Figure 6.1. If the TOC were to lie in the salt section (as shown in Figure 5.1) then the salt would be able to flow into the cavity, displacing the old mud there. This would cause an increase in wellbore pressure and would eventually result in casing collapse. If the TOC lies above the salt then there is a greater likelihood that the cement seal will be able to withstand the pressure exerted by the salt.

The likelihood of achieving a TOC above the salt is increased for casing strings set immediately below and just above the salt [13]. This can be understood with the aid of Figures 5.1 and 6.1. If the casing is set immediately below the salt then it is more likely that the calculated cement volume may be sufficient to produce an adequate cement seal.

6.4 Casing Type Selection

The use of thick wall casing is preferred to high collapse strength casing because higher tensile strength steels are more brittle, whereas thicker wall, lower tensile steels “bend” more; ultimately failing, but possibly after a longer period of time.

Point loads, from ledges produced by salt washout, have been estimated to be greater than the highest collapse strength casing available [13].

Casing can also fail due to the non-uniform loads caused by salt movement. The salts washout unevenly during drilling, however, the salt flows back towards the wellbore at an equal rate from all directions. At some point, one sector of the circumference of the casing is subjected to the salt loading prior to the rest. The failure resistance for a non-uniformly loaded casing is considerably lower, between 5 - 10% than the uniform loading capability, depending on the type of support provided by the cement or wellbore. A casing capable of completely resisting non-uniform loading would require a four fold increase in the standard API wall thickness. Standard thick wall casings provide sufficient time, however, for the salt to flow fully around the casing, thus allowing the loading to become uniform before failure can occur [11].
Hydrogen embrittlement is a real risk for higher strength steels and they should not be used in sour gas environments unless they are made from sour gas resistant steel [18].

6.5 **BI-CENTRE AND ECCENTRIC DRILL BITS**

Bi-centre bits are considered to produce a slightly larger diameter hole than the bit diameter and, therefore, the incidences of stuck pipe would be reduced for OBM or heated salt saturated WBM. Although a consistent hole is produced it has been noted that the bits lack a refined design and directional control abilities are questioned. This use in highly deviated holes is not generally recommended since they tend to drop angle [13], however, this can be planned for [1]. Also, some experiments have been carried out on eccentric PDC (polycrystalline diamond compact) bits for drilling salt while using OBM and some success has reportedly been achieved [11].

6.6 **FAST DRILLING**

Another way of preventing stuck pipe is to drill the well as quickly as possible and then case and cement it with a uniform cement sheath [13]. Drilling, casing and cementing as quickly as possible can reduce the time available for the salt movement into the wellbore.

6.7 **LCM OPERATIONS**

Loss circulation material (LCM) can be pumped into loss zones in an attempt to remedy the situation. LCM can consist of granules of various sizes. The granule size has to be comparable to the loss geometry and there has to be a graduation in size in order to build-up an effective seal. Small granule LCM’s have greater success with filtration losses where the geometry is the pore size. Larger granule LCM’s have greater success with fracture losses where the loss geometry is the fracture size. If salt movement or salt washout were to be misinterpreted as a loss of wellbore fluids, then it is expected that pumping LCM would be of little use. Alternatively for low loss rates, it may be possible for normal drilling continue.

6.8 **SEISMIC SURVEY**

The presence of dolomite rafts within the Zechstein can sometimes be detected by seismic, and thus avoided during drilling [1].

6.9 **CEMENT SELECTION**

The possibility of casing failure because of cement strength deterioration caused by contact with salt zones should be considered. Further consideration should be given to the application of specialised magnesium resistant cements. This will reduce the potential for casing failure caused by insufficient cementation strength [1, 11].

6.10 **VARIATION OF ANNULAR PRESSURE**

If stuck pipe occurs during drilling, the well can be shut-in and the annular pressure increased, using the pumps. The increased annular pressure forces the salt back into
the formation. The effect on any open formations in terms of losses and strength must be taken into account [1, 11].

6.11 FRESHWATER SPOTTING

In an attempt to cure stuck pipe, a small freshwater pill (~2 m³) can be spotted across the salt section. This has the minor disadvantage of producing short washouts in the order of 10 to 25 mm over the section where it is spotted [11, 20].

6.12 SIMULTANEOUS UNDERREAMING AND DRILLING

One method to help avoid stuck pipe is to use a modified bottomhole assembly (BHA). The most important functions of the BHA for salt drilling have been identified as follows:

- BHA must have the ability to side-cut in order to keep the moving salt intervals cut away from the wellbore.

- BHA must have the capabilities of back-reaming through the moving salt intervals when the BHA is pulled or tripped out of the salt.

- BHA must be stiff enough to allow good bit stabilisation and minimise dogleg severity.

With these factors in mind [20], a packed BHA was designed with aggressive mills built specifically for salt drilling. All of the mills are full 12 1/4" gauge with aggressive side cutting structures. The spiral of the blade cutting structure is reversed on the upper side of the mill to enhance a back-reaming operation.
7. ANALYSIS OF DOCUMENTED INCIDENT DATA

In this section, a number of actual recorded incidents of operational problems encountered while drilling through Zechstein will be analysed in an attempt to gain insight into the problems, the alleviation procedures, and the resulting safety issues, that may be useful in similar future events.

The type of incident chosen for this next stage are kick incidents, and there are three reasons for this choice.

Firstly, out of all the Zechstein operational problems, kicks are the events that are recorded with the most detail. This is because the symptoms (pit gain, increased flowrates, gas shows, shut-in pressures etc.) of a kick can be readily quantified and recorded on the rig floor. The majority of these are continuously measured during the drilling process by mud logging service companies, independently of whether a kick has been detected, therefore, providing a definite record of well responses to downhole events.

Secondly, Zechstein kicks rarely occur in isolation from the other behavioural mechanisms, such as washout, losses and salt movement. A detailed record of well responses to downhole events may, therefore, provide insight into these other mechanisms and their interaction.

Thirdly, a number a particularly advanced kick simulators exist which can provide insight into kick mechanisms, and the wider Zechstein behavioural mechanisms. The simulator results can be matched to the recorded data thus revealing the history of the kick. It may be possible to model the other behavioural mechanisms that affect the development of the kick within the simulator, thus taking their affect directly into account. Otherwise, where a particular mechanism cannot be modelled within the simulator, the difference between the recorded and simulated data can be explained in terms of the affect of the unmodelled mechanism.

These incident data sets have been used to reconstruct kick incidents within the simulation environment offered by an advanced kick simulator. This approach allows kick initiation, kick detection and well control procedure to be analysed, thus revealing any phenomena uniquely associated with Zechstein kicks and possible options for dealing with these.

7.1 WELL INCIDENT #1

The objective of this study is to examine and evaluate the initial kick detection phase of a well control incident using a kick simulator. The emphasis of the study will be to:

- Attempt an explanation for the occurrence of two influxes in close succession.
- 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 key events immediately before and during this well incident are summarised below:

**TABLE 7.1 SEQUENCE OF WELL CONTROL ACTIONS**

<table>
<thead>
<tr>
<th>Start Time [hrs]</th>
<th>Duration [hrs]</th>
<th>Description</th>
</tr>
</thead>
</table>
| 22 00            | 01 06         | Drilling ahead  
Av. ROP 30 ft/hr from 6732 ft to 6760 ft MD. 
6291 ft TVD.  
630 pptf  
470 GPM.  
Influx approx. start time 2258 hrs. |
| 23 06            | 00 02         | Flow check |
| 23 08            | 01 15         | Shut-in  
SIDPP 890 psi, SICP 1050 psi at 2349 hrs.  
Final pit gain 12 bbl.  
Calculated kill mud to be 770 pptf. |
| 00 23            | 00 42         | Circulate through choke  
Displace drillpipe with 780 pptf kill mud.  
130 GPM. |
| 01 05            | 00 05         | Shut-in  
Check for zero SIDPP. |
| 01 10            | 03 40         | Circulate through choke  
Displace annulus and circulate.  
Gas peak 6.4% after mud-gas separator. |
| 04 50            | 00 15         | Flow check  
Over choke. |
| 05 05            | 01 05         | Circulate through choke  
Gas peak 8.1%. |
| 06 10            | 00 15         | Flow check  
Over choke. |
| 06 25            | 00 50         | Shut-in  
SIDPP 40 psi, SICP 45 psi, final pit gain 2 bbl. |

The main feature of Well Incident A is that two influxes occurred in close succession, interestingly enough, without any further drilling having taken place between their occurrences.

On detection of the first influx, the well was shut-in and the resulting stabilised SIDPP, as read presumably from a gauge on the drillers console, was used to calculate the mud weight required to kill the well. The original mud weight was 630 pptf (6291 TVD ft), SIDPP as reading from the drillers console was 890 psi, a safety factor of 10 pptf was included, which using the equation below gives a kill mud weight of 780 pptf.

\[
MW_{kill} = MW_{erg} + \frac{1000 \times SIDPP}{TVD} + SafetyFactor
\]
Once this mud was circulated, however, a secondary influx of about 2 bbl was detected without any further drilling having taken place.

Two independent records of SIDPP readings have been made available:

- Spot readings of SIDPP presumably made from the gauges on the drillers console. First influx, SIDPP 890 psi and was used to calculate kill mud weight of 780 ppi. Second influx, SIDPP 40 psi.

- Continuous log of measured standpipe pressure. First influx, SIDPP 950 psi. Second influx, SIDPP ~ 10 psi.

There is a discrepancy between these two sets of pressure readings. One set is likely to resemble the actual pressures more accurately than the other, however, this does not rule out the possibility of both being inaccurate. Two scenarios can be conceived assuming that one or the other of the sets is the more accurate.

