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Evaluation of Automated Drilling Technologies Developed for Petroleum Drilling and Their Potential when Drilling Geothermal Wells

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ABSTRACT

The recent years, the petroleum industry has experienced increased drilling costs. One of the major challenges has been related to the narrow well bore pressure profile gap between the formation collapse pressure profile and the formation fracture pressure profile.

Standard operational procedures, such as pipe connections and drill string tripping lead to pressure fluctuations. These pressure fluctuations may lead to drilling problems such as well bore collapse.

The petroleum industry are currently developing and testing new technology, such as the Managed Pressure Drilling technologies, where new equipment and automated procedures are utilized to reduce the drilling costs.

This paper presents an evaluation of the various automated drilling technologies now being utilized to reduce both the drilling time and the drilling costs. The focus has been to evaluate the potential of these automated technologies when used for drilling geothermal wells.

Different well bore geometries have been evaluated; shallow wells, medium deep wells, deep wells, and ultra-deep wells. The results indicate that the geothermal drilling industry has a large potential in reducing the drilling costs when utilizing automated drilling technology, especially when drilling deep wells.

1. INTRODUCTION

The economic incentives for reducing drilling costs are now becoming more visible for the petroleum companies. Due to reduced availability of trained drilling crews, in addition to the fact that the remaining petroleum reserves are located in difficult accessible area, several oil companies, such as Shell, ConocoPhillips, BP and StatoilHydro are having increased focus on automated drilling procedures.

Prior to drilling operations, the various procedures are planned in detail prior to the drilling operation. However, since this planning is performed under large uncertainty, based upon the information available prior to drilling, the operating conditions for the drilling operations such as actual drilling fluid flow rate and weight-on-bit are often updated manually during the drilling operation. The change of operating conditions is due to the increasing amount of information gathered during the drilling operation.

Due to the increased challenges of drilling operation, new drilling concepts have been developed, introducing new equipment that the drilling crew must operate correctly. As the drilling crew is mainly operating the drilling rig manually, challenging situations may occur for the drilling crew when they try to coordinate the operation of the various equipments.

To accomplish an optimal operation of the equipment available, there have been introduced automatic procedures and control systems which are able to control and coordinate the various equipment more optimal for the overall drilling operation.

The current effort within technology development to enhance extraction of geothermal energy, the drilling concept and method are given high focus. One of the most important challenges is to support the development of more cost effective solutions supporting the recovery of geothermal energy sources. Today the drilling costs normally represents around 60 – 70% of the overall project cost, and often turn out to be a “show stopper” for the project. The technology utilized in drilling for geothermal energy should be based on the latest know-how from the petroleum drilling methods.

This paper is divided into seven sections. The next section presents the various drilling challenges that typically are encountered during drilling operations, both when drilling geothermal wells and when drilling petroleum wells. The third section describes the various equipment and automatic control now being developed to address the drilling challenges. Section four presents the various costs involved during drilling operations. The fifth section discusses the need for training of the drilling crew, and full scale testing of the equipment. The following section presents an evaluation of how the new automated drilling systems may affect drilling costs when used for various well geometries. The last section gives the concluding remarks and suggestions for further work.

2. DRILLING CHALLENGES

The increased oil price in the years of 2005 until 2008 gave an incentive for the petroleum companies to start drilling operation is areas and at locations that were previously deemed to be to expensive to drill, due to challenging formation pressure constrains and remotely located drilling sites.

Several oil companies, especially in the high cost region of the world, such as the North Sea between Norway and United Kingdom, started research programs to develop equipment and systems that would enable the petroleum companies to drill at such challenging locations.

This section present and discusses some of these drilling challenges, which mainly are related to the two factors common to geothermal drilling, which is problems related to the formation pressure constraints, and problems related to the hole cleaning properties of the well (Bjelm, 2006), (Petty et. al, 2005), (Melosh et.al, 2008).

