

Closed-Loop Steerable Drilling Tools for High Temperature Application

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Key Words: Drilling, Directional control, Two-way communication link, Automatic downhole closed loop, High temperature rated.

ABSTRACT

The drilling environment today calls for drillers to be able to access deeper, high temperature and high pressure reservoirs, where high temperature is defined as 200° C and high pressure to 0.9 psi / ft. Temperatures during geothermal applications can be well in excess of 200°C.

A new family of automatic drilling tools has been introduced which provides automatic steering within ultra deep formations under high temperature and high pressure (HTHP) conditions. Another important use of this system is foreseen in the drilling of wells with extended reach horizontal sections. The directional changes in the Closed-Loop Drilling System are automatically generated on the basis of Measurement While Drilling (MWD) measurements taken directly within the tool. Since the major application aims at the very deep hydrocarbon layers, all components are designed to operate at temperatures between 185 to 200°C. Special consideration is given to the design of downhole motor elastomer and electronic components of the MWD.

In preparation for the field application of the complete fully directional tool, field tests have been performed with a Straight Hole Drilling Closed-Loop System and other essential system components. The Straight Hole Drilling Device has been designed to drill a straight vertical well. It has been successfully run on various onshore and offshore European locations; where in one case a maximum depth of over 7,200 m was attained. Additional field case histories are provided in this report on high temperature downhole motors. The complete fully directional system will be ready for field application within the first half of 1995.

1. INTRODUCTION

Drilling deep HTHP wells often requires the application of versatile systems for directional control. Current directional drilling state-of-the-art, for standard applications, implies the use of a bottom hole assembly (BHA) for directional control comprised of a steerable downhole motor based on the tilt angle principle and a MWD with directional capabilities (inclination, azimuth and toolface). Formation evaluation sensors may be included as additional features. These include Gamma Ray and Resistivity. Conventional operational temperatures are limited to 125°C, with 150°C the absolute maximum. The critical temperature-sensitive components are the electronic hardware of the MWD; as well as, the elastomer and bonding system in the mud motor.

The subject of this paper is a directional drilling tool based on an alternative steering principle, which has been designed for 200°C survival and 185°C operational temperatures. Formation evaluation and directional control capabilities are included. A high temperature downhole motor is included within the BHA. Field tests on basic components of the new drilling system are reported as case histories.

2. ROTARY CLOSED-LOOP SYSTEM

Standard steerable motor directional drilling equipment is generally based on the tilt angle principle. A bent housing section, with angles in a range from 0.5 to 2.5°, which depends on the tool geometry, provides the bit offset necessary to initiate and maintain

changes in course direction. Three geometric contact points, i.e., drill bit, first stabilizer, and top stabilizer, approximate a circular arc which defines the wellpath and dog leg severity. The curvature is formed and built in the sliding mode. When rotating the drill string from the surface, the tool will drill a straight, slightly oversized, section.

These tools generally require continuous wellpath control by the driller, with the drawback of interaction from surface via the rotary table. Conventional practice is to alternatively rotate the entire drill string from surface to drill a straight well path, and to stop drill string rotation and use the downhole motor tilt angle to correct the well path. While drilling in this "oriented mode", the entire drillstring has to "slide". However, as drillstring drag can be overcome by drill string rotation, drag forces increase when in the oriented mode and there is a reduction in rate of penetration. For extended reach drilling (ERD), the drag limits may reduce the final length of the wellpath [1, 2, 3, 4]. To overcome these limitations the "Rotary Closed-Loop System" (RCLS) was designed to control the well automatically, even while rotating the drill string.

With this system, the wellpath is adjusted by hydraulically powered expandable ribs, that generate a radial steering contact force from the borehole wall. The steering direction is defined by the amount of pressure distributed selectively to every stabilizer pad, thus forming a resultant force vector. Again, the wellpath is defined by the three geometrical contact points, i.e., the drill bit, the near bit expandable stabilizer, and the top stabilizer. By selectively actuating one or more of the ribs, the eccentricity of the expandable stabilizer is determined.