**Scenario #1 - Spot readings are the more accurate**

A kick zone is encountered that is overpressured by 890 psi. On detection, the well is shut-in and a SIDPP measurement of 890 psi is made. This value is used to estimate a kill mud weight of 780 ppi which is enough to kill the well. It is necessary, however, to postulate that some time after the circulation of the kill mud, a further kick zone, which has always been present but never active, suddenly begins to flow and is overpressured by 40 psi relative to the kill mud.

The Zechstein can be regarded as a difficult sequence to drill because a number of physical mechanisms can occur, possibly at the same time, which produce well responses observed on the drill floor that can be difficult to interpret. Assuming that the spot readings are the more accurate, it is necessary to postulate the existence of a further kick zone that stays dormant for approximately seven hours and then begins to flow into the wellbore, presumably initiated by no external stimulus, and that is capable of producing a SIDPP of 40 psi within 50 mins of the well being shut-in.

**Scenario #2 - Continuous log is the more accurate**

Alternatively, a kick zone is encountered that is overpressured by 950 psi as indicated by the continuous log. On detection, the well is shut-in and an inaccurate SIDPP measurement of 890 psi is made. In this pressure range, the spot readings are assumed to give a value which is 60 psi too low. This inaccurate value is used to estimate a kill mud weight of 780 ppi which leaves the well statically underbalanced by about 6.5 psi. When the well is shut-in or flow is ceased then the kick zone will flow.

A secondary influx is detected after a flow check and the SIDPP is measured to be 40 psi according to the spot readings and around 10 psi on the continuous log. In this pressure range, the spot readings are assumed to give a value which is 30 psi too high.
The first scenario seems difficult to justify. Why should a second kick zone remain dormant for so long? and then what is the stimuli to cause it to flow assuming no unreported well intervention other than the circulation of a kill mud?

The second scenario seems the more likely of the two. The continuous log can be assumed to represent an accurate record of SIDPP, however, it is the inaccurate values from the spot readings which are used to incorrectly calculate the kill mud weight thus making a secondary influx possible.

The simulations reported in this technical note are based on the assumption that the continuous log pressure data are an accurate record of well pressure and that the spot readings are in error.

The following data was made available:

- Daily drilling reports.
- Record of spot shut-in pressures and pit gains.
- Continuous logs of pit volume, torque, gas show, standpipe pressure, weight on hook and hook height.
- Geolograph records.
- Well geometry information.

This incident has been modelled, and simulations produced, using the Health & Safety Executive Gas Kick Simulator (RMODEL) and SideKick v3.0 kick simulator. All steps in the well control operation shown in Table 7.1 have been modelled, however, emphasis has been placed on matching the shut-in pressures to provide insight into the origin and nature of the two influxes.

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 original mud column plus the shut-in pressure registered on the continuous log.

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 shut-in pressures to determine the details of the kick mechanism and thus provide some explanation of the two influxes.

A match of the shut-in drillpipe pressure (SIDPP) readings and optimised simulation results are shown in Figure 7.1. The simulation results have been optimised against the continuous logs according to scenario #2. The kick zone properties to give the best match are:

- 950 psi static kick zone overpressure
- 600 mD kick zone permeability and 4 ft kick zone penetration (Kh ~ 750 mD m).
- 1 scf/bbl gas brine kick with 400 g/l salt concentration brine

This match was achieved using the SideKick v3.0 kick simulator which has a number of additional features to v2.0 including a mixed gas brine modelling capability.

Initial attempts to model this influx with the RMODEL assumed a kick of 100% gas as shown in Figure 7.2, however, it was not possible to produce a SIDPP profile anything like that recorded on the continuous log: build-up from 0 to around 950 psi over initial 3 minutes and then stabilisation at this pressure for 75 minutes. If a match with the long-term stabilised SIDPP was attempted then a low Kh gas kick had to be assumed, however, the match to the rapid SIDPP build-up phase would be poor. Likewise, an attempted match with the rapid SIDPP build-up phase required a high Kh gas kick to be assumed, however, so much gas entered the well that gas migration up the wellbore became significant resulting in a poor match with the long-term stabilised SIDPP readings.

Finally, SideKick v3.0 was used to model the influx as a mixed gas brine kick which are reported as being not unusual for Zechstein formations. A good match was achieved for a range of gas to brine ratios, however, as the gas content was increased, gas migration would become significant and the match would be lost.

Brine is virtually incompressible compared to gas and, therefore, causes the shut-in pressures to rise more sharply than for a gas influx. Stabilised shut-in pressures, however, tend not to rise because gas migration is non-existent or insignificant. It may be feasible to think of brine or gas brine kicks as having a 'shut-in pressure profile' that distinguish them form gas kicks.

These simulation results have been based on the assumed accuracy of the continuous log according to scenario #2. On detection, the well is shut-in and an inaccurate spot reading of SIDPP 890 psi is made. The spot readings are assumed to give a value which is 60 psi too low in this pressure range. This inaccurate value is used to estimate a kill mud weight of 780 ppg which leaves the well statically underbalanced by about 6.5 psi. No flow into the well occurred during normal circulation because the
mud equivalent circulating density (ECD) is greater than the kick zone pressure, however, once circulation ceases, during shut-in or flow check, then flow begins.

After a period including a shut-in and two flow checks, a secondary influx is detected via a 2 bbl pit gain and the well is shut-in. A match of SIDPP readings and simulation results, optimised against the first influx, are shown in Figure 7.3. The continuous log gives a value of about 10 psi, although it is difficult to distinguish down to this scale, however, it is certainly not zero. The spot readings give a value of 40 psi which is assumed to be inaccurate giving a reading which is 30 psi too high in this pressure range. The simulated SIDPP rises from 0 to about 5 psi, in accordance with the 6.5 psi static formation overpressure calculated earlier, but then diminishes to zero over the remainder of the shut-in period. This behaviour is difficult to explain and may result from some aspect of the numerical scheme applied to find a solution or may be a normal consequence from the interaction of a number of modelled processes such as the cooling of drillpipe mud and its subsequent increase in density.

There is, however, a discrepancy in modelling the secondary influx. Over the 15 min. duration of the second flow check, the simulation predicts very little pit gain, however, a field measurement of 2 bbl is reported. One possible explanation is that while the simulation has been optimised for the first influx some further optimisation is required for the second.

**Figure 7.1. SIDPP MATCH FOR FIRST INFLUX COMPARING CONTINUOUS LOG AND SPOT READINGS AGAINST SIMULATION RESULTS**
**Figure 7.2. Results from Various Modelling Attempts for First Influx**

**Figure 7.3. SIDPP Match for Second Influx Comparing Continuous Log and Spot Readings Against Simulation Results**
7.2 WELL INCIDENT #2

The emphasis of this incident study will be to:

- Attempt an explanation for the occurrence of the loss-gain situation and test this by comparing field data to simulation results.

- 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.

During the drilling of this well, three separate kick incidents occurred. The first kick occurred at 10310 ft and was killed using the conventional Weight and Wait method. The second kick occurred at about 10402 ft and appears to be a loss-gain situation. The third kick occurred at 10478 ft and was initiated by swabbing.

The first kick was successfully handled using a conventional well control approach and, therefore, it is unlikely that great benefit can be derived from its analysis. The third kick was initially swabbed and resulted in a protracted well control attempt. Analysis of this kick would be difficult because swab kick models are not yet widely available within kick simulation codes. The second kick appears to be a loss-gain situation, which are reported as being common when drilling Zechstein, and was killed using the original mud weight. Analysis of this kick is possible with current kick simulators and may provide insight into a common Zechstein drilling problem.

The key events immediately before and during this incident are summarised below:

### TABLE 7.2 SEQUENCE OF WELL CONTROL ACTIONS

<table>
<thead>
<tr>
<th>Start Time [hrs]</th>
<th>Duration [hrs]</th>
<th>Description</th>
</tr>
</thead>
</table>
| 01 00            | 01 00          | Drilling ahead  
|                  |                | Av. ROP 15 ft/hr from 10402 ft to 10417 ft MD.  
|                  |                | 15.7 ppg.  
|                  |                | 60 bbl/hr losses.  
|                  |                | Pump mica in attempt to reduce losses.  
|                  |                | Increase in flow out. |
| 02 00            | 00 05          | Flow check  
|                  |                | Negative. |
| 02 05            | 00 20          | Circulate through annulus  
|                  |                | Reduce pump rate to circulate out connection gas.  
|                  |                | 12 bbl pit gain. |
| 02 25            | 00 05          | Flow check  
|                  |                | Positive. |
| 02 30            | 01 00          | Shut-in  
|                  |                | SIDPP 250 psi, SICP 300 psi.  
|                  |                | Mud in pit cut to 15.4 ppg from 15.7 ppg.  
|                  |                | Weight mud up to 15.7 ppg. |
| 0330             | 01 00          | Driller’s method  
|                  |                | Circulate out influx using Driller’s method. |
The main features of this well control incident are that a loss-gain situation was encountered and that the well was killed using the original mud weight.

At 10402 ft, there is a transition between the Werraanhdrit formation (anhydrite) and the Zechsteinkalk formation (limestone). On drilling into the latter, losses of 60 bbl/hr were noted. Mica was pumped in an attempt to stem these losses. Shortly afterwards, an increase in flow out was noted, however, the following flow check was negative. Next, the well was circulated at a reduced pump rate to remove connection gas and a pit gain of 12 bbl was recorded. Another flow check was performed and was positive. In response, the well was shut-in and stabilised readings of SIDPP 250 psi and SICP 300 psi were taken. The mud in the pit was cut to 15.4 ppg. The mud was weighted up to 15.7 ppg and the well killed using the Driller’s method.