2.1 Formation Pressure Constraints

The formation pressure constraints are of particular concern when drilling petroleum wells. There are several governmental restrictions that secure the environment for avoiding critical situations such as a blow-out. To avoid such situations, there are several safety systems that are arranged at the drilling location.

One of the main barriers for avoiding an un-intentional loss of drilling fluids into the formation, is to use a drilling fluid system that maintains a correct down-hole pressure below the formation fracture pressure, $p_{frac,}$ along the whole well bore. The down-hole pressure must be kept within the formation pressure constraints, giving the following relation,

$$p_{coll}(t,z) < p_{well}(t,z) < p_{frac}(t,z), \qquad (1)$$

where t is time, z is the depth, p_{coll} is the formation collapse pressure, p_{well} is the well bore pressure, and p_{frac} is the formation fracturing pressure, respectively.

Another pressure property in the reservoir is the formation pore pressure, p_{pore}. If p_{well} is above p_{pore}, then the drilling operation is denoted overbalanced drilling. Under-balanced drilling is when p_{well} is below $p_{pore.}$ Under-balanced drilling has shown to improve the rate of penetration in hard formations (Bjelm, 2006). Keeping p_{well} equal to p_{pore} is difficult, but this is often denoted as Managed Pressure Drilling, which requires some extra equipment during the drilling operation.

During drilling, a drilling fluid is circulated through the drill string and drill bit. The drill bit is equipped with a check valve, which prevents the drilling fluid in the annulus to return into the drill string. The drilling fluid flows through the annulus between the drill string and the walls of the well.

The hydrostatic pressure in the well depends on the fluid density. The hydrostatic pressure in the well p_h can be modeled as

$$p_h = \rho_{mix} gh, \qquad (2)$$

where ρ_{mix} is the density of the fluid mixture in the annulus, g is the gravity and h is the true vertical depth (TVD) of the well. In a conventional drilling operation, the drilling fluid pump circulates the drilling fluid at the specified mass rate, and exits through the upper part of the annulus section of the well bore. The pressure is often measured at the drill bit using the bottom hole pressure (BHP) gauge. The fluid mixture in the annulus consists of several components. Primarily, it consists of the drilling fluid that was injected into the drill string. In addition there will be cuttings from the drilling process that are transported away along with the drilling fluid. Also, if the well pressure is above the pore pressure in the formation section of the well, then drilling fluids might migrate into the formation.

The fluid friction inside the drill string and the annulus influence the resulting pressure. The friction pressure loss, p_f in a pipe can be modeled by

$$p_f = \frac{2\rho_{mix} f_{mix} L v_{mix}^2}{D} \qquad (3)$$

where f_{mix} is the friction factor which is related to the Reynolds number of the mixture, L the total length of the well, D is the hydraulic diameter and v_{mix} is the mixture fluid velocity.

It is a challenge to control the well pressure gradient at all times during the drilling operation, since the pressure loss caused by fluid friction might have a dominant effect. The drill string consists of several segments of pipe joined together, and the fluid flow must be stopped at distinct time intervals to be able to connect the pipe segments together, as the drill string is penetrating deeper into the formation. The fluid flow fluctuation causes variations in the well pressure. Other operations during drilling, such as inserting the drill string into the well and pulling the drill string out of the well, also cause pressure variations in the well annulus.

One special concern while drilling a well is when the drilling fluid density has to be lower than what is typical for drilling fluids consisting of liquid only. In such cases, gas is injected into the drill string or the annulus part of the well. The low density of the gas reduces the hydrostatic pressure, but results in additional complexity of the well fluid behavior as it introduces two-phase fluid flow in the well. The gas will be compressed along the well trajectory, depending on the friction pressure and hydrostatic pressure.

When drilling in a part of the formation where formation fluids may migrate into the well bore the influx of formation fluids causes changes in the pressures in the well annulus.

