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Validation of Advanced Hydraulic Modeling using PWD Data

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Abstract

Using Pressure-While-Drilling (PWD - measurement of downhole annulus pressure and temperaure), an extensive campaign was undertaken on recent North Sea ERD wells to compare measured ECDs and static mud densities with hydraulic model predictions. In addition, the effects of drill pipe rotation and reciprocation have been analysed. The hydraulic model used to calculate downhole pressures predicts fluid downhole density and rheology according to surface properties, pressure and temperature input. Results show that using a Herschel-Bulckley law, ECDs are accurately predicted both in laminar and turbulent regimes. The causes of serious mud losses on two wells have been identified and operationnal procedures were changed to successfully reduce drilling risks.

Introduction

Complex wells have made, the control of downhole pressure whilst drilling more and more important. For instance, in HP/HT wells, the margin between pore and fracturing pressures can be very small, sometimes less than 0.1 SG. In such cases, the precise knowledge of downhole equivalent static density and ECD (Equivalent Circulating Density) are therefore of a strategic importance.

In current Drilling Engineering, static density is adjusted at the surface and ECDs are calculated using hydraulic models. This practice sometimes leads to uncertainties larger than the required precision.

Surface density which is generally measured (using a classical mud balance) in the mud pits or at the mud return is very sensitive to pressure and temperature. Depending on the case, downhole density can be smaller or larger than surface density.

The main input of ECD models are the well geometry (hole, string including tool joints, BHA, bit), mud rheology (calibrated on classical FANN measurements - mainly Bingham, Ostwald or Herschel-Bulckley) and flow rate. These models generally assume that the drill pipe is centred and they rarely take into account pipe vertical movements (reciprocation) and rotation.

There is therefore no doubt that measurement of downhole pressure[1,2] and downhole temperature while drilling should allow to adapt real time the surface mud properties to obtain the required downhole conditions. It can also help in the development and improvement of hydraulics models by providing calibration points.

Apart from the validation of static and ECD models, a real time acquisition of downhole pressure and temperature can also provide valuable information about operational problems such as :

-hole cleaning and optimisation of tripping procedures,
-detection of abnormal thick cakes (reduced hole),
-detection and control of mud losses,
-better optimisation of bit hydraulics,
-better estimation of LOT and FIT,
-better control of downhole mud properties (mud sagging).

The Dunbar field

The Dunbar field is located in the nothern part of the North Sea (Vicking Graben - **Fig. 1a**). The three main targets (below 3500mTVD) are in the middle and bottom Jurassic (respectively Brent and Stafjord reservoirs) and in the Triassic (Lunde reservoir). Depending on the location they can be oil bearing, gas bearing or both. Typical well design, mud weight strategy, and leak of test values are presented in **Fig. 1b**. After batch setting a conductor pipe (26") 80 meters below the sea bed, drilling is initiated in 23 1/2" with a 1.08SG water base mud. The 18 5/8" casing shoe (where a LOT in the range of 1.30SG to 1.35SG is classically obtained) is set in the bottom of these recent (mainly sandy) sediments. The 17 1/2" phase (Oligocene, Eocene and Paleocene) is resumed with a water base mud 1.10SG in the Oligocene then raised to 1.22SG just before reaching the Eocene. Depending on the well profile, deviation at the 13 3/8" casing (set in the top Cretaceous) is classically between 20 deg and 45 deg.

A minimum LOT of 1.70SG is required before beginning the 12 1/4" phase. The latter is drilled with a pseudo oil base mud in the range of 1.50SG to 1.55SG. The 9 5/8" is generally set just above the reservoir section in the Kimmeridge clay (top Jurassic) where a very high LOT value (up to 2.15SG) is obtained. In case of ERD wells, inclination sometimes goes up to 70 deg at the 9 5/8" casing shoe and, to ensure stability of the Kimmeridge, the mud weight has to be raised to 1.65SG. Finally, the reservoirs are drilled in 8 1/2" diametre and covered with a 4 1/2" cemented liner providing full bore access to the 4 1/2" tubing.

We analyse below the results of several PWD runs performed in different wells of The Dunbar field (North Sea) both in 12 1/4" and 8 1/2" sections.