In order to explain this well incident, it is necessary to make a number of assumptions, or compose a scenario, about the well behaviour. This scenario can then be used as a starting point from which to perform simulations. The validity of the scenario can be judged on how well the simulation results match the field data provided.

Scenario

On drilling into the Zechsteinkalk losses of 60 bbl/hr (1 bbl/min or 42 gpm) are encountered. It is assumed that these losses are stemmed by pumping mica downhole. The 1 bbl/min of mud previously being lost to the formation is now flowing out of the annulus and is assumed to account for the observed increase in flow out. It is further assumed that this observed increase in flow is misinterpreted as an influx and, in response, drilling is stopped and a flow check performed.

In addition, it is assumed that the equivalent circulating density (ECD) of the mud exerts a pressure greater than the formation pressure and, thus, causes the losses. No pump rates have been supplied, however, a typical value of 500 gpm has been assumed for drilling ahead and a typical value of 150 gpm has been assumed for the circulation of connection gas. The static density of the mud, however, exerts a pressure lower than the formation pressure which allows the influx, see Figures 7.4. and 7.5. The evidence for this assumption is that the well is capable of being killed with the original mud weight suggesting that ECD effects are important.

Also, it is assumed that the influx is mostly brine. The supporting evidence is that a 12 bbl pit gain occurred in less than 30 min. suggesting that the permeability, K, or the penetration of the kick zone, h, or both are reasonably high, however, after 60 min. of shut-in there are no reported effects due to influx migration suggesting the influx is mostly liquid.
Figure 7.4. Simulated bottomhole pressure and pump flowrate for detection and initial shut-in period. Formation pressure is also shown.

Figure 7.5. Simulated bottomhole pressure and brine influx rate for detection and initial shut-in period. Formation pressure is also shown.
The following data was made available:

- Daily drilling reports
- Geological information
- Well geometry information

This incident has been modelled, and simulations produced, using SideKick v3.0 kick simulator which includes a loss modelling facility. All steps in the well control operation shown in Table 7.2. have been modelled with particular emphasis placed on matching the numerical data points where available.

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 original mud column (~8500 psi) plus the shut-in pressure value reading (SIDPP ~250 psi).

As mentioned previously, the entire well incident has been modelled with emphasis placed on matching numerical data points where available to determine the details of the kick mechanism and thus provide some explanation of the two influxes.

The kick zone properties to give the best match are:

- 250 psi static kick zone overpressure.
- 1500 mD kick zone permeability and 1.5 ft zone penetration (Kh ~ 700 mD m).
- 1 scf/bbl gas brine kick with 400 g/l salt concentration brine.

**Correspondence with Rig Observations**

The simulation results have been optimised against the available data for surface responses. Unfortunately, no continuous logs of well parameters were available. The incident has been reconstructed against the qualitative and quantitative data in the daily drilling reports. As well as the approximate timings of events, the following information is available for each surface response:

- **Differential flow:** Initial increase in flow, first flow check negative, second flow check positive.
- **Pit gain:** Approx. 12 bbl before second flow check.
- **Shut-in pressures:** SIDPP 250 psi, SICP 300 psi.
- **Mud weight:** Mud cut from 15.7 to 15.4 ppg.

The simulation results for differential flow rate during detection and initial shut-in are shown in Figure 7.6. together with the brine influx rate and the loss rate. Prior to
pumping mica, the losses are 42 gpm. For the purposes of the simulation, the mica is assumed to sharply reduce the losses once it has reached the loss zone. Now, 42 gpm of mud that was previously being lost to the formation is flowing up the annulus and into the pits, thus producing an increase in differential flow. In response, a flow check is performed that is reported as negative, however, the simulation predicts a flow of about 20 gpm for the duration of the flow check. The second flow check is reported as positive and the simulation predicts a flow of about 30 gpm for the duration of the flow check.

The simulation results for pit gain during detection and initial shut-in are shown in Figure 7.7, together with the brine influx rate and the loss rate. Prior to pumping mica, mud is lost from the pit at a rate of 1 bbl/min. Once the losses stop and a flow check is performed, the BHP is reduced sufficiently to allow a brine influx. The pit gain is about 12 bbl when the well is finally shut-in.

The simulation results for standpipe pressure and annulus pressure during detection and initial shut-in are shown in Figure 7.8. The simulated SIDPP is approximately 250 psi and simulated SICP is approximately 300 psi both of which match measured field data reasonably well.

There is a discrepancy in that the simulation fails to predict the mud cut form 15.7 to 15.4 ppg. Assuming the influx begins at the first flow check and that the subsequent pump rate is 150 gpm, the brine influx would not have reached surface by the time of shut-in and, therefore, it is necessary to propose some other explanation for the mud cut. One possibility could be that the influx contained a significant amount of gas that migrated up the wellbore faster than the brine thus accounting for the cut mud, however, the well was shut-in for 60 min. with no reported pressure increases caused by migration thus suggesting that the gas content was low. Another explanation could be that a further brine zone may have been flowing prior to this well control incident that caused the mud cut. A further brine zone would, however, need a formation pressure greater than the pressure exerted by the mud ECD and, therefore on shut-in, would display shut-in pressures greater than those reported. A further explanation could be that the cause of the mud cut has no relation to this particular well control incident.
Figure 7.6 Simulated differential flow and brine influx rate for detection and initial shut-in period. Loss rate is also shown.

Figure 7.7 Simulated pit gain and brine influx rate for detection and initial shut-in period. Loss rate is also shown.
7.3 WELL INCIDENT #3

The emphasis of this incident study is to:

- Attempt to reproduce the surface indications seen in the field during kick development.
- Identify any difficulties in reconciling field data and simulation results.
- Seek to identify aspects of the incident which might justify further analysis to improve the effectiveness of well control operations in Zechstein in the future.

When drilling the well which is the subject of this reconstruction, a series of well control events occurred from the top of the Plattendolomite (9400 ft MD) to the liner target depth (11697 ft MD) which resulted in a total lost time of about 4 days. One particular well control event has been selected for modelling from all those that occurred in this period. The selection was made on the following basis:

- Requirement to derive the maximum benefit in terms of useful insight into the cause of events and possibly help avoid or remedy these in the future.
- Requirement to determine whether the simulator can model adequately the key physical processes of the event.
At 9670 ft MD, a flowcheck was performed which indicated that the well was flowing. The well was shut-in: SIDPP read 60 psi and SICP initially read 360 psi rising to a stabilised value of 500 psi. The mud was weighted-up from 17.0 ppg to 17.1 ppg and circulated. The mud weight was incremented up to 17.5 ppg before further drilling took place, however, the well always seemed to flow when performing a flowcheck.

The remit of this preliminary analysis is to examine and evaluate the initial kick detection phase because such a study is likely to yield information on how the event could possibly have been avoided or its effects reduced. The key events leading up to this well control incident are summarised below:

**Table 7.3 Sequence of Well Control Actions**

<table>
<thead>
<tr>
<th>Start Time [hrs]</th>
<th>Duration [hrs]</th>
<th>Description</th>
</tr>
</thead>
</table>
| 09 30            | 06 30          | **Drilling Ahead**  
Av. ROP 40 ft/hr from 9404 ft to 9670 ft MD.  
17.0 ppg.  
453 gpm pump rate. |
| 16 00            | 04 00          | **Flowcheck**  
Well flowing |
|                  |                | **Shut-in well**  
SIDPP 60 psi.  
Initial SICP 360 psi rising to 500 psi. |
|                  |                | **Driller's method**  
Prepare well for kill operation using Driller's method.  
17.1 ppg.  
180 gpm pump rate. |
|                  |                | **Flowcheck**  
Well flowing at ~30 bph. |
|                  |                | **Shut-in well**  
SICP 80 psi. |
| 20 00            | 01 00          | **Weight-up mud**  
17.2 ppg and add mica. |
| 21 00            | 02 00          | **Circulate through choke**  
17.2 ppg.  
180 gpm pump rate.  
Choke partially closed.  
Losses ~15 bbl/circ. |
| 23 00            | 02 30          | **Flowcheck**  
Well flowing.  
**Shut-in well**  
SICP 140 psi.  
**Weight-up mud**  
17.4 ppg. |
<p>| 01 30            | 03 00          | <strong>Circulate through choke</strong> |</p>
<table>
<thead>
<tr>
<th>Time</th>
<th>Action</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>04 30</td>
<td>Flowcheck</td>
<td>Well flowing</td>
</tr>
<tr>
<td>05 30</td>
<td>Shut-in well</td>
<td>Stabilised SICP 80 psi</td>
</tr>
<tr>
<td>05 30</td>
<td>Weight-up mud</td>
<td>17.5 ppg</td>
</tr>
<tr>
<td>06 00</td>
<td>Circulate through choke</td>
<td>17.5 ppg</td>
</tr>
<tr>
<td>06 00</td>
<td>Flowcheck</td>
<td>Well flowing at ~1.5 bhp</td>
</tr>
<tr>
<td>07 30</td>
<td>Circulate through choke</td>
<td>17.5 ppg</td>
</tr>
<tr>
<td>07 30</td>
<td>Flowcheck</td>
<td>Well flowing at ~4.5 bhp</td>
</tr>
<tr>
<td>07 30</td>
<td>Drill ahead</td>
<td>Av ROP 20 ft/hr from 9670 ft to 9680 ft MD</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.5 ppg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>453 gpm pump rate</td>
</tr>
</tbody>
</table>

The main feature of this incident is that flowchecks would always appear positive despite increases in mud weight to restrain the kicking formation.