On the opposite, if drilling through formation zones where the well bore pressure exceeds the formation fracturing pressure, then the drilling fluid might migrate into the formation, and drilling fluid losses occur.

2.2 Hole Cleaning Properties

During drilling operation, the cuttings from the drilling process are transported from the bit using the drilling fluid. The efficiency of the cuttings transportation is dependent of the drilling fluid flow rate and some of the drilling fluid properties, such as the viscosity.

The amount of generated cuttings is dependent of the rate of penetration during the drilling operation, using the relation

$$q_{cutt} = A_{bit} v_{bit}, \qquad (4)$$

where q_{cutt} is the volume rate of cutting, A_{bit} is the cross sectional area of the bit, and v_{bit} is the rate of penetration.

Since the hole cleaning properties is dependent of the drilling fluid properties, the rate of penetration must be kept in constant, relative to the drilling fluid properties. When drilling the rate of penetration might vary due to variations in the formation properties. If the formation properties changes locally in the well bore, then the rate of penetration might increase if the weight-on-bit is kept constant.

If the rate of penetration increases too much, related to the drilling fluid properties, then the cuttings transportation will be reduced, resulting in a poor hole cleaning. The result may be increased torque readings and stuck pipe conditions. Another consequence of poor hole-cleaning would be a pack-off condition in the annulus section, resulting in an increased pressure below the pack-off. The increased pressure could then cause formation fracture and loss of drilling fluid into the formation.

3. AUTOMATED DRILLING TECHNOLOGIES

The challenges described in the previous section, such as the formation pressure constraints and the hole cleaning properties has always been present in drilling operations, but since the drilling industry now are drilling into formations where such problems are more likely to occur, then these problems has been further addressed the recent years. There is a need for further automation of the drilling operations to avoid drilling problems (Thorogood et.al, 2009). Several systems that is designed for automatically prevent failure situations are currently being commercially available.

The following sections focus on some of these enhanced drilling systems, ranging from automatic drilling surveillance system, active failure prevention systems, continuously circulation systems, managed pressure drilling systems, remote operated drilling rigs and coordinated control systems for drilling operations.

3.1 Automatic Drilling Surveizllance

In a drilling surveillance system the focus has been on presenting various status settings of the drilling machinery, such as the draw-works position and the top-drive torque and RPM measurements. In addition, logging-while-drilling (LWD) data from the well, such as the porosity and resistivity measurements is presented as raw data to the drilling crew. In geothermal drilling, there are often hard formations to be drilled through. A surveillance system for diagnosing the drill bit efficiency will be useful (Wise, 2005).

As more data is becoming available for the drilling crew, there has been a need to develop assisting systems that analyze the situation in the well bore by combining and evaluate the various available measurements. (Hovda et.al, 2008) One example is a system that is automatically updating the expected torque readings at various drilling depths. (Cayeux and Daireaux, 2009). This system is combining several measurements from the drilling operation and relates these measurements to a detailed simulation model of the well bore in real time.

The model includes both mechanical effects such as torque and drag, in addition to a dynamic hydraulic model. The model is constantly update based on available quality assured measurements. Based on the calibrated model, the varying trend of the down-hole friction can be identified and an alarm can be issued to the drilling crew if the friction exceeds predefined limits.

3.2 Active Failure Prevention

During drilling operations the drilling crew must assure that the operating conditions such as the drilling fluid flow rate is kept within certain constraints to avoid that the pressure in the well exceeds the formation fracture pressure or falls below the collapse pressure of the well. A typical situation is during tripping. During a tripping-in operation the tripping velocity must be kept below a certain limit to avoid that the well bore pressure increases too much.

In (Cayeux et. al., 2009) a pilot test of such a system was described, where an analyzing system is evaluating the conditions of the drilling operation, and automatically calculates active tripping acceleration and velocities. The system then prevents the drilling crew from tripping with too high velocities. The system also limits the main drilling fluid pump operations, to avoid a fracturing situation during pump startup.