Validation of the DFG model (static conditions)

Sperry sun PWD is a sub approximately 1 m long which can be included in the BHA. Four transducers (2 pressures and 2 temperatures) allow measuring pressure and temperature both in the annulus and in the drill pipe. Depending on the application, the data can be transmitted real time using a MWD or back loaded from a downhole *"death"* memory afterwards.

From a set of raw data, it is quite easy to separate static (no movement) from dynamic data since when adding a stand, all mud and string movements being stopped, the pressure instantaneously drops to its static value. As pointed out in **Fig. 2**, the lower bound corresponds to static conditions whereas the upper bound characterises the ECD (in broad sense).

Parameters affecting static mud density. Numerous parameters affect the static density of a mud but, by far, the most important are the solid content, the pressure and the temperature. Among the latter, pressure and temperature play in opposite direction : density increases with increasing pressure (the volume decreases for a constant mass) but decreases with increasing temperature.

In current drilling practice, mud density is measured at the mud return or in the mud pits by using a conventional mud balance. This measurement is carried out at atmospheric pressure and at a temperature between surface and downhole temperatures. Very often, it is considered in a first approach that pressure and temperature effects compensate so that the surface density is close to the downhole density. However when drilling HP-HT wells, the precise control of downhole pressure becomes of paramount importance because of the narrow margin between pore pressure and fracturing gradient. In that case, downhole density has to be recalculated according to downhole conditions (that is pressure and temperature). Several models allowing to recalculate downhole densities according to downhole pressure and downhole temperature have been developed during the last fifteen years[3,4,5]. We compare below PWD data with the forecasts of the Baroid-DFG program.

Comparaison between actual and calculated densities. The surface data required to run the program (oil/water ratio, salinity, surface density and surface temperature) are provided by the rig mud èngineer whereas, the downhole temperature is directly issued from the PWD itself (**Table 1**). For this range of depths and for the synthetic oil base mud used, the pressure effect is thus larger than the temperature effect. For the 12 1/4" phase, difference between surface and downhole temperatures is in the range of 25 C to 30 C whereas for the 8 1/2" phase it reaches 65 C (the temperature at the mud return is lower for the 8 1/2" phase because the mud flows during a larger time in the raiser - flow of 1900 l/min in 8 1/2" against 2800 l/min in 12 1/4" - 140 m of water depth).

As pointed out in **Fig. 2a** and **2b**, in all cases the downhole density is higher than that measured at the surface. However, according to the smaller temperature effect, the difference is in the range of 0.025SG in 12 1/4" phase, less than 0.015SG in 8 1/2" phase. Both in 12 1/4" and 8 1/2" phases, the mud weight calculated by the DFG program gives satisfactory results but slightly overestimates the actual value.

Validation of the DFG model (dynamic conditions)

The various sources of ECD. The **ECD** (**E**quivalent **C**irculating **D**ensity) is the pressure on the formation exerted by the mud column whilst moving mud or string in the well. ECD has roughly three main origins : **circulation, rotation and reciprocation**. These three effects can occur separately or simultaneously depending on the envisaged operation. For example, rotary drilling implies both circulation and rotation. When reaming a stand circulation, rotation and reciprocation can occur simultaneously. The ECD which results in frictional forces in the well system can be quite difficult to describe mathematically particularly when the string is rotating, moving up or down but also due to its eccentricity in the well. Only the ECD issued from circulation are commonly calculated in drilling practice[6]. Various rheological models exist in the literature.

The most common is the Bingham model which assumes that under a given shear stress (called Yield Point), the viscosity is infinite (**Fig. 3a**). Above this value, the viscosity remains constant and equal to the Plastic Viscosity. More sophisticated models [i.e Ostwald, Herschel-Bulckley[7]] describing the fuid behaviour on a continous manner are particularly useful at low shear rates where the viscosity strongly varies.

Using a FANN35, a general drilling practice is to estimate the parameters of a Bingham model (Yield Point and Plastic Viscosity) with only two experimental points at 300 and 600 RPM. As pointed out on **Fig. 3b**, this simplified methodology overestimates the apparent viscosity at low flow rate. Another technique consists in covering a larger range of shear rate range then estimating the Bingham parameters by a linear regression. In that case, one obtains a better estimation of the Yield Point but, the apparent viscosity at high flow rates is overestimated. Finally, the best fitting is obtained by using the

Herschel-Buckley model (power law with a threshold). Rotation and reciprocation are the other sources of ECD.