The amount and direction of the steering force is controlled by the downhole electronics, which are capable of steering the well to the desired direction. The electronics compare the drilled wellpath with a pre-set course. Upon any variance between the two, the electronics will control the hydraulic power distribution. To enable the tool to correct the well during rotation, expandable ribs and part of the downhole electronics with the directional sensors, are located on a non-rotating sleeve close to the bit. Rotation of the drill string is transmitted to the bit through the non-rotating sleeve via a drive shaft.

The downhole tool includes a turbine-driven alternator for electric power supply to the downhole electronics, and a mud pulse telemetry system for data transmission to the surface. The hydraulic power for actuating the expandable ribs is generated by a turbine-driven oil pump and controlled via electrical pressure control valves. Also included are formation evaluation sensors located near the bit for geo-steering capabilities. A mud motor positioned 20 meters above the bit provides for rotation of the complete drill string from the rotary table, or for sliding the assembly through the formation with rotation of the string below the motor. In the rotary mode, the motor will add to the effective RPM available at the bit. A schematic of the downhole tool is shown in [Figure 1](#).

With standard steerable motor directional drilling tools, the wellpath is controlled by switching between the rotary and the sliding mode, where the tilt angle orientation is adjusted as desired with the rotary table. In contrast, with the current version of the Rotary Closed-Loop System the control mechanism is achieved by communicating the desired course to the downhole tool from the surface.

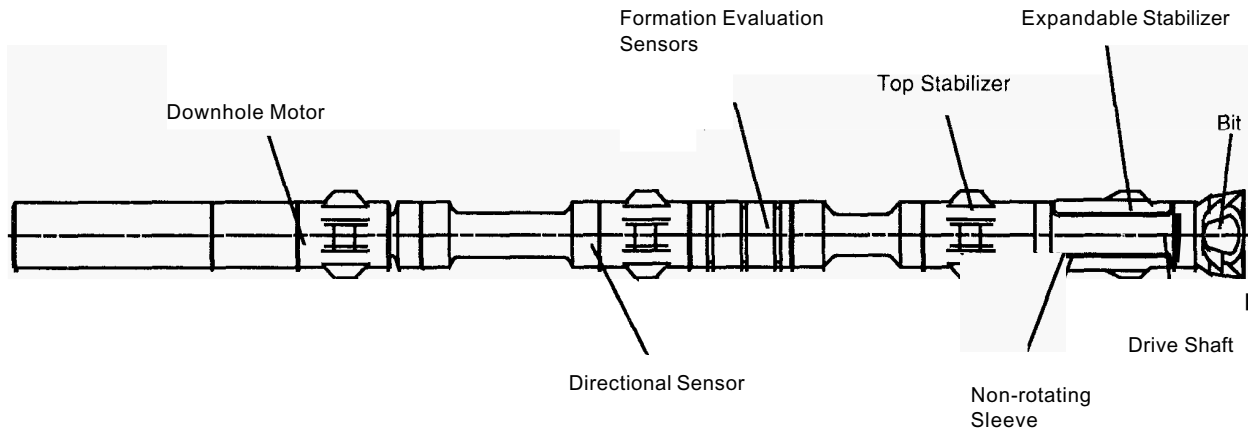


Figure 1: Rotary Closed-Loop System

Then the tool will drill into the newly programmed direction until a new course is set. Any deviation from the pre-set direction will be automatically compensated by the downhole closed loop control. With this method the control of the well at surface is achieved without interruption of the drilling process or any restrictions on drill string rotation, as is necessary with standard steerable tools.

The downhole communication is established via a downlink transmission system. A by-pass actuator diverts part of the mud flow at surface back to the mud pits. The corresponding flow rate variations are detected downhole through the voltage variations generated by the mud turbine driven alternator. The sequence of flow rate changes carrying the instructions is decoded downhole.