The active failure prevention system is designed using a detailed model of the well bore, and the available measurements are used to update the model, ensuring that the model describes the real well behavior sufficiently accurate. The active operational limits are then calculated using the calibrated model.

3.3 Automated Managed Pressure Drilling

The recent decade, various automatic choke valve units have been introduced to improve the ability to drill into formation with narrow pressure gaps. The pressure gaps are the pressure between the formation collapse pressure, the formation pore pressure and the formation fracturing pressure. Further development of the automatic control systems may be needed to utilize the available equipment further. (Godhavn, 2009).

3.3.1 Annulus Backpressure Concept

In Fig. 1, a system denoted annulus backpressure is presented. The main pump is pumping the drilling fluid through the drill pipe as in conventional drilling. As the drilling fluid is flowing upwards in the annulus section of the well, a rotating seal is placed in the upper part of the annulus. This gives the possibility of providing a backpressure in the upper part of the annulus, by providing a pressurizing pump and a choke valve system that is used to adjust the backpressure in the annulus. The backpressure is automatically adjusted to ensure that the down-hole well bore pressure is kept at a constant level, slightly above the well bore pore pressure.

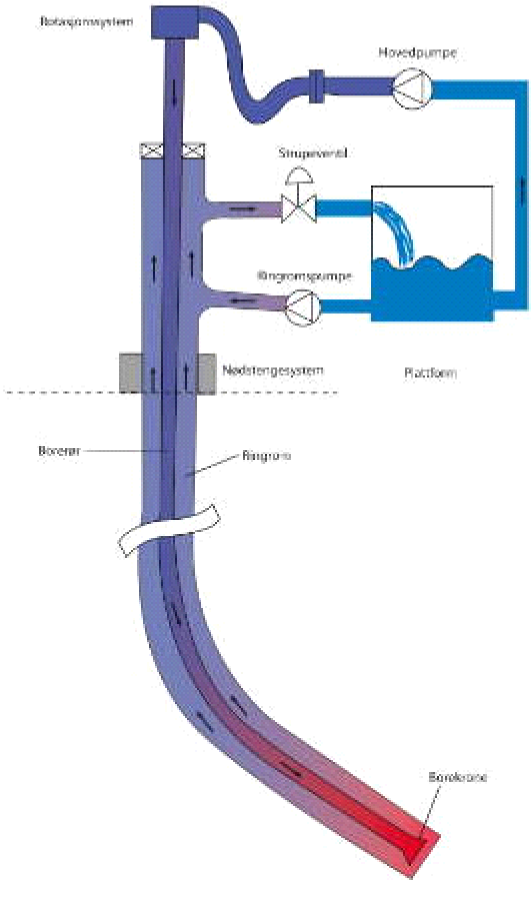

Figure 1: Schematic view of a well drilled with MPD setup using annulus backpressure equipment.

3.3.2 Continuous Circulation Concept

In addition to the annulus backpressure concept, there are also other drilling concepts that can be used to reduce the pressure fluctuation during drilling operations. One such concept is the continuous circulation system, where the pressure oscillations caused by pump shut-down and startup is avoided by arranging special seals and valves that makes it possible to continue to circulate the mud in the annulus even during pipe connections. There are mainly two concepts of continuous circulation:

- Utilizing drill string
- Utilizing dual casing/parasite string

When utilizing the drill string for continuous circulation, then a valve and seal system is used to allow the pipe segment to be disconnected while the flow in the drill string in maintained. When utilizing a dual casing or a parasite string, then a separate flow line is placed into the well bore in addition to the drill string. When this concept is used, then the circulation in the annulus can be maintained when the main drilling fluid pump is stopped. If the flow through the dual casing or parasite string is adjusted correctly, then the down-hole pressure may be maintained at a constant level.