Rotation effects can be properly studied using the Taylor's dimensionless number[8,9] which takes into account both the annulus geometry and the drill string rotation[10]. Below a critical value of the Taylor number, the shearing induced by rotation reduces the apparent viscosity and consequently the ECD. By contrast, if the Taylor number exceeds its critical value (condition nearly always fulfilled in drilling applications), the rotation induces additional dissipation and increases the ECD. The trend also depends on the flow rate. For low Reynolds numbers (laminar flow), the ECD strongly increases with rotation whereas at higher flow rate (above critical Reynolds) additional instabilities arising from rotation have a smaller effect. At very high Reynolds numbers, the ECD becomes insensitive to rotation.

Swab and surge pressures are associated with fluid flow caused by running equipment (drill string but also casing) in the hole. For instance, if the drill string is lowered into the well, the drilling fluid moves upward to exit the region being entered by the new iron volume.. As a consequence, the pressure into the well increases. In the same way, the upward movement of the drill string creates a decrease of annulus pressure (swabbing pressure). Since the initial work of Burkhart[11] various models have been proposed in the literature[12,13,14].

To better understand the whole process it is thus necessary to separate the different sources of ECD. For this reason, three different special tests are required : step rate tests (no rotation and no reciprocation), rotation tests (no reciprocation, constant circulation) and finally swab and surge tests (reciprocation, constant circulation, no rotation).

Measured ECDs (circulation only) have then be compared to the forecasts of the the Baroid DFG model. The latter allows calculating ECDs (circulation only) by using a predicted fluid downhole density and rheology according to surface properties, downhole pressure and temperature.

Step rate tests. Step rate tests (no rotation, no reciprocation) have been carried out both in 12 1/4" and 8 1/2" sections of three different Dunbar wells. They consist in measuring (for a given depth) the stabilised annulus pressures versus flow. For each test the mud (synthetic OBM XP07) has been calibrated by using FANN35 measurements. The drill string (only drill collars, 5" and 5 1/2" drill pipes have been considered) are detailed in **Table 2**. The tool joints have been introduced as a cumulated piece of drill string with enlarged outside diameter.

For the first step rate test (12 1/4" section - MW=1.53SG), the measured ECD (in the range of 0.02SG) is a slightly decreasing function of the flow rate. This can possibly be explained by a decrease in viscosity following the shearing of the fluid at high flow rate through the bit nozzles (above 2500 l/min). As pointed out on **Fig. 4a**, measured ECD fits quite well with the calculated ECD when using the Herschel-Bulckley's model. If the secant Bingham model (linear regression through the 8 FANN values) remains quite satisfactory, the results issued from the tangent Bingham model (rheogram with only two FANN values 300 and 600 RPM) give out of range results. Finally, calculations show that the flow regime remains laminar for the covered range of flow rates even in the most reduced section of the drill string/annulus system (drill collars and tool joints of the 5.5" drill pipes).

In the 8 1/2" section, two step rate tests have been carried out. They essentially differ by the drill string (5.5"+5" DP for the first one, only 5" for the second one - see **Table 2**).

For the first case (5"+5.5"DP - **Fig. 4b** - black squares) and at low flow rate (1000 to 1500 l/min), the regime remains laminar and the excess ECDs with respect to the static density (MW=1.62SG) are in the range of 0.07SG to 0.10 SG. However, above 1500 l/min, a sharp increase in ECD is observed due to the appearance of turbulence in the annulus. At 2000 l/min, ECD (only due to circulation we may recall), reaches 1.78SG (0.16SG excess with respect to the static density). As pointed out on **Fig. 4b**, the Herschel Buckley model fits very well the experimental data and catch remarkably the transition between turbulent and laminar regimes.

For the second case (only 5"DP - **Fig. 4b**), the measured ECD (clear squares) are systematically below those of the first test. Putting the two tests in the same conditions (the static mud weight was higher for test 1 -1.62SG against 1.61SG- and the drain was longer - 4317 mMD against 3765 mMD), the difference in ECD remains small under 1500 l/min, but strongly increases above 1500 l/min, the main difference being that with 5" drill pipes, the flow remains laminar over the whole range. Using Herschel-Buckley model, the calculated ECD slightly overestimates the measured values but the order of magnitude remains very satisfactory.