Drilling proceeded from the top of the Plattendolomite, down to about 9670 ft MD, where a flowcheck was performed and found positive. The well was shut-in with recorded pressure readings of SIDPP 60 psi and SICP initially 360 psi rising to a stabilised 500 psi. The SIDPP value was used to calculate the kill mud weight. The original mud weight was 17.0 ppg, the depth of the kick zone was 9670 ft TVD (vertical well), SIDPP 60 psi, which using the equation below gives a kill mud weight of 17.1 ppg.

\[
MW_{kill} = MW_{orig} + \frac{SIDPP}{0.052TVD}
\]

Once this mud was circulated, however, a subsequent flowcheck revealed the formation was still flowing. In response, the mud was incrementally weighted-up and circulated a number of times before further drilling could proceed.

The process of setting up a simulation is similar to the process of planning a kick control operation on a well. In real life, the assessment of the cause and plan to control the kick is tested by the control operations success. If the incident can be simulated,
alternative plans and explanations of unexpected features can be explored with the benefit of hindsight.

Assessment of Cause

When attempting to model a kick incident, the kick zone pressure can usually be estimated from the sum of the stabilised SIDPP, reported as 60 psi, and the pressure exerted by the static mud column.

\[ \text{Formation Pressure} = \text{Stabilised SIDPP} + 0.052 \text{ MW TVD} \]

Where pressures are measured in psi, the mud weight, MW, is in ppg, and total vertical depth, TVD, is in feet. During normal drilling, the pressure exerted by the mud column is due to its hydrostatic pressure (0.052 MW TVD) plus annular pressure losses due to the circulating mud (ECD pressure).

\[ \text{Mud column pressure} = \text{ECD Pressure} + 0.052 \text{ MW TVD} \]

A kick can be initiated, therefore, either when there is no circulation, for instance during a flowcheck, or when the formation static overpressure is large enough to overcome ECD effects.

With a reported stabilised SIDPP of 60 psi, an annular pressure loss of about 350 psi predicted by the simulator, and a previous 6.5 hrs period of drilling without any reported influx, two conclusions can be drawn:

- Formation is only being restrained by ECD effects during normal drilling.
- The first flowcheck, intended to detect the presence of an influx, actually causes an influx because the ECD effects are removed, see Figures 7.9 and 7.10.
Figure 7.9 Simulated pump flowrate and bottomhole pressure for periods of initial drilling, flowcheck, and shut-in.

Figure 7.10. Simulated brine influx rate and bottomhole pressure for periods of initial drilling, flowcheck, and shut-in.
A kill mud weight of 17.1 ppg is calculated from the SIDPP value of 60 psi and circulated using the Driller's method. On completion, a further flowcheck is performed, however, the well is still flowing. The well is shut-in again and the SICP is now 80 psi. Two explanations can be proposed for the remaining overpressure:

- The true formation static overpressure is greater than the original SIDPP reading of 60 psi because of a float valve (non-return valve) in the drillpipe.

- The Plattendolomite pore pressure is initially less than that exerted by the circulating mud column, however, it becomes charged somewhat by ECD effects (453 gpm pump rate) as drilling proceeds. When a flow check is performed, the bottomhole pressure is reduced and mud which had previously invaded the formation sweeps back into the well bringing brine with it. During the circulation of 17.1 ppg kill mud, the pressure in the Plattendolomite is relieved somewhat by the reducing pump rate (180 gpm) and by the presence of brine in the wellbore lowering the hydrostatic head. A residual pressure remains in the formation which is a function of pump rate and cannot be controlled by increases in mud weight.

It is known from the daily drilling reports that at the time of the kick a float valve was present in the drillpipe and, therefore, the first explanation applies.

The situation is, however, not so straightforward. In a conventional kick situation the SICP is a measure of the formation static overpressure (stabilised SIDPP) plus the hydrostatic pressure reduction in the annulus due to the presence of low density kick fluids:

\[
\text{Stabilised SICP} = \text{Stabilised SIDPP} + 0.052 h_{\text{kick}} (\text{MW} - \rho_{\text{kick}})
\]

Where \(h_{\text{kick}}\) is the effective height of the influx within the annulus and \(\rho_{\text{kick}}\) is the effective density of the kick fluids. SICP is usually larger than SIDPP because the mud density is usually greater than the influx density. With the 17.1 ppg kill mud in the well, the recorded SICP was 80 psi, however, it is known that the well still flowed with a 17.5 ppg kill mud in the well which is the equivalent at bottomhole to a 17.1 ppg mud plus a stabilised SIDPP of at least 200 psi if no float valve were present. There are two possible explanations:

- The density of the brine influx is greater than the mud weight.

- The formation pressure is being charged by the circulating mud, and is thus is a function of the pump rate, mud loss rate, and mud weight, as described earlier.

Brine influxes with densities greater than the insitu mud have been suspected in other wells where SICP was reported greater than SIDPP. While it is certainly possible that a dense brine could be the explanation here, other evidence suggests that the formation pressure charging is the cause of the wells behaviour.

It is likely that during normal drilling the Plattendolomite is charged with the circulating mud ECD pressure (~350 psi see Figure 7.11.), however during the
flowcheck, the SIDPP is limited to 60 psi by the float valve. Stabilised SICP is reported as around 500 psi which probably results from the 350 psi charged formation pressure and 150 psi due to the reduction in hydrostatic head from the presence of brine in the annulus. A kill mud weight of 17.1 ppg is then calculated and the Driller's method employed holding 60 psi (from the measured SIDPP) on bottomhole pressure. The pressure of the charged formation is relieved down to 60 psi above the pressure of the static mud column. When a flowcheck is performed, the well is still flowing because the 60 psi charge has been held on the formation. On shut-in, the SICP is 80 psi which probably results from the 60 psi charged formation and 20 psi to the reduction in hydrostatic head from the presence of brine in the annulus.

![Figure 7.11 Simulated Overbalance and Annular Pressure Loss for Periods of Initial Drilling, Flowcheck, and Shut-in.](image)

Other supporting evidence is that the 17.2 ppg mud was circulated all the way round on the choke which resulted in 15 bbl loss and a SICP of 140 psi suggesting that the increased pressure from the choke increased the pressure to which the formation was charged. Whereas, later when the 17.4 ppg mud was circulated with the choke fully open, no losses occurred and the SICP was 80 psi.

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 original mud column (~8550 psi) plus the effect of ECD charging (~350 psi).
correspondence with rig observations

As mentioned previously, the initiation of the well incident has been modelled with emphasis placed on matching numerical data points where available to determine the details of the kick mechanism and thus provide some explanation of the occurrence.

The kick zone properties to give the best match are:

- 350 psi static kick zone overpressure.
- Kh ~300 mD m kick zone.
- 1 scf/bbl gas-brine kick with 400 g/l salt concentration brine.

This match was achieved using the SideKick v3.0 kick simulator which has a mixed gas-brine modelling capability.

The simulation results have been optimised against the available data for surface responses. Unfortunately, no continuous logs of well parameters were available. The incident has been reconstructed against the qualitative and quantitative data in the daily drilling reports. As well as the approximate timings of events, the following information is available for each surface response:

- **Differential flow**: Increase in flow at first flowcheck.

- **Shut-in pressures**: Stabilised SICP ~500 psi at first shut-in (SIDPP 60 psi is not modelled because SideKick v3.0 has no facility to model the pressure loss through a float valve).

The simulation results for differential flow rate and blowout preventer (BOP) pressure during initial drilling, the first flowcheck and the first shut-in is shown in Figure 7.12. During normal drilling, there is a nominal differential flowrate believed to be caused by the difference in pressure and temperature at the top of the annulus and standpipe, thus affecting the volumetric flowrates. During the first flowcheck, the influx begins and consequently the differential flow increases thus allowing detection. The well is shut-in and the BOP pressure (SICP) rises to around 500 psi.

The simulation has been terminated after the initial shut-in because it has been assumed that the Plattendolomite is charging and relieving depending on the circulating pressure of the mud. SideKick v3.0 cannot, however, model the charging nor depletion of formations and, therefore, the behaviour predicted by the simulator for subsequent events will not be expected to match the observed behaviour.
**Figure 7.12 Simulated differential flow and BOP pressure for the periods of initial drilling, flow check, and shut-in.**

### 7.4 Well Incident #4

The objective of this study is to examine and evaluate the initial kick detection phase of this well incident. The emphasis of the study will be to:

- Attempt to reproduce the surface indications seen in the field during kick development.
- Identify any difficulties in reconciling field data and simulation results.
- Seek to identify aspects of the incident which might justify further analysis to improve the effectiveness of well control operations in Zechstein in the future.

When drilling the well which is the subject of this analysis, the Plattendolomite was encountered at about 7500 ft MD. At 7533 ft MD, a loss of 30 bbl occurred. On circulating bottoms up, there was an increase in flow that resulted in a pit gain of about 40 bbl. The well was shut-in with gas at surface. A further eleven days were to follow of losses, gains and attempted well control actions before reaching the liner target depth of 9105 ft MD where the liner was run and cemented.