Major areas of application for this automatic steering system are ERD as well as drilling directional wells in very HTHP applications. Thus, the tool is designed to drill under downhole conditions of up to 200°C static temperature with a maximum operational temperature of 185°C. The system is capable of operation under maximum downhole pressures as high as 14,000 psi. Critical components in this temperature range are the downhole electronics and the downhole motor.

Only very few electrical components are designed for a survival temperature of 200°C by the manufacturer. In most cases the challenging temperature requirements for the MWD can only be met by carefully selecting individual components and long term laboratory screening under various temperature conditions.

Downhole motor sections of the Moineau type consist of two main components, i.e., the rotor and the stator. The profile of the stator is formed by an elastomer that is bonded to the outer stator housing. For high temperature applications using Moineau motors, elastomers must fulfill major requirements, such as:

- Physical static properties (strength and elongation)
- Physical dynamic properties (fatigue resistance)
- Chemical resistance
- Processing properties (molding process performance)
- Bond properties (elastomer and metal bond)

All of these requirements have to be compromised to find a working elastomer system for the specific downhole conditions. Laboratory tests include different optional mud types and the proper technology to bond the elastomer to the metal housing. Recent achievements indicate, that with current HNBR elastomers, some room for improvement exists with respect to bonding performance, by special emphasis on the process parameters. EPDM is another candidate to supplement NBR mixtures.

In addition to all theoretical design and laboratory testing efforts, field testing of components and complete systems is essential to prove the required performance capabilities.

3. FIELD EXPERIENCE

3.1 High Temperature Downhole Motor Field Application

The Continental Deep Drilling Program of the Federal Republic of Germany (KTB) is a research project to investigate the deep continental crust at a depth of 9,000 m and more. The ultra deep well was completed in November 1994 at a depth of 9,101 m. During the final phase, from 8,625 m to 9,101 m, a total of ten runs with high temperature downhole motors was carried out. The following case history describes one example run with a known temperature condition.

3.1.1 High Temperature Motor Case History

The referenced run was carried out in the beginning of the 6 1/2" hole section at a depth from 8,581 m to 8,669 m. A cemented whipstock was set at 8,625 m. Prior to the described run an attempt was made to drill a new hole from the whipstock into the formation. This attempt failed, and the BHA drilled back into the original hole. After subsequent cementing, the plug was drilled out with a 6 1/2 rotary BHA, which included a mechanical temperature measuring sonde. The resulting temperature chart is shown in Figure 2.

This run extended from 7,760 m [start of circulation] to 8,580 m (pull out of hole). Mud was circulated through the drill string below 7,760 m. The measured peak temperature was 193°C, with an operating temperature of 155°C. The approximate static temperature at a depth of 8,580 m is 260°C.

The purpose of the next run was again to drill out of the cemented hole into the formation off the whipstock. To minimize damage of the cementation, a downhole motor was used. A straight motor with high-torque characteristics and bearing housing stabilizer was used with a conventional roller cone bit.

The downhole motor was equipped with a high temperature stator made of a special HNBR elastomer and appropriate bond system. The elastomer and bond system had demonstrated satisfactory performance in the laboratory under high temperature and dynamic load conditions with water based mud.

The BHA was run in the hole to a depth of 7,661 m. This corresponds to the starting point for temperature measurement in the previous run. In order to reduce the effective temperature at the elastomer, circulation was established after connection of each stand for about 5 minutes. The downhole motor started drilling at a depth of 8,581 m. The cement plug was drilled out with an average ROP of 3.4 m/h. Total time on bottom was 25.5 hours, with a total circulation time of 68.75 hours. However, the cementation was too weak to allow drilling a new hole. Instead the BHA re-drilled the cemented hole. The BHA was then pulled at a depth of 8,669 m.