Looking in further details at the repartition of the pressure drop along the drill string (Test 1 - **Fig. 5**), it is obvious that turbulent regime only prevails face to the tool joints of the 5 1/2" drill pipes (7 1/2" outside diameter in a 8 1/2" well). Above 1500 l/min (the current flow in 8 1/2" section is 1900 l/min) the pressure drop due to these 5 1/2" tool joints (only 2 % of the total length) represents more than 50 % of the total pressure drop. By contrast, when using only 5" drill pipes (6 5/8" OD tool joints), the flow regime remains laminar over the whole range of flow rates.

Rotation tests. A first serie of rotation tests have been performed at constant flow rate for 12 1/4" (2700 l/min) and 8 1/2" (1700 l/min) sections. In both cases, the drill string was a mixed 5"+5 1/2".

As pointed out in **Fig. 6a**, the effect which remains very small in 12 1/4" phase (less than 0.01SG excess ECD for 200 RPM) reaches for the same rotation speed 0.04SG in the 8 1/2" section. According to the experimental results, the ECD increases roughly linearly versus the rotation speed. We should note that in reduced holes[15] where the effect becomes of paramount importance, rotation can possibly be used to monitor gas kicks.

Combined circulation/rotation tests. Rotation tests (50, 100, 150 and 200 RPM) have also been carried out at different flow rates (5" drill pipes only - 8 1/2" phase). The results which are presented on **Fig. 6b** show that flow rate does not affect the trend (no obvious decrease of the rotation effect at higher flow rate - 2000l/min). They are consistent with the theory (above critical Taylor number but below critical Reynolds number, ECD increases with rotation speed).

Surge tests. Results of surge tests at different running speeds (8 1/2" - mixed 5"+5 1/2") are presented on **Fig.** 7. In that specific case the excess of ECD induced by surging (the tests were performed with a flow rate equal to 1700 l/min) at 0.6 m/sec reaches 0.14SG. The intensity of swab and surge pressures (for a same pipe speed they are normally equal in intensity but opposite in sign) depends on numerous parameters (drilling fluid, rheology, pipe running speed, well, drill pipe and tool joints diameters, BHA...).

More in depth analysis are currently investigated to calibrate rotation and surge models.

Further applications of PWD

The interest of PWD is not only the measurement of static density and ECD. The knowledge of real time downhole pressure can help to identify earlier potential problems like mud losses, pack-off or stuck pipe. Furthermore, the measurement of drill pipe pressure can be used to better estimate pressure drop through the bit for further hydraulics optimisation. Two of these specific applications are analysed below.

Mud losses in a depleted reservoir. For obvious equilibrium reasons, fracturing pressures decreases with depletion. In some cases, the ratio reaches 0.8 (1 bar of decrease in reservoir pressure corresponds 0.8 bars decrease in fracturing pressure)[16]. Consequently, risk of massive losses through a hydraulic fracturing process strongly increases in depleted reservoirs.

The 8 1/2" phase of the considered well has been characterised by severe losses when entering into the Brent formation (top Brent at 3550mTVD). Drilling was initiated with a static mud weight equal to 1.62SG, a flow rate approximately equal to 1950 l/min and a rotation speed of 200 RPM. The resulting ECD during this first phase was in the range of 1.82SG (**Fig. 8a**). At the end of the considered stand, two quick reciprocation cycles were performed. As pointed out on **Fig. 8b**, the surge pressure resulting from the first cycle reaches in terms of ECD 1.87SG. After adding a stand, the circulation was resumed (2000 l/min) but the ECD instantaneously dropped to 1.72SG and large mud losses (1000 l/min - phase 2) initiated. The flow rate was then reduced to 1500 l/min but the losses did not stop (766 l/min during phase 3). During phase 3, the ECD stabilised at 1.71 SG. 3 times, fluid was supplied to the active pit. A total of 25 m^3 of POBM was lost during less than 1 hour. According to the PWD results, the origin of the losses is easily explained by the very high surge pressure (1.87 SG) associated with the first reciprocation cycle. The latter exceeding the leak off limit in the Brent, a hydraulic fracture initiates. Given the high brittleness of the rock, this first peak can be considered as a breakdown pressure. When the flow is resumed (same rate), the fracture propagates at a much lower value (reopening pressure). The difference between breakdown (1.87SG) and reopening pressures (1.72SG) is due to the reduced rock strength (cohesion), lost after the first cycle.