3.4 Automated Coordinated Control

The Active Failure Prevention systems and the Automated Managed Pressure Drilling system, gives an important basis to develop systems that are automatically coordinating the relation between the various subsystems of the drilling rig. In Fig. 2, a piping and instrumentation diagram combining the various main components which is important for defining the rate of penetration during drilling while maintaining a correct down-hole pressure.

The purpose of the diagram is to show that the drilling control system can be viewed as a process system similar to a processing plant. In the process industry there have been developed control methods such as Model Predictive Control to improve the overall efficiency of the process plant.

In Fig 3. a method for organizing the coordinated control system is shown.

The important focus when coordinating the various pumps, top drive, draw-works and valves is to optimize the rate of penetration, while maintaining correct hole cleaning properties and down-hole pressure requirements. In (Nygaard et. al, 2007) such a control system is described which coordinated the tripping speed and the backpressure pump during a tripping operation. Having such a control system will ensure that the down-hole pressure is kept at a constant level even when tripping. Further automation is being developed; including methods for automatically coordinating the control of the main drilling fluid pump during drilling operations.

3.5 Remote Operational Drilling Rigs

A new type of autonomous drilling rigs is also being developed. These drilling rigs are specifically design to reduce the manual handling of drill pipe and pump systems. Such remotely operated drilling rigs will utilize the automation solutions now being developed for conventional drilling rigs.

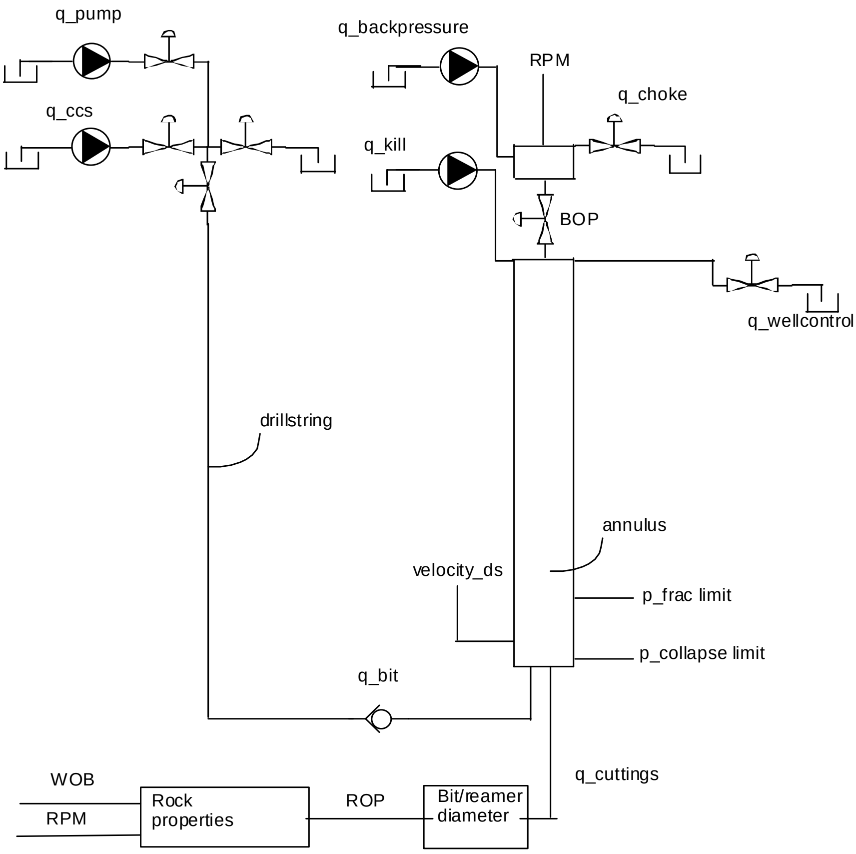

Figure 2: A piping and instrumentation diagram presenting the various additional drilling units that may be utilized in managed pressure drilling operations.