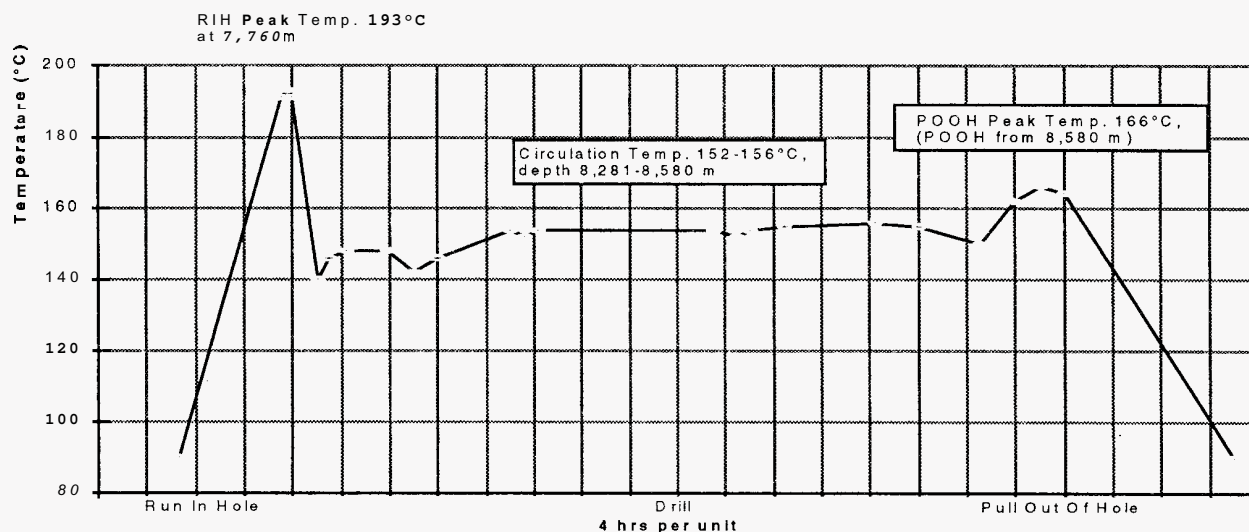


Figure 2: Temperature log of KTB ultra-deep well between 7,760 m and 8,850 m

The environmental conditions of the motor run were very similar to those with the mechanical temperature sonde. The downhole peak temperature exiting at the mud motor was about 190°C, with an operating temperature while drilling of about 155°C. The mud motor was pulled out of the hole without failure.

A total number of ten runs with high temperature motors was then carried out in the KTB 6 1/2" hole section. Four motors failed while drilling due to the high temperature, with cracks in the elastomer. Six runs were successful, where the average circulation time downhole was 67 hours. The bottom hole temperature curve is comparable to the diagram shown in Figure 2. All mud motors were run in the hole with continuous circulation through the drill string, in order to reduce temperature peaks on the motor.

3.1.2 HT Motor Performance Evaluation

The high temperature mud motors exhibited reasonably acceptable performance at high temperatures of up to 190°C. However, some of the motors failed under the combination of high temperature and dynamic mechanical loading. Although some encouraging results with high temperature stators have been achieved, further development efforts are necessary to finally arrive at a mud motor for temperatures of up to 200°C with a downhole life of 150 hours.

3.2 Field Testing of Straight Hole Drilling Devices

The directional control concept of the Closed-Loop Drilling System is based on expandable ribs to steer the tool into the desired direction by applying radial forces from the borehole wall. This basic technology had been developed in connection with the KTB project [5, 6]. The purpose of the Vertical Drilling System, VDS-5, has been to drill a straight vertical course, thereby reducing torque and drag while drilling or running casing. The VDS 5-12 is a motor based configuration, with the expandable ribs fixed to the outer housing. Thus, during drill string rotation no steering action can be performed.