The hydraulic process can be better understood if the characteristic points corresponding to phases 1, 2 and 3 are integrated in the ECD/flow diagram[1] of **Fig. 9**. The latter, being built only with circulation as an active source of ECD, the rotation effect (see **Fig. 6a** - in the range of 0.035) has first to be eliminated from the raw data (points 1, 2 and 3 are shifted downwards towards 1', 2', 3' - **Fig. 9**). After this correction, 1' (no losses) integrates quite well the flow data whereas points 2' and 3' (large losses) remain out of range. However, if the loss rates (1000 l/min for phase 2 and 766 l/min for phase 3) are subtracted from the total rate (points 2' and 3' move to 2" and 3"), the two abnormal points perfectly fit with the results issued from the step rate test. In other words, the ECD measured after initiation of losses corresponds to the actual annulus flow rate (total flow minus losses) and not to the total flow as in the virgin case. From large losses can eventually results a bad hole cleaning since only part of the flow rate is used to remove the cuttings.

Pressure drop through the bit. The knowledge of both drill pipe and annulus pressures allows estimating the pressure drop through the bit. In certain cases, when the PWD is located above some downhole tools (MWD for instance) through which the pressure drop is not properly known, it is never easy to extract the bit from the rest of the BHA. However, for the 8 1/2" phase, the PWD being located close from the bottom hole (no motor, no MWD), pressure drop through the bit can be directly estimated by subtracting drill pipe and annulus pressures.

As pointed out on **Fig. 10** and for a large range of flow rates (between 1000 l/min and 2000 l/min), there is a quite good correlation between PWD data and those predicted by the Bernouilli's formula (using a 0.95 correction factor).

Conclusions

Three PWD runs have been carried out successfully while drilling 12 1/4" section and 8 1/2" section of several Dunbar wells. From a general view point, very reliable data have been obtained.

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[1] The black squares of **Fig. 9** are similar to those of **Fig. 4b**.

The downhole static density is always larger than the surface density (0.02 to 0.03 SG excess can be considered as an average). Using surface values issued from the mud report and PWD measured temperature, DFG program predicts quite well the downhole static density (0.01 SG maximum difference) and justifies that for this range of depths the pressure effect generally dominates the temperature effect.

The XP07 POBM has been calibrated using classical FANN35 values. The fluid *"follows"* very well the Herschel-Buckley's model (power law+threshold) which describes properly its behaviour at low shear rate. However, Bingham model overestimates the Yield Point and consequently the apparent viscosity at low flow rate both in its tangent (using only measurements at 300 and 600 RPM) and secant (linear regression through 7 FANN values) versions.

In the 12 1/4" phase, the ECDs due to circulation are in the range of 0.02 to 0.03 SG. Among the various ECD models, the Herschel-Buckley fits quite well with the experimental data while Bingham model which predicts a too high viscosity clearly overestimates the ECD. In 8 1/2" phase, the very high ECDs (1.79 for a 1.62 static mud weight) observed during the first test are clearly due to the tool joints of the 5 1/2" drill pipes. Once more, the Herschel-Buckley model predicts remarkably the downhole pressure and catch very well the laminar/turbulent transition located face to the tool joints of the 5 1/2" drill pipes.

Rotation and reciprocation have only a slight impact on ECD in the 12 1/4" phase (less than 0.01SG at 200 RPM). However, in 8 1/2" phase the effect of rotation reaches 0.04SG at 200 RPM and the surge effect 0.14SG at 0.6 m/sec. No calculation of rotation and surge effects have been carried out in the scope of this study.