The remit of this preliminary analysis is to examine and evaluate the initial kick detection phase because such a study is likely to yield information on how the event could possibly have been avoided or its effects reduced. The key events leading up to this well control incident are summarised below:
TABLE 7.4 SEQUENCE OF WELL CONTROL ACTIONS

<table>
<thead>
<tr>
<th>Start Time</th>
<th>Duration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0600</td>
<td>01 00</td>
<td>Top of Plattendolomite 7500 ft MD 7326 ft TVDSS</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Drilling ahead</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Av. ROP 8 ft/hr from 7525 ft to 7533 ft MD.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.0 ppg mud.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>445 gpm pump rate.</td>
</tr>
<tr>
<td>0700</td>
<td>01 30</td>
<td><strong>Loss encountered</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 bbl mud loss @ 7533 ft MD.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pump rate reduced to 212 gpm causes 16 bph loss.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pump rate increased to 297 gpm causes 18 bph loss.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Circulated bottoms-up at 297 gpm.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Flow increase close to bottoms-up.</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Flow check</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stop pump.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Well flowing.</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Shut-in</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shut-in with gas at surface.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Initial SIDPP 20 psi rising to 80 psi.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Initial SICP 143 psi reducing to 137 psi.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Final pit gain about 40 bbl (including initial 30 bbl loss).</td>
</tr>
<tr>
<td>08 30</td>
<td>03 30</td>
<td><strong>Driller’s method</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Prepare well for kill operation using Driller’s method.</td>
</tr>
</tbody>
</table>

The main features of this incident are that a loss-gain situation was encountered that involved a significant gas influx.

During the course of this well, the top of the Plattendolomite was encountered at 7500 ft MD and a 30 bbl loss occurred at 7533 ft MD. Drilling ceased and pump rate was decreased from 445 gpm to 212 gpm which resulted in a loss rate of about 16 bph. The pump rate was increased to 297 gpm, which resulted in a loss rate of about 18 bph, and the well circulated bottoms-up. Close to bottoms-up the flow increased due to gas expansion. The well was shut-in with gas at surface. Initial SIDPP read 20 psi rising to 80 psi, initial SICP read 143 psi reducing to 137 psi, and the final pit gain was about 40 bbl including the initial 30 bbl loss.

The process of setting up a simulation is similar to the process of planning a kick control operation on a well. In real life, the assessment of the cause and plan to control the kick is tested by the control operations success. If the incident can be simulated, alternative plans and explanations of unexpected features can be explored with the benefit of hindsight.
Assessment of Cause

When attempting to model a kick incident, the kick zone pressure can usually be estimated from the sum of the stabilised SIDPP, reported as 80 psi, and the pressure exerted by the static mud column.

\[
\text{Formation Pressure} = \text{Stabilised SIDPP} + 0.052 \text{ MW TVD}
\]

Where pressures are measured in psi, the mud weight, MW, is in ppg, and total vertical depth, TVD, is in feet. During normal drilling, the pressure exerted by the mud column is due to its hydrostatic pressure (0.052 MW TVD) plus annular pressure losses due to the circulating mud (ECD pressure).

\[
\text{Mud column pressure} = \text{ECD Pressure} + 0.052 \text{ MW TVD}
\]

A kick can be initiated, therefore, either when there is no circulation, for instance during a flowcheck, or when the formation static overpressure is large enough to overcome ECD effects.

With a reported stabilised SIDPP of 80 psi and no cease in circulation prior to the start of the kick, it is difficult to imagine how the kick started as the annular pressure loss never falls below the formation static overpressure.

**Table 7.5. Comparison of ECD Effects and Formation**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.) 445</td>
<td>0</td>
<td>160</td>
<td>80</td>
</tr>
<tr>
<td>2.) 445</td>
<td>30 bbl over 5 min.</td>
<td>110</td>
<td>80</td>
</tr>
<tr>
<td>3.) 212</td>
<td>16</td>
<td>130</td>
<td>80</td>
</tr>
<tr>
<td>4.) 297</td>
<td>18</td>
<td>140</td>
<td>80</td>
</tr>
</tbody>
</table>

Two explanations can be proposed for the occurrence of this kick:

- The true formation static overpressure was not reflected by the stabilised SIDPP reading because of a float valve or other restriction in the drillpipe.

- The Plattendolomite pore pressure is initially less than that exerted by the circulating mud column, however, it becomes charged by ECD effects as drilling proceeds. When the loss occurs and the pump rate is reduced, mud which had invaded the formation sweeps back into the well bringing brine and gas with it. During the circulation of bottoms-up, the pressure in the Plattendolomite is relieved by reduced pump rate and by the presence of gas and brine in the wellbore lowering the hydrostatic head.
It is reported that there is a sensitive relationship between pump rate and downhole loss rate which indicates that the permeability and porosity are sufficient for the formation to accept, and discharge, fluids. It would, therefore, appear that the second explanation would seem to be the most probable.

The Plattendolomite becomes charged by ECD effects as drilling proceeds to a value equal to an annular pressure loss of 160 psi which corresponds to a pump rate of 445 gpm. At 7533 ft MD, a fracture is assumed to have been encountered to which 30 bbl are lost over 5 min. (arbitrary time for loss). The flow up the annulus and, therefore, the annular pressure loss is reduced sufficiently to allow an influx. The influx continues while the pump rate is reduced temporarily to 212 gpm (associated loss rate 16 bph) and then increased to 297 gpm (associated loss rate 18 bph) because the ECD pressure is less than that which originally charged the formation, see Figure 7.13 and Table 7.5.

It seems to go against intuition that losses and gains can occur in what is thought to be a reasonably homogeneous formation, however, this is what has been reported in this well incident and also in others drilled through the Zechstein. An explanation has been proposed with reference to Figure 7.14. The mud filters into the formation and, over time, charges it to the pressure exerted by the circulating mud column. The rate of charging of the formation pressure will be a function of the permeability and porosity. As drilling proceeds, new openhole will be exposed to the pressure of the circulating mud column, therefore, deeper openhole sections will have been exposed to the circulating mud column pressure for less time than those higher up the wellbore. There is likely to be a gradient of charged pressure along the formation adjacent to the openhole with high pressure charge at the top section and low pressure charge at the bottom section. If a sudden loss or reduction in pump rate occurs then the pressure exerted downhole by the circulating mud column will reduce possibly allowing the charged formation at the top of the openhole to flow back into the wellbore while the uncharged formation at the bottom continues to loose mud.

In this well incident it would appear that, as the mud filtered into the surrounding formation, it mixed with the existing pore fluids of gas and brine as charging took place. When the pressure in the wellbore was reduced, an influx of mud, brine and gas seems to have occurred.
**Figure 7.13** Simulated overbalance and annular pressure loss for periods of initial drilling, loss, and circulating bottoms-up.

**Figure 7.14.** Schematic illustrating mechanism for simultaneous loss and gains during formation pressure charging.
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 original mud column (~5450 psi) plus the effect of ECD charging (~160 psi, see Table 7.5).

The height of the kicking formation has been estimated from the penetration of the formation most likely to become charged. This is the Plattendolomite and extends from 7500 ft MD to 7533 ft MD i.e. 33 ft of exposure. The permeability was then chosen to give a pit gain of about 40 bbl after a circulating bottoms-up for around 90 min. at 297 gpm.

**Correspondence with Rig Observations**

As mentioned previously, the initiation of the well incident has been modelled with emphasis placed on matching numerical data points where available to determine the details of the kick mechanism and thus provide some explanation of the occurrence.

The kick zone properties to give the best match are:

- 160 psi static kick zone overpressure.
- 100 mD kick zone permeability and 33 ft zone penetration (Kh ~ 1000 mD m).
- 1000 scf/bbl gas-brine kick with 400 g/l salt concentration brine.

This match was achieved using the SideKick v3.0 kick simulator which has a mixed gas-brine modelling capability and a loss zone modelling capability.

The simulation results have been optimised against the available data for surface responses. Unfortunately, no continuous logs of well parameters were available. The incident has been reconstructed against the qualitative and quantitative data in the daily drilling reports. As well as the approximate timings of events, the following information is available for each surface response:

- **Differential flow:** Initial mud losses of 30 bbl, 16 bph (212 gpm), 18 bph (297 gpm), and the increase in flow as bottoms-up nears surface.
- **Pit gain:** Approx. 40 bbl as bottoms-up nears surface.
- **Shut-in pressures:** SIDPP 20 psi rising to 80 psi, SICP 143 psi reducing to 137 psi.
- **Gas show:** Gas seen at surface on shut-in.

The simulation results for differential flow rate during detection and bottoms-up circulation are shown in Figure 7.15, together with the brine influx rate. The loss starts 8 min. into the simulation and there is a corresponding fall in differential flow over the period for which the 30 bbl loss is assumed to occur (5 min.). The subsequent
reduction in ECD pressure allows the influx to start. The volumetric brine influx rate is shown here as a comparison to the differential flow. At downhole pressures, the volumetric gas influx rate would be negligible compared to that of the brine. As the bottoms-up circulation proceeds, the brine influx rate is slightly greater than the differential flow rate because of the 18 bph loss to the formation. As the influx nears the surface, however, the gas begins to expand and the differential flow rate becomes greater than the brine influx rate.

The simulation results for pit gain during detection and initial shut-in are shown in Figure 7.16. There is a reduction in pit level of about 30 bbl which corresponds with the loss downhole. The pit gain reduces further slightly because the initial influx rate is less than the 18 bph loss rate at 297 gpm pump rate. The pit gain, however, increases as the influx rate increase and gas expansion takes place.

The simulation results for standpipe pressure and annulus pressure during detection and initial shut-in are shown in Figure 7.17. The simulated stabilised SIDPP appears to be approximately 150 psi and simulated stabilised SICP appears to be approximately 700 psi then, just before 120 min., gas migration effects begin to dominate sending the pressures even higher. These are a very poor match to the reported values of SIDPP 80 psi and SICP 137 psi. The explanation, as stated earlier, is believed to be that the charged formations are relieved somewhat during the circulation of bottoms-up at a reduced pump rate and by the reduction in mud hydrostatic head from the influx of brine and gas. Sidekick v3.0 cannot, however, model the charging nor depletion of formations and, therefore, the behaviour predicted by the simulator for the shut-in period is not expected to match the observed behaviour.