A vertical hole is essential if very deep targets have to be reached. In the case of the KTB well, the VDS kept the hole vertical down to 7,200 m with a predominant formation dip angle of 60°. The horizontal displacement at a depth of 7,200 m was kept below 10 m. Figure 3 shows an example of the inclination change achieved with this closed-loop drilling system. Within 25 hours the inclination was decreased from 1.5° to zero at a rate of 0.35°/10 m. The presented data are taken from the downhole tool memory.

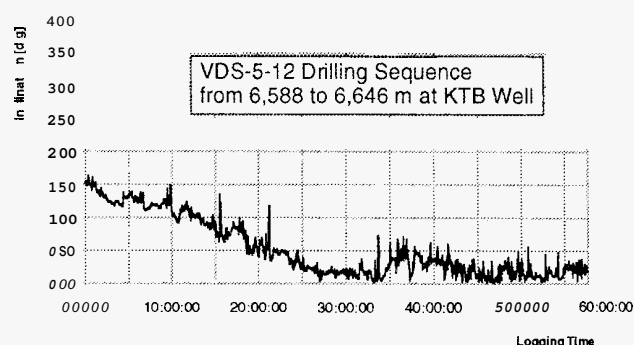


Figure 3: Example of inclination curve taken from the downhole tool memory

The static formation temperature at 7,200 m is 200°C. Trip in peak temperatures during the last VDS runs were 160°C, while the circulation temperature during drilling was 110°C. No component failure due to the high temperatures occurred. The total number of runs with the VDS performed at KTB was 98. The KTB experience very clearly proved the feasibility of the expandable rib steering concept.

For broader applications in commercial oil and gas drilling, major components of the automatic drilling device were reviewed and modified. The changes included the downhole electronics to gain wider computing capabilities, the electronics power supply and the hydraulic system. The new Straight Hole Drilling Device, SDD 6-12, was developed within the framework of an AGIP/Baker Hughes INTEQ joint development project. The tool is designed to drill a straight vertical well, and is still a motor based system with expandable ribs and a non-rotating housing. While steering the tool it is operated in the sliding mode. The first field test of this tool was carried out at Case Pinelli 1 in Italy.

3.2.1 New Straight Hole Drilling Device at Case Pinelli 1

Case Pinelli 1 is a gas exploration well in the Po valley in northern Italy. The target depth was 3,200 m. A 16" hole section from the surface to 502 m was cased with 13 3/8" casing. The 12 1/4" section had a planned target depth at a TVD of 2,000 m. No build-up tendency from the formation was expected. The drilled formation to 2,000 m was clay and shale, with minor contents of sandstone. A fresh water mud FWCLi at 1.15 kg/dm³ and low solids content was used.

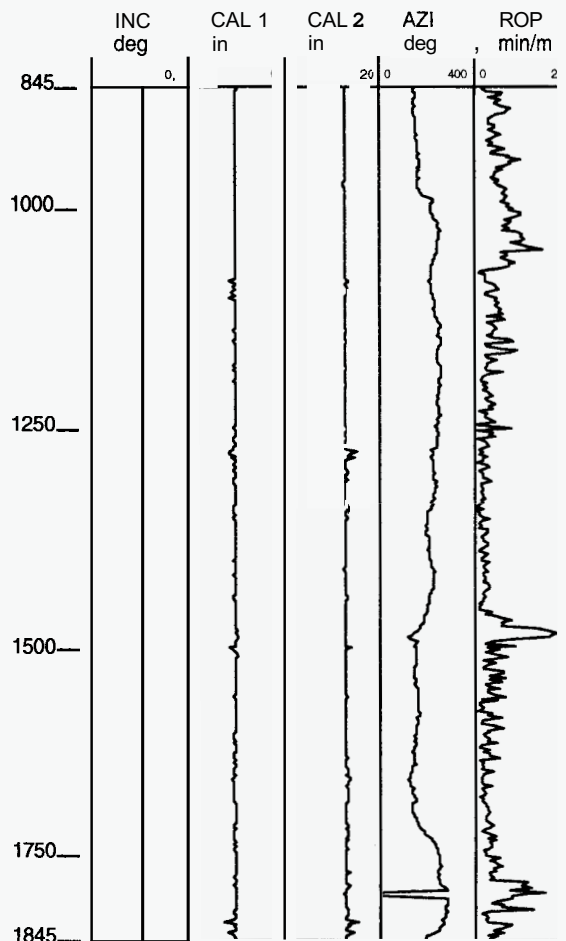


Figure 4: Calliper Log of Case Pinelli 1 (845m to 1,845m)