Several specific applications have also been studied. The PWD has been used to analyse mud losses experienced when entering the depleted Brent. Losses occurred following a strong surge peak (1.87 SG - initiation of a hydraulic fracture) and were followed by an instantaneous drop in ECD. A detailed analysis of the data have showed that after the losses have initiated only part of the flow rate (total flow rate minus losses) was "seen" by the PWD. The PWD has also been used to validate the pressure drop through the bit. The classical Bernouilli's law used in current drilling packages fits quite well with the PWD data.

Acknowledgement

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Phase	TMD	TVD	Tsurf	BHT
	m	m	C	C
12 1/4"	2840	2478	50	73
12 1/4"	3015	2599	55	81
12 1/4"	3200	2692	56	83
8 1/2"	4450	3696	43	104
8 1/2"	4589	3809	39	108

Table 1 - Measured temperature (circulating conditions)

	12 1/4"		8 1/2" (1st)		8 1/2"
Section	OD	Length	OD	Length	Length
	in	m	in	m	m
DP 5.5	5.5	860	5.5	1741	▨
TJ 5.5	7.5	82	7.5	166	▨
DP 5	5	1504	5	1979	3196
TJ 5	6.625	57	6.625	177	306
HW1	6.625	155	5	198	192
TJ	8	9	6.5	11	10
DC	8	58	6.5	43	48

Table 2 Composition of the drill string (step rate tests)

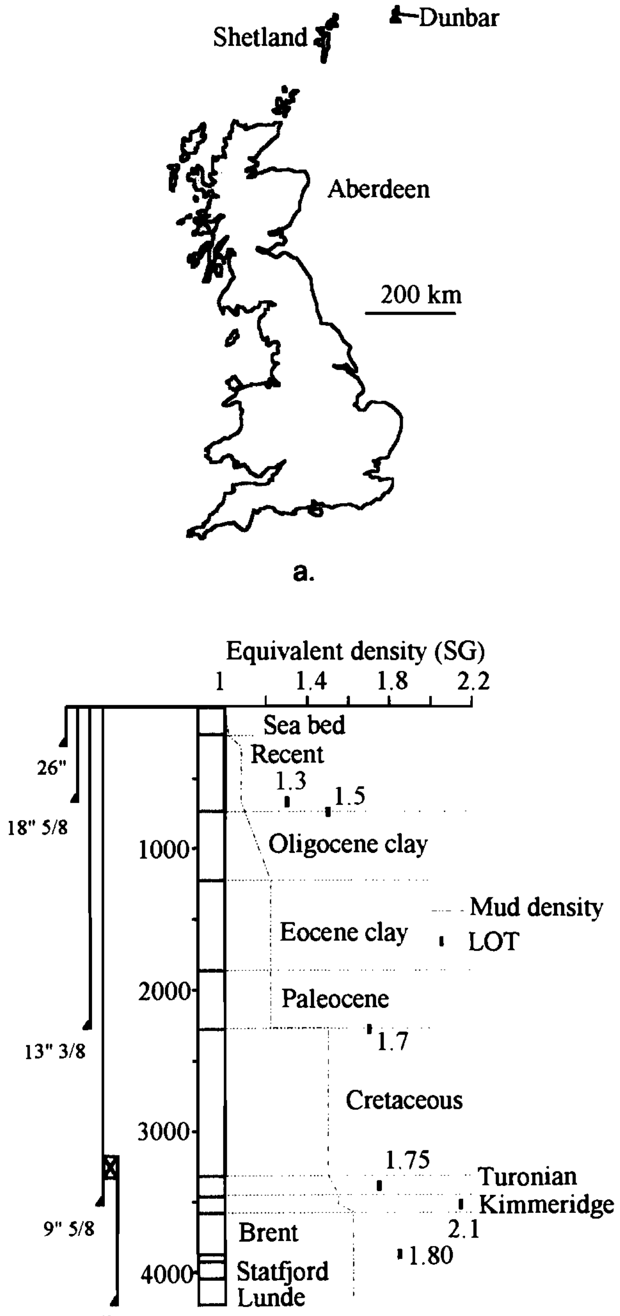


Fig. 1 a - Location of the Dunbar field
b. Typical stratigraphic column and casing points