The simulation results for the gas and brine distributions along the wellbore immediately prior to shut-in are shown in Figure 7.18. The gas void fraction is predicted to be 5% just a couple of hundred feet below the BOP's.
**Figure 7.15** Simulated differential flow and brine influx rate for periods of initial drilling, loss, and circulating bottoms-up.

**Figure 7.16** Simulated pit gain for periods of initial drilling, loss, and circulating bottoms-up.
**Figure 7.17** Simulated standpipe pressure and annulus pressure for periods of initial drilling, loss, and circulating bottoms-up.

**Figure 17.18.** Simulated gas and brine distributions immediately prior to shut-in.
7.5 \textbf{WELL INCIDENT #5}

The objective of studying this well incident is to explain the rise in pressure in the well when gas is entering at a low rate and contrast with typical gas rates [16]. The main feature of interest is that there was no pressure build-up on shut-in, and therefore no stabilised SIDPP was observed. The correct selection of kill mud could, therefore, not be made. This resulted in a period of 20 hours circulating successively higher weighted muds until the well was finally under control and gas shows ceased.

The key events leading up to this incident are summarised below:

\begin{table}[h]
\centering
\begin{tabular}{|c|c|l|}
\hline
Start Time & Duration & Description \\
[0.5ex]
\hline
05 15 & 01 45 & Drill ahead from 6305 ft to 6363 ft. Av. ROP 44 ft/hr. Sudden increase in flowrate and gas show (15.6%). Mud weight 520 ppg. \\
\hline
07 00 & 00 15 & Shut-in No pressure build-up observed. \\
\hline
07 15 & 03 00 & Circulate over choke with 420 gpm. Sample at 6330 ft showed 80\% dolomite. Gas show constant at 13\% with 548 ppg mud. \\
\hline
10 15 & 00 30 & Observe well for 10 mins. No pressure build-up. Inflow test well over choke into trip tank for 20 mins. Negative. Open up well. \\
\hline
10 45 & 00 30 & Circulate 50\% of annulus contents. Observe 35\% gas on drillfloor and 21\% after poor boy degasser. \\
\hline
11 15 & 02 15 & Shut-in and circulate over choke Max. gas B/U 13\%, thereafter remaining constant at 8\%. \\
\hline
13 30 & 01 00 & Observe well whilst mixing 630 ppg and 450 ppgf mud to 590 ppgf kill mud. No inflow. \\
\hline
14 30 & 01 00 & Circulate well Displace well to 590 ppgf mud. Max. gas during displacing 9\%. Final gas show 12\%. \\
\hline
15 30 & 01 00 & Circulate through annulus Max. gas 31.2\% in mud at header box decreasing to 16\%. Commence increase in mud weight to 650 ppgf. \\
\hline
16 30 & 00 30 & Shut-in Flow check over choke. Static Open well. \\
\hline
17 00 & 05 30 & Circulate well to 640 ppgf mud. Max. gas 35\%. Weigh up mud to 700 ppgf. Circulate to 700 ppgf mud. Max. gas 37\%. Increase mud weight to 750 ppgf. Gas peak at 39\%, decreasing to 0.7\%. No free gas at rotary table. \\
\hline
22 30 & 00 30 & Flow check Static \\
\hline
23 00 & 01 00 & Circulate At 50\% B/U gas at 6\% and rising. Close in well and circulate over choke. Gas peak at 20.5\%. \\
\hline
00 00 & 00 15 & Circulate two times B/U. Max. gas 0.7\%. \\
\hline
00 15 & 02 15 & Circulate Increasing mud weight from 750 ppgf to 770 ppgf. Gas free. \\
\hline
02 30 & 00 30 & Flow check Negative. \\
\hline
\end{tabular}
\end{table}

This well control incident has been explained in terms of an extremely low permeability overpressured formation.
**Figure 7.19 Schematic showing SIDPP versus time for a gas influx from a typical and extremely low permeability formation.**

This phenomenon of slow pressure build-up and no stabilisation of SIDPP can be explained by reference to Figure 17.19. In a shut-in well, SIDPP can rise due to two mechanisms:

- Gas influx into the wellbore from the formation
- Gas migration up the wellbore

For formations of typical permeability, as shown in the left-hand column of Figure 7.19, the rate of increase of pressure due to gas entering the wellbore is much greater than the rate of increase of pressure due to gas migration. An apparent stabilisation of SIDPP is observed, therefore, when gas stops entering the wellbore. However, the rate of increase of SIDPP due to gas entering the wellbore is related to the effective Kh...
value. As the effective Kh decreases so does the gas rate into the wellbore. In extremely low permeability formations, as shown in the right-hand column of Figure 7.19, the rate of increase of pressure due to gas entering the wellbore becomes comparable, or even dominated by gas migration, therefore no apparent stabilisation of SIDPP occurs and no kill mud weight value can be obtained.

The predicted pressure build-up for the first shut-in period of 15 mins. is shown in Figure 7.20 for a permeability of 0.05 mD. A shut-in period of about 4 hours produces a stabilised SIDPP value that can be used to estimate the kill mud weight.

![Graph showing pressure build-up](image)

**Figure 7.20 Simulation results of first shut-in period showing expected shut-in time to achieve stabilisation of SIDPP for a permeability of 0.05 mD.**

For an effective permeability of 0.005 mD, there is no clear stabilisation in SIDPP, Figure 7.21. Over a shut-in period of about a day, SIDPP rises but does not stabilise. No stabilised value of SIDPP, and therefore no kill mud weight value can be determined.

This well incident was simulated using the ŠideKick v2.0 kick simulator by modelling the kicking formation with a very low effective Kh value of ~0.001 mD m (0.0005 mD and 5 ft).

According to the simulations, for extremely low effective permeabilities, a stabilised SIDPP is never achieved. Instead SIDPP slowly increases until the formation fracture pressure is reached. An explanation for this behaviour is that for extremely low permeability formations the rate of increase of SIDPP due to gas entering the wellbore is comparable or even dominated by the rate of increase of SIDPP due to gas migration up the wellbore, therefore no apparent stabilisation is achieved.
7.6 DISCUSSION

The main feature of well incident #1 is that a high pressure Zechstein dolomite formation was encountered which resulted in two predominately brine influxes being taken in close succession.

Two scenarios can be conceived to explain the occurrence: one related to known Zechstein behaviour and the other related to pressure gauge error. The latter was made possible because of the existence of two independent shut-in pressure records with a discrepancy between them. As this study is part of an ongoing drilling safety issues review into the Zechstein Supergroup, it could of been attractive to attempt an explanation in terms of known Zechstein behaviour and this may well of been the case if only one of the pressure records had been made available. An approach based on the inaccuracy of one of the pressure records, and the subsequent decisions made on these inaccurate readings, seems to be the likely explanation and produces simulation results which match most of the well incident events.

Also, to emerge is the possibility of a ‘shut-in pressure profile’ associated with brine or gas brine kicks that is different from that associated with a predominantly gas kick which could be used as a means of kick fluid identification and, thus, well control procedure selection, before circulation of bottoms-up.

The main features of well incident #2 are that a loss-gain situation was encountered and that the well was killed using the original mud weight.

An explanation has been proposed to this well control incident. The pumped mica is assumed to stem the losses, thus, the flow (1 bbl/min.) previously lost to the formation
was subsequently directed up the annulus accounting for the initial increase in differential flow. It is further proposed that the well was acting such that losses were taken when circulating at high flowrates but would flow when static or circulating at low flowrates. The following flow check and circulation of connection gas lowered the BHP sufficiently to initiate an influx.

The simulation results and incident data do not provide much insight into the origin of the overpressured zone. The formation may have naturally had a static overpressure of 250 psi. Alternatively, the formation may have been charged (or supercharged) by the difference in static and flowing BHP. It may seem more than a coincidence that the formation static overpressure (250 psi) is so close to the BHP difference (300 psi) between static and flowing at 500 gpm with 42 gpm downhole losses.

Four issues emerge from a preliminary analysis of this incident:

- Possible misinterpretation of a well response from a successful pumping of loss circulation materials (LCM).
- Flow checks (procedures applied to detect downhole influxes) actually being the cause of influxes in situations where the well is controlled by ECD effects.
- Wells acting such that losses are taken when circulating at high flowrates but that kick when static or circulating at low flowrates.
- Formations being charged by ECD pressure which later kick when static or circulating at low flowrates.

The main feature of well incident #3 is that flow checks would always appear positive despite increases in mud weight to restrain the kicking formation.

An explanation has been proposed to this well control incident. The Plattendolomite has a pore pressure lower than that exerted by the circulating mud column. As drilling proceeds, the mud filters into the formation eventually charging-up the brine already present in the pore space to the pressure of the static mud column plus the pressure due to ECD effects. When a flow check is performed, the formation overpressure causes brine and previously lost mud to flow into the wellbore.

Two issues emerge, in addition to those above, from a preliminary analysis of this incident:

- Float valves can give misleading SIDPP values. If these values are believed to be accurate and acted upon then the well control situation may get worse both in terms of wrong actions being taken and possible confusion to why the well is not behaving in the expected way.
- If it is not understood at the time of the incident that pressure charging of the formations is taking place then increasing the mud weight, as for a more conventional well control incident, is likely only to make the problem worse. This
is because the ECD pressure is a direct function of the mud weight as shown in the equation below:

\[
\text{ECD Pressure} = f(\text{1/2 MW} \cdot \text{v}^2)
\]

The main features of Well Incident #4 are that a loss-gain situation was encountered that involved a significant gas influx.