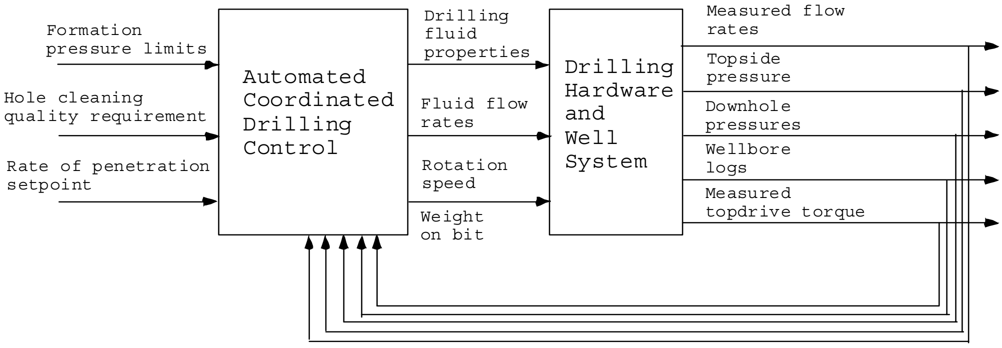

Figure 3: Schematic layout of the automated coordinated drilling control system.

4. DRILLING COSTS

30% - 60% of the total costs of a geothermal project are connected to drilling costs. The cost beneficial savings are large by taking technology described in the previous chapter. Advanced drilling systems can easily being taken into use in geothermal projects, even if they are developed for the oil industry. However, further analyses are needed to detect possible adaptations.

4.1 Avoiding Well Bore Stability Problems

In the oil industry, typically 10% – 30 % of total well cost is caused by well bore instability problems as lost circulation, hole cleaning, stuck pipe, etc. (Ward and Wilson, 2005). Different solutions are in progress to reduce and minimize such incidents. Pilots of the automatic drilling surveillance and active failure prevention technology described in the previous chapter have been run at installation and operation centers of the North Sea. At the moment there are no available statistic known to the authors showing development of well bore stability problems when using such technology. Data from the ongoing automatic drilling surveillance pilot test, including automated detection of possible stuck pipe incidents as described in section 3.1 will be available within October 2009.

Stuck pipe, fishing and possible side-tracking are very time consuming and expensive operations. To avoid pipe getting stuck, correct action at an early stage is crucial. Human factors have turned out to be a significant factor to avoid stuck pipe. Experiences with training and awareness campaign in the oil sector gave a decrease in stuck pipe incidents with 50% (Skalle et al.,1998), but decay of campaign lead to decay of alertness and the level of stuck pipe incidents returned to historical level.

56% of the stuck pipe incidents happen while tripping and 30% while pipe is stationary (Skalle et al., 1998). Automated handling to prevent stuck pipe is in progress in the active failure prevention system and will be able to take care of most incidents occurring when tripping and during pump startup.

Similar challenges are common in geothermal wells, e.g. in Soultz (Idao National Laboratory, 2006), Groβ Schönebeck (Brandt, 2007), and Reese River (William, 2008). Lost circulation and related problems as hole-cleaning and in worst case stuck pipe accounts for 10% -20% of the cost of a typical geothermal well. (Glowka, 1997). Transfer of experience and utilization of software and technology developed in the oil industry can potentially reduce well stability problems also for geothermal industry.

4.2 Reducing Casing Costs

A MPD operation will require one extra pump at the rig, but can make it possible to reduce the number of casing strings. The cost benefits are large for deep wells. If increasing the number of casing strings from 4 to 5 in a 5000 m deep well, the total well cost will increase with 18.5%. Similar, by increasing the number of casing strings from 5 to 6 in a 6000 m deep well will increase the total well cost with 24% (Idao National Laboratory, 2006). The cost saving potential increases with depth and the limitation of the number of casing strings.