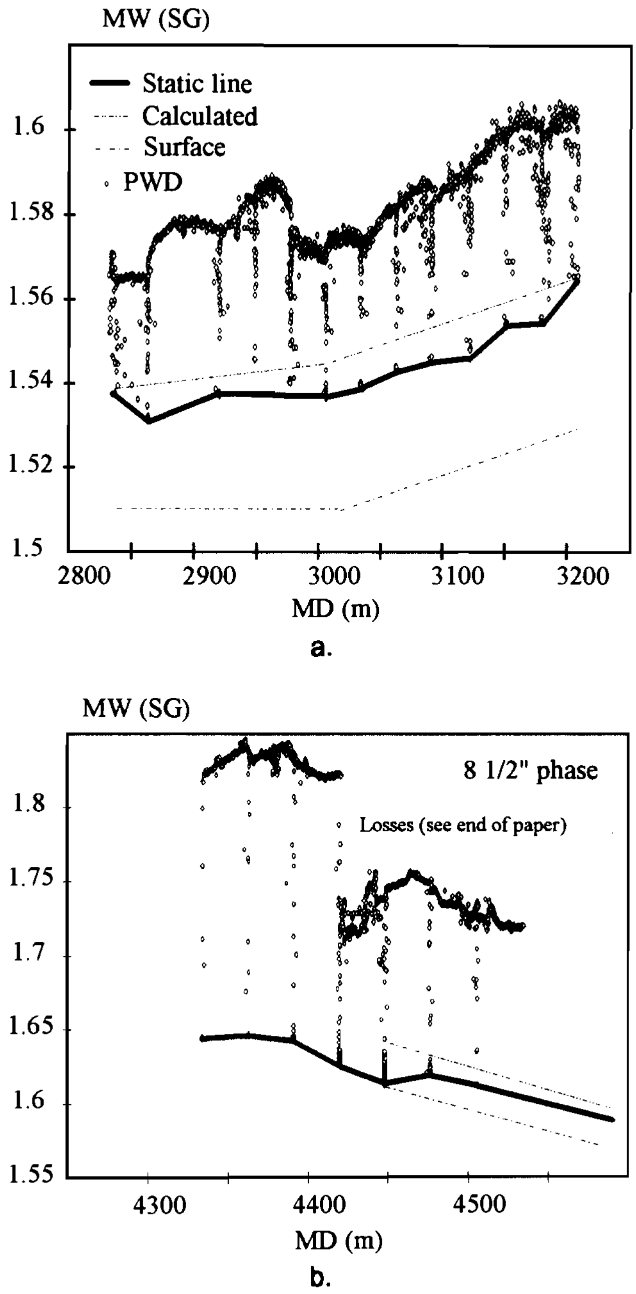
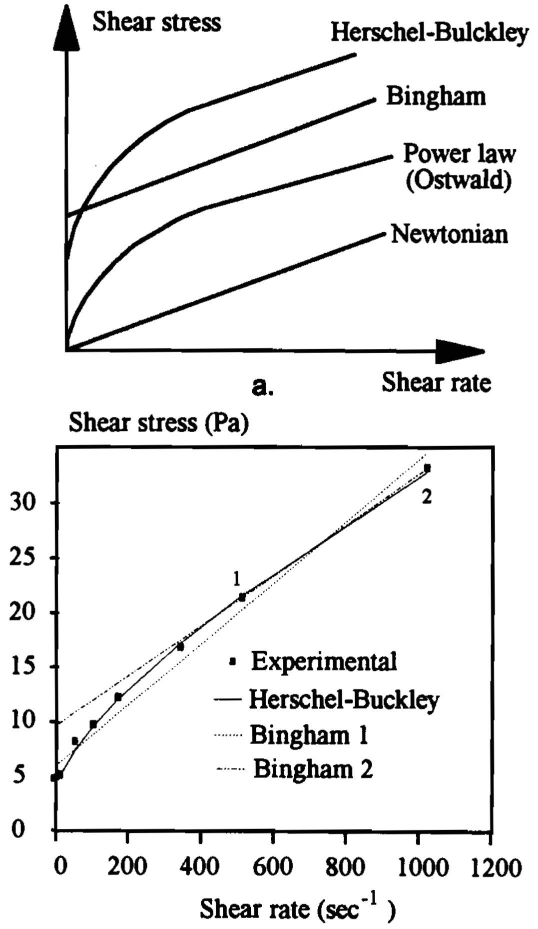