An explanation has been proposed to this well control incident. The Plattendolomite has a pore pressure lower than that exerted by the circulating mud column. As drilling proceeds, the mud filters into the formation eventually charging-up the existing pore fluids of brine and gas to the pressure of the static mud column plus the pressure due to ECD effects. When circulation is reduced, either due to downhole losses or pump rate reduction, then the formation kicks with the mud, brine, and gas flowing into the wellbore.

A further two issues emerge, in addition to those above, from a preliminary analysis of this incident:

- The well seems to undergo losses and gains simultaneously, and not in succession.
- The mud which filters into the formation can mix with existing pore fluids of gas and brine. If the bottomhole pressure is reduced then the mud can sweep gas and brine into the wellbore. A gas kick is far more hazardous than a brine or return mud kick.

The main feature of Well Incident #5 is that on shut-in no stabilised value of SIDPP was observed.

An explanation was proposed in terms of a kicking high pressure formation with an extremely low permeability formation. According to the simulations, for extremely low effective permeabilities, a stabilised SIDPP is never achieved. Instead SIDPP slowly increases until the formation fracture pressure is reached. An explanation for this behaviour is that for extremely low permeability formations the rate of increase of SIDPP due to gas entering the wellbore is comparable or even dominated by the rate of increase of SIDPP due to gas migration up the wellbore, therefore no apparent stabilisation is achieved.

The overall objective of conducting analyses of documented incident data was to gain insight into Zechstein well control problems, and the resulting safety issues, and to uncover any information that may be useful in avoiding or remediating similar future events. The initial phase of the incidents (kick initiation, kick detection, and shut-in) were analysed using either SideKick v2.0 or v3.0 kick simulators. The latter of these is the more sophisticated allowing mixed gas-brine kicks and losses to the formation to be modelled, however, no modelling facility is directly available for the charging mechanism. If charging was suspected then this would have been inferred from incident data and from simulation results. From the five incidents considered here, there appears to be three types of well control problem:
- **High pressure formation brine kicks** Zones can be drilled which are naturally highly overpressured and contain mostly brine, with some gas and oil. These kicks are capable of being killed in a conventional manner, however on shut-in, the build-up of wellbore pressure may risk the integrity of the openhole.

- **Charged formation kicks** From the incidents considered here, kicks from zones charged by ECD can be mistaken for kicks from naturally overpressured zones and attempts may be made to kill them using conventional well control procedures. Such an approach only wastes time and increases the charged zone pressure. Once, it is realised that pressure charging is occurring, the zone can be depleted and normal drilling continued. In the next section, a preliminary method to determine whether a zone is naturally overpressured or ECD charged that was developed from these incident studies is presented.

- **Low ‘Kh’ formation kicks** A further category of kick appears to be those from high pressure low permeability zones. On shut-in, there is often little or no build-up in SiDPP, and therefore, no kill mud weight can be determined. The approach taken with such kicks is to circulate successively heavier muds until the gas shows cease. This, however, can take many days to achieve. In the next section, possible methods to make an earlier determination of BHP are discussed.
8. DISCUSSION AND DEVELOPMENT OF PROVISIONAL DECISION TOOLS

This report forms a review of the operational problems that occur when drilling Zechstein wells, and the procedures that can be applied to alleviate them. The emphasis has been placed on health and safety implications.

Operational problems present some intrinsic hazard or safety risk to rig personnel. Additionally, the procedures applied to alleviate these problems also present a safety risk, as they usually are non-routine and unfamiliar, thus increasing the likelihood of errors of judgement or mis-application. It is clear, therefore, that both the problems encountered and the alleviation procedures applied in Zechstein formations are inextricably linked to health and safety.

Zechstein has been drilled in the North Sea ever since the earliest years of exploration in this region. It is reasonably common for operators to drill through these formations, particularly to reach the gas fields of the Southern North Sea. A large number of operators on the UKCS have experience in drilling Zechstein, and are therefore, familiar with the problems that can occur.

There is an understanding within industry that wells drilled through Zechstein may present problems during drilling, or even after many years of production, and that these problems can prove very costly. Predicting when and with which wells these problems will occur, however, is extremely difficult. Industry has a familiarity with the different types of problem that can occur within these wells, and these are widely accepted to fall into the following categories:

- Kicks and Wellbore Gains
- Wellbore Losses
- Stuck Pipe
- Casing Collapse
- \( \text{H}_2\text{S} \)

In response, a number of procedures to attempt to alleviate these problems have been developed, and these are:

- Well Control Procedure
- Mud Type Selection
- Casing Setting Selection
- Casing Type Selection
- Bi-centre and Eccentric Drill Bits
- Fast Drilling
- LCM Operations
- Seismic Survey
- Cement Selection
- Variation of Annular Pressure
- Freshwater Spotting
- Simultaneous Underreaming and Drilling
These procedures fall into two categories: those applied at the well planning stage in anticipation of the problems that may occur, and those applied on the rig floor in reaction to a problem that has already arisen. Procedures exist to tackle all the operational problems. Each procedure has had some success in alleviating its corresponding problem. Industry is, on the whole, familiar with the range of alleviation procedures that have been developed.

An operational problem, as recognised through well responses observed on the rig floor, may be caused by a number of different mechanisms. The range of behavioural mechanisms that are currently believed responsible are:

- Salt Washout
- Salt Movement
- Brine and Gas Kicks
- Formation Fracture
- Formation Filtration
- Brine Flows from Zero Porosity Salt

On the rig floor, it may not be immediately clear which mechanism is responsible for a particular problem. The success of an alleviation procedure to a particular problem can be sensitive to the mechanism causing the well response.

On the rig floor, a number of well responses may be observed in close succession. A wellbore loss may occur which is rapidly followed by a wellbore gain or vice versa. These are loss-gain situations and are particularly troublesome as there are no accepted procedures for adequately alleviating them. Loss-gain situations are the result of a number of downhole mechanisms interacting to give confusing well responses.

If a kick is taken, the well will respond by showing a gain at the mud pits. The accepted procedure is to kill the well with a mud weight sufficient to restrain the pore pressure. However, there is typically little margin between the pore and fluid loss pressure (either by fracture, filtration, or outward salt movement) in Zechstein. Therefore, it is entirely possible that at some point along the open hole section the fluid loss pressure is exceeded leading to loss-gain situation. Moreover, fluid loss will lower the hydrostatic head of mud, thus inducing further kicks, possibly before any loss prevention procedures can be applied. It can be seen that a procedure for alleviating kicks, which is perfectly satisfactory when applied in isolation of other downhole mechanisms, can cause an escalation of the problem.

Procedures have been developed and are reasonably successful in alleviating the problems that occur in isolation within Zechstein. However, these alleviation procedures may have consequences for the other mechanisms that can occur downhole leading to complex well control and behavioural situations.

This characteristic of complex well behaviour is typical of Zechstein formations, and is the source of hazard. Decisions may be made by a drill crew under considerable
stress and time pressure, and on limited well information. An alleviation procedure may be decided upon that could take many hours, or even days, to complete resulting crew fatigue. If the well does not behave in the expected way then this may increase the levels of stress experienced by the rig crew, and possibly leading to misinterpretation of well responses and inappropriate actions, which present additional hazards. Such problems are considered to have a certain inevitability, despite the safety implications and huge costs, caused by the particular attributes of these formations.

Five Zechstein well control incidents have been analysed as part of this review. The objective was to gain insight into Zechstein well control problems, and the resulting safety issues, and to uncover any information that may be useful in avoiding or remediying similar future events. Three types of well control problem, that differ from what can be considered typical or text book well control, have emerged:

- High pressure formation brine kicks
- Charged formation kicks
- Low ‘Kh’ formation kicks

The first of these concern kicks from formations which are naturally highly overpressured and contain mostly brine, with some gas and oil. These kicks are capable of being killed in a conventional manner, however on shut-in, the build-up of wellbore pressure may risk the integrity of the openhole.

Kicks from formations charged by ECD can be mistaken for kicks from naturally overpressured zones and attempts may be made to kill them using conventional well control procedures. Such an approach only wastes time and increases the charged zone pressure. Once, it is realised that pressure charging is occurring, the zone can be depleted and normal drilling continued. Consideration of all the well incidents where charging was suspected has lead to the development of a preliminary decision tree analysis that might help in circumstances such as these. This is presented in Figure 8.5.

Once an influx occurs, the well is shut-in and the stabilised SIDPP is measured. A useful suggestion might be to have a pre-calculated chart at the drill site showing the annular pressure loss for the programmed mud weights and pump rates for all depths of the planned well. The annular pressure loss would represent the maximum static overpressure (SIDPP) to which the formation could be charged.

Thus if a kick occurred, and the measured stabilised SIDPP was greater than the calculated annular pressure loss then the overpressure could not have been caused by charging and, therefore, it may be possible to kill the well in the conventional manner by pumping a kill mud weight based on the SIDPP measurement.

If, however, the stabilised SIDPP was smaller than the calculated annular pressure loss then the kick could not have been initiated during normal drilling because the annular
pressure losses would have kept the well dynamically killed. The kick, therefore, is likely to have been caused by one of the following:

- swabbing.
- heavy formation losses reducing ECD pressure.
- lower pump rate reducing ECD pressure.
- flowcheck.

The overpressure of the kicking formation could have its origin in one of the following:

- natural static overpressure determined by sediment deposition history and subsequent geological processes.
- ECD pressure charging.
- combination of the above.