The cement and 13 3/8" float equipment plug was drilled with a standard rotary assembly down to a depth of 551 m. Then the SDD 6-12-1 was run in the well with a tricone bit. This tool drilled from 552 m to 752 m depth with time on bottom of 10.14 hours and total circulation time of 19.45 hours. The inclination was dropped from 0.4 to 0.0-0.25°. The tool had to be pulled out of the hole due to a data transmission problem.

Thereafter the back-up straighthole drilling device, SDD 6-12-2, was run in the hole. A total of three runs was carried out with intermediate POOH for bit changes. Total drilled meters was 816 m with time on bottom of 88.82 hours and total circulation time of 108.44 hours. The borehole was kept perfectly vertical in a range of 0.0 to 0.25°.

The general drilling performance of the SDD was satisfactory. However, during the last run the ROP dropped from 12 m/h to below 1 m/h. The ROP could only be increased by applying string rotation to the tool. As a motor based system, the SDD would not steer during rotation. Therefore, the tool was pulled at a depth of 1,682m, and the section was completed with a rotary assembly.

Figure 4 shows a log taken of Case Pinelli 1 from 845 m to a depth of 1,845m. The inclination of the complete drilled section is 0.25°. Both the development of rugosity and calliper log data prove that, especially from 845 to 1,200m, the hole was drilled very smoothly and straight. This reduced torque and drag and simplified running casing. The section drilled after the SDD with a rotary assembly resulted in an overgauged hole with rather high rugosity. This positive performance of the SDD as compared to the rotary assembly in terms of the hole condition clearly demonstrates the principal advantage of automatic downhole closed loop steering with expandable stabilizer pads.

3.2.2 SDD Field Performance

This field test was performed to test the new components of the tool under actual drilling conditions. No failures were encountered with the downhole electronics or the hydraulic system. Only minor problems were identified for the electrical supply.

The general performance of the tool was good. Sticking problems during the last run were related to the SDD drilling a full gauged hole, with slight tendency to over gauge, while a full gauge stabilizer was run above the tool. Additionally, the power output of the integral mud motor was most probably reduced through a by pass in the lower rotor section that occurred during the run.

The major purpose of this field test was to investigate the performance of the new components. The basic steering capabilities of such a device had already been successfully confirmed at the KTB well and elsewhere. The formation at Case Pinelli 1 had only a minimum build up tendency. Future field application of the SDD will be carried out to confirm the increased ROP and reduced dog leg severity available when drilling with the Straight Hole Drilling Device.

3.3 RCLS Bidirectional Communication Link

Course corrections from the surface with conventional steerable motor systems are made by switching between rotation and non-rotation of the drill string. A Closed-Loop Drilling System in the current development stage makes it possible to change the pre-programmed course from the surface by direct communication with the downhole tool. This communication link is provided by a mud flow diversion at the surface. Variations in the flow rate will be detected downhole by the turbine driven alternator and further processed as data signals in the electronic assembly.

This type of communication link is completely new in the drilling industry. Therefore, basic field trials have to be performed to gain experience with factors that influence the decoding performance. The following major parameters are expected to influence the downlink capabilities:

- duration of flow rate variation cycles
- rate of change of flow (signal slope shape)
- amount of flow rate separation
- depth of borehole or mud column length
- mud fluid properties

Additionally there is a requirement to keep the disturbance of the drilling process as low as possible. The volume of flow rate change therefore has to be kept low, in order to continue drilling and not to shorten pump life. The purpose of the first field test was to investigate these major influencing factors.