It is not only the reduced number of required casing strings that has a cost beneficial effect on the total well cost. Electric power production has requirements on the flow rates that again put requirements on the completion diameter. If reducing the number of casing strings, the surface casing diameter can be reduced correspondingly. A lot can be saved on smaller rigs and rig equipments and also on mud costs.

4.3 Reducing Crew Costs

By taking autonomous drilling rigs into use, it is possible to run several operations from one operation center simultaneously. The required man-hours to run operations will be reduced significantly and work packages can be moved from the rig site to an operation center. The ongoing technology development within this area has to take some steps further before it will be realistic with such operations.

5. TESTING AND TRAINING FACILITIES

When drilling rigs are equipped with additional system for automating and coordinating the various subsystems of the drilling rig, then proper training of the drilling crew is essential for having a safe and efficient operation. This section is divided into two subsections; first a simulator training facility described, and secondly is a full scale drilling rig is presented. The drilling rig is designed for training and testing purposes.

5.1 Simulator Training Facilities

New automated systems such as the active failure prevention and the managed pressure drilling system, give new challenges for the drilling crew. Since the system are more complex to operate, the system is typically operated by an automatic control system. Since such systems deviates from conventional drilling system, then the drilling crew should be trained in a simulator to better utilize the benefits of the system.

Such a simulator system for MPD operations is developed in conjunction with the Ullrigg Drilling and Well Centre in Stavanger, Norway. The system is referred to as a Virtual

Rig system, there the driller and assistant driller in addition to the MPD operator is trained in an environment similar to the drilling rig. Fig. 4 shows a picture of the Virtual Rig facilities.

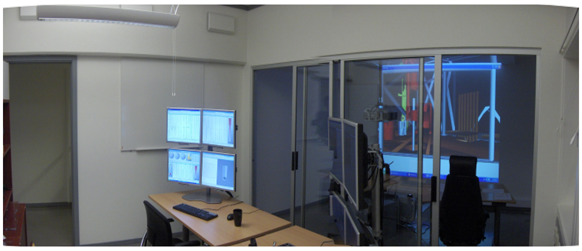

Figure 4: The Virtual Rig Drilling Simulator.

This picture shows the view from the experimentalist room. The experimentalist sets up the drilling case that is used for the simulator training. The experimentalist can activate various drilling scenarios, such as a pack-off situation or a loss of drilling fluid situation. The drilling crew can then experience how they can interact with the automated procedures and the failure conditions.

5.2 Full Scale Testing and Training Facilities

In addition to test the drilling crew in the Virtual Rig simulator, there is also a need to test and evaluate some of the systems in full scale. In Stavanger, Norway, the Ullrigg Drilling and Well Centre is an independent research test site for full-scale testing of drilling and well operations in the oil & gas industry. A layout of the test centre is shown in Fig. 5.

The existing Ullrigg infrastructure features a full scale drilling rig prepared for full drilling automation, advanced drilling control and monitoring system. The site has 7 wells, vertical and horizontal whereas two of these are deviated and multilateral wells. A complete 2” coiled tubing test facility, flow laboratories and high temperature/high pressure test cells for testing at down-hole conditions rated to -50DegC - +250DegC and pressure up to 2000bar.

Along with the infrastructure, the Ullrigg test centre is equipped with various systems for automated drilling, such as systems for active failure prevention. With the extended experience within petroleum drilling, the adaptation to drilling and well construction for geothermal wells is important for the geothermal drilling industry.

Based on the experiences from the petroleum drilling, then the infrastructure, the research outcome and new technologies (methods, equipment, and simulators) will meet the industry’s demand for new well construction solutions, reduced drilling and well costs, improved safety and environment, and support the development of new drilling concepts fit to geothermal drilling.

6. EVALUATIONS

This section describes the various automated solutions which are developed for the petroleum drilling industry, and evaluates the cost impact on different types of geothermal wells.