An attempt could be made to bleed off the charged pressure. On bleeding, the original SIDPP value would fall until it became constant at the value of the natural formation static overpressure. This final bled SIDPP value could then be used to calculate the kill mud weight. The influx could then be circulated out using the kill mud in the conventional manner.

The procedure outlined here is a possible suggestion based on preliminary analyses of incidents where charging was suspected. Further work plus input from drilling engineers is likely to be required to assess the viability of such a procedure and bring it to the stage where it, or a similar procedure, can be applied beneficially.

A further category of kick appears to be those from high pressure low permeability zones. On shut-in, there is often little or no build-up in SIDPP, and therefore, no kill mud weight can be determined. The approach taken with such kicks is to circulate successively heavier muds until the gas shows cease. This, however, can take many days to achieve.

Ideally, a method to make an early determination of the BHP is required so that the well can be killed quickly. There appears to be two possible approaches to this problem.

Firstly, the study conducted here only considered one low ‘Kh’ incident. By studying other similar incidents, as for ECD charging incidents, some parameter, other than SIDPP, may possibly be identified that allows an early determination of BHP, and therefore of the kill mud weight.
Secondly, it may be possible to estimate the BHP through circumstantial evidence and the use of a simulator. The amount of gas exiting the wellbore is measured as a percentage which may be convertible to a gas flow rate with an understanding of the physics of the gas measuring instrumentation. An order of magnitude estimate of the permeability may be possible from knowledge of the formation from the mud log. The thickness of the kick zone could be estimated from knowledge of when the influx started and a back-calculation assuming gas migration rates. This information could be used together with a simulator to estimate the BHP, and therefore the kill mud weight.

Decision tree analysis is a useful tool that can be applied to these types of problem to rationalise actions. Such analyses can be applied at the well planning stage, to help avoid or anticipate a particular operational problem, or at the drill site to help remedy a problem that has already arisen. A particular operational problem may be caused by one or more of a number of downhole mechanisms, and it is the mechanism, rather than the problem, which determines the most appropriate alleviation procedure. Some further well response should, therefore, be sought that distinguish the responsible mechanism. For example, stuck pipe can be caused by salt ingress or filtration losses leading to differential sticking. Full circulation is, however, usually possible for differential sticking, whereas salt ingress could cause restricted circulation. Another example, shut-in pressure can be caused by a naturally overpressured zone or by an ECD charged zone. A method is proposed which can be applied at the drill site to distinguish between these mechanisms. Preliminary decision tree analyses have been conducted and provisional diagrams have been produced for wellbore gains (Figures 8.1, 8.2, and 8.7), wellbore losses (Figures 8.3 and 8.4), suspected charging (Figure 8.5), loss-gain situations (Figure 8.6), stuck pipe (Figure 8.8), and casing collapse during drilling (Figure 8.9).
Avoid Dolomite rafts detected with seismic

Choose mud weight greater than expected pore pressure

Choose mud weight sufficient to restrain salt flow

H₂S likely

No

Yes

Use sour gas resistant materials

Wellbore gains?

No

END

Yes

WELLBORE GAINS

FIGURE 8.1 WELLBORE GAINS AVOIDANCE
**Figure 8.2 Wellbore Gains Remedy**

1. **Gas show?**
   - Yes: **H₂S present?**
     - Yes: Gas kick with H₂S
       - Use breathing apparatus with cascade air supply
       - Shut-in pressure?
         - Yes: Determine kill mud and circulate to kill well
         - No: Circulate successively weighted muds until gas shows cease
       - END
     - No: Gas kick
       - END
   - No: Mud weight reduction?
     - Yes: Brine kick
       - Shut-in pressure?
         - Yes: Determine kill mud and circulate to kill well
         - No: Incremental depletion of brine accumulation
       - END
     - No: Salt movement?
       - Shut-in and pump salt back
       - Increase mud weight
       - END
Choose mud weight close to expected pore pressure

Choose mud weight to balance salt flow.

Use OBM, heated salt-saturated WBM, or mixed salt WBM

Wellbore losses?

No → END

Yes → WELLBORE LOSSES

FIGURE 8.3 WELLBORE LOSSES AVOIDANCE
FIGURE 8.4 WELLBORE LOSSES REMEDY
**Figure 8.5 Wellbore Gains Remedy (Suspected Charging)**

1. **Shut-in and measure stabilised SIDPP**
2. **SIDPP =< ECD pressure**
   - **Bleed off any charged pressure**
   - **Final bled SIDPP**
     - **= 0**
       - **Entirely charged**
         - Circulate out influx
         - **END**
     - **> 0 > original SIDPP**
       - **Partially charged partially natural overpress**
         - Determine kill mud from final bled SIDPP and circulate to kill well
         - **END**
3. **SIDPP > ECD pressure**
   - **SIDPP = original SIDPP**
   - **Natural overpressure**
     - Determine kill mud from stabilised SIDPP and circulate to kill well
     - **END**
* Depends on nature and rate of influx (mud, brine, gas, H2S) and rig situation (land vs off test string availability etc.).

**FIGURE 8.6 LOSS-GAIN REMEDY [27]**
**Figure 8.7 Mixed Influx Avoidance and Remedy**

1. **Case & Cement Sections**
   - TD Section
   - Plug back

2. **Drill Ahead Using ECD**
   - Yes: Brine contamination
   - No: Drill ahead using ECD drilling techniques

3. **Severe Brine Contamination**
   - Yes: Brine contamination of OBMs
   - No: Yes: Drill ahead using ECD drilling techniques

4. **Drill Ahead to Kill**
   - Yes: No drill ahead to kill
   - No: Drill ahead to kill

5. **Treat Surface Mud**
   - Yes: Treat surface mud
   - No: Drill ahead to kill

6. **Weight Up KILL**
   - Yes: Yes: Drill ahead to kill
   - No: Drill ahead to kill

7. **Flow via Choke to Flare**
   - Yes: Flow via choke to flare
   - No: Drill ahead to kill

8. **Remedy**
   - Yes: Record SIDP & SCIP
   - No: Drill ahead to kill

9. **Run Tail in for Build Up**
   - Yes: Run tail in for build up
   - No: Drill ahead to kill

10. **Run Tail in for Build Up**
    - Yes: Run tail in for build up
    - No: Drill ahead to kill

11. **Record SIDP & SCIP**
    - Yes: Record SIDP & SCIP
    - No: Drill ahead to kill
Choose mud weight close to expected pore pressure

Drill slightly out-of-gauge hole

Undertake

Stuck pipe?  
No → END

Yes

STUCK PIPE

Restricted circulation?

Yes

Salt movement

Method to free pipe?

Shut-in and pump salt back

Spot fresh-water pill to produce slight washout

END

No

Filtration losses

Reduce mud weight

END

FIGURE 8.8 STUCK PIPE AVOIDANCE AND REMEDY
Use OBM, heated salt-saturated WBM, or mixed salt WBM

Use thick wall casing

Set casings just above and just below squeezing salt sections

Accurate determination of cement volume required

Ensure effective cement sweepage particularly for washout zones

Drilling casing collapse? No → END

Yes

DRILLING CASING COLLAPSE

Salt washout

END

Salt movement → END

**Figure 8.9 Drilling Casing Collapse Avoidance and Remedy**
Further work or research concerning Zechstein drilling problems would be considered to be of benefit. These translate into the following areas of further work:

- **Viability of Decision Tree Analysis Approach:** The decision tree analyses conducted here are provisional and are based on all the information gathered from the open literature, dialogue with industry personnel, and interpretation of well incidents using kick simulator technology. Input from drilling engineers is likely to be required to bring these analyses to the stage where they can be applied to produce the maximum benefit.

- **Improvement in Well Control Modelling Capabilities:** The study of well incidents revealed that current kick simulators need to be modified to take into account some of the physical mechanisms that occur within Zechstein (see Figures 3.5a & b) such as ECD charging and swabbing, or their consequences, such as brine kicks breaking down OBM which may cause washout or increase frictional pressure losses or both.

- **Further Application of Kick Simulator Technology:** Further application of kick simulators both to specific research projects to acquire technical information (such as analysis of other low ‘Kh’ incidents) and to regular well design (such as the production of ECD charts to help assess charging situation or to back-calculate the BHP for low ‘Kh’ situations) would be of benefit.

- **Salt Movement (Wellbore Ballooning) Modelling:** Experience has been gained in the mechanism of salt movement from related work carried out into the storage of radioactive waste in Zechstein diapirs [26]. The information gathered has been used to predict the behaviour of Zechstein salts at depths of ~2000 ft. This information may be applicable, with some modification, to the greater depths typical when drilling Zechstein in the Southern North Sea.

- **Cement Volume Estimation:** Washouts beyond the range of calliper logs (22") have been experienced downhole. One consequence of this is difficulty in accurately estimating the cement volume required. Calliper logs represent a lower limit on the cement volume. It could prove useful to develop an algorithm, for various geometries, flowrates, geothermal gradients and solubilities, capable of estimating an upper limit on the level of washout, thus bounding the required cement volume.

- **Cement Sweepage Efficiency Estimation:** Also, it could prove useful to develop a similar algorithm capable of estimating the efficiency of cement sweeping out the original mud from washed out cavities. This will determine the strength of cement bonds between the formation and the casing strings.

The health and safety aspects of both the operational problems and alleviation procedures stem from the uncertainty associated with how these events will unfold. This uncertainty comes from not being able to predict the complex interaction of the different Zechstein behavioural mechanisms. The overall objective of further work is to reduce this uncertainty.
9. REFERENCES

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