3.3.1 Bidirectional Communication Field Test At Case Pinelli 1

The first field test with the by pass actuator for downlink communication was also performed at Case Pinelli 1 in northern Italy. This tool was run in the 8 1/2" hole section at a depth of 2,500 m. A drilling mud of the FWCIL type with a mud weight of 1.45 kg/dm³ was used. The test itself took 3 hours on the rig. The pump rate was adjusted to 1,700 l/min with continuous drilling while testing. During the test time the rotary assembly drilled 10 m with an average ROP of 3 m/h.

The complete set-up is shown in Figure 5. The downhole tool consisted of a 6 3/4" MWD with turbine driven alternator, mud pulse telemetry system, and logging capabilities. The downhole tool was designed to continuously record the alternator voltage for later examination at the surface. Several series of flow rate variations were transmitted downhole by the actuator.

The data sets were modified by applying different percentages of mud flow diversion; fast, medium and slow, flow changes; and continuous pulse length variation in a wide range. One example of the detected flow rate variation at the surface (pump pressure) and downhole (voltage change) is shown in Figure 6.

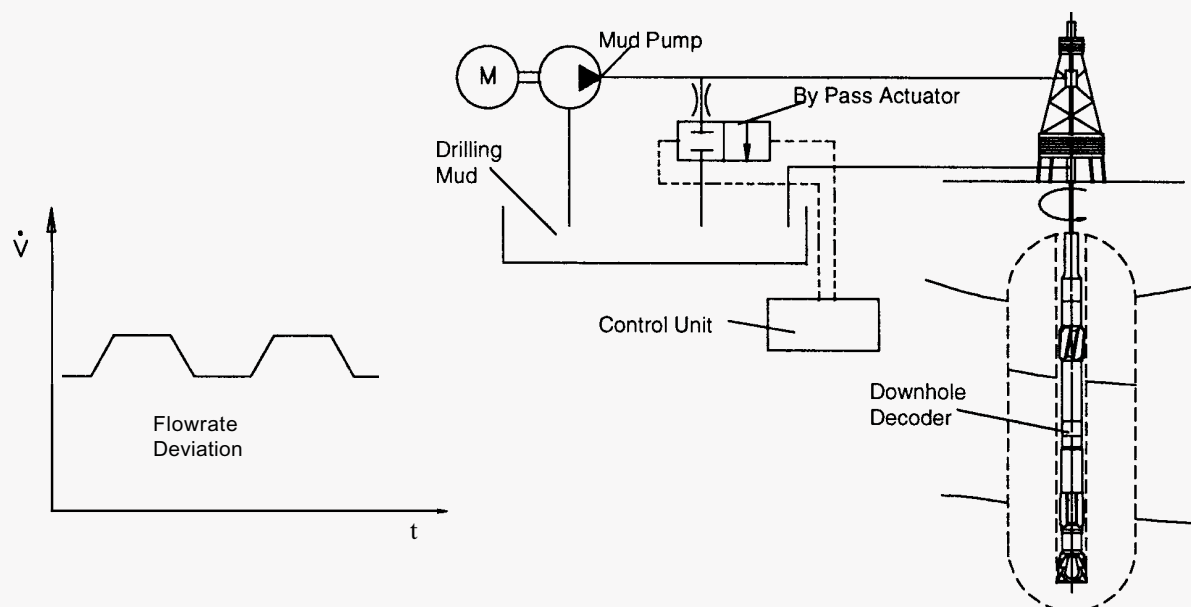


Figure 5: Field test set-up of down-link communication system

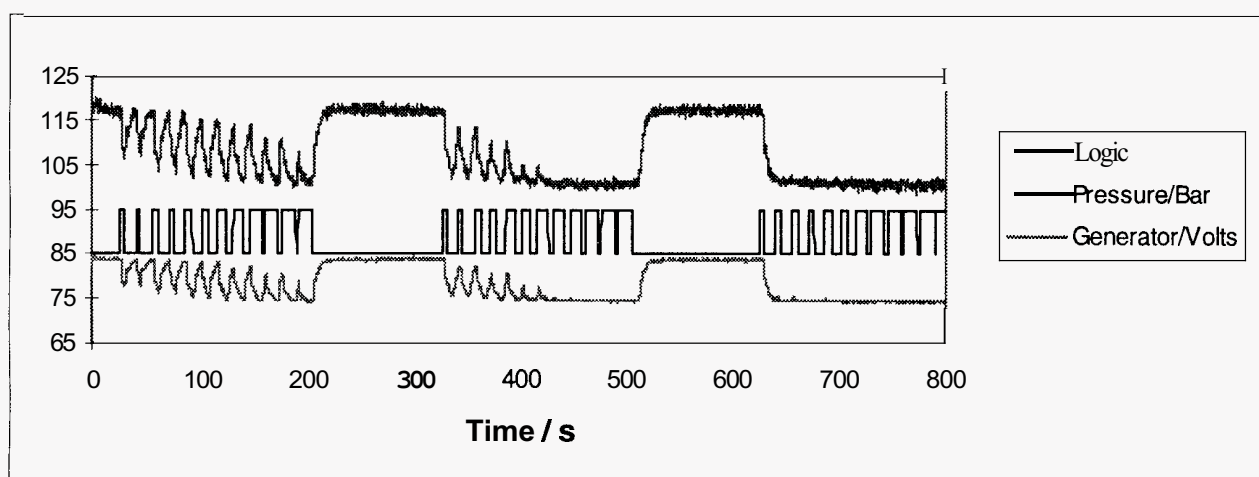


Figure 6: Example of a down-link communication data set

3.3.2 Performance Of Down-Link Communication

The flow rate variations at the surface were clearly detectable downhole. However, a pulse length of less than 5 seconds and medium or slow flow changes were not sufficient for decoding. A pulse length of 10 seconds with fast flow changes, and a flow volume separation of 10%, depending on the borehole depth, seems to be sufficient for a reliable decoding behaviour downhole. The drilling process was not interrupted by activation of the flow rate diverter. The influence of the flow division on the drilling was intended to be minor. In an additional field test a complete set of data will be transmitted downhole, decoded and sent back to the surface as a further check. This test will be carried out at different borehole depths to gain experience of this effect.