The upcoming computer system for surveillance of the drilling operations where the focus is on analyzing the available data by utilizing a detailed model of the well bore is an important step towards understanding the well bore situation. As these systems are operating automatically and are able to warn the drilling crew before the situation becomes critical, then such system will have a large impact on the drilling costs. As no mechanical equipment is needed, then the investment cost is fairly low. This makes these systems economically for the all the various classes of wells; shallow, medium, deep and ultra deep wells.

The system for active failure prevention requires that the equipment that should be operated securely by the drilling crew, can be interfaced and operated through a computer controlled drilling cabin. The active failure prevention system is then installed as an analyzing system, where the active constraints of the drilling equipments are continuously updated. The infrastructure needed to be able to install the system, require a high-end quality drilling rig. This may result in a higher installation cost than actually needed for the easy accessible, shallower geothermal wells. However, if the drilling crew is not that experienced, then such system would reduce the unexpected failures during the drilling operation.

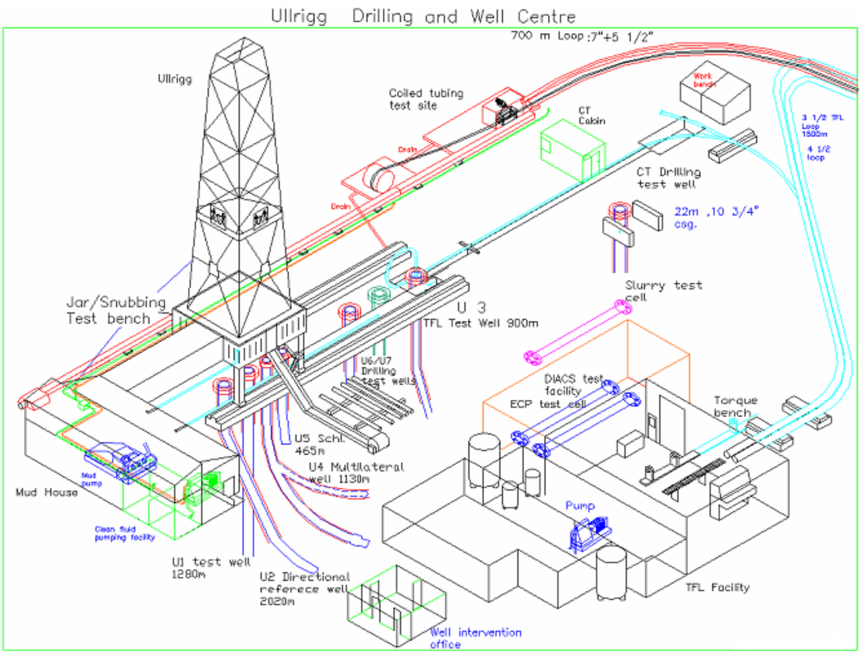

Figure 5: An overview drawing of the Ullrigg Drilling and Well Centre.

Advanced drilling systems such as the managed pressure drilling systems and the systems for coordinated control, require a higher investment when compared to the drilling surveillance tools. However, for deep geothermal wells, there will probably be several different formation pressure profiles that have to be taken into account when performing the drilling operation. Having a managed pressure drilling system that are able to reduce the critical events such as a loss of drilling fluid or well bore collapse, then such a system would be able to reduce the overall drilling costs.

The new drilling concepts involving autonomous drilling rig, is designed to be less expensive than conventional drilling rigs. The new generation of autonomous drilling rigs will give a considerable cost saving potential for all types of geothermal wells.

7. CONCLUSIONS

Different automated drilling systems have been presented and evaluated for geothermal wells with different depths.

Introducing the automated drilling technology developed for the petroleum drilling industry such as automated drilling surveillance and system for active failure prevention will have a considerably cost saving potential when drilling geothermal wells.

In deep geothermal wells with varying formation pressure profiles, then utilizing advanced automated system for managing correct well bore pressure will be beneficial.

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