The field test at Case Pinelli has proven the communication down-link by means of flow rate variations to be feasible.

4. FUTURE FIELD APPLICATION OF THE CLOSED-LOOP DRILLING SYSTEM

The Rotary Closed Loop System (RCLS) has been designed as a steering system for fully automatic directional drilling. The tool is capable of actively control the borehole course during rotation of

the drill string as well as in the sliding mode. The capability to control a well with a long straight inclined section with rotation of the drill string optimizes ROP, and still provides sufficient cutting transport. At the same time the dog leg severity is minimized through the controlled build up rate.

Drilling in HTHP wells is another major area of application. Because the complete tool is designed for 200°C survival temperature allows for steering in ultra deep formation layers with high static temperatures. Formation evaluation sensors located near the bit provides the capability of geo-steering through the reservoir. Thus, the tool will offer the potential to reach deep reservoirs which are currently hard to explore due to missing HT capabilities of conventional drilling tools.

Major field tests of components have been successfully carried out as described above. A first field test of a complete Rotary Closed Loop System is currently planned in an 8 1/2" hole section during the first half of 1995.

5. ACKNOWLEDGEMENTS

The authors wish to thank especially the personnel involved in laboratory and field testing of the Closed Loop Drilling System.

Also appreciation is extended to AGIP S.p.A. and Baker Hughes INTEQ for their support and permission to publish this paper. Furthermore we would like to thank Western Atlas Wireline Services for providing calliper log data and NLfB/KTB for their permission to use temperature data out of their ultra-deep well operation.

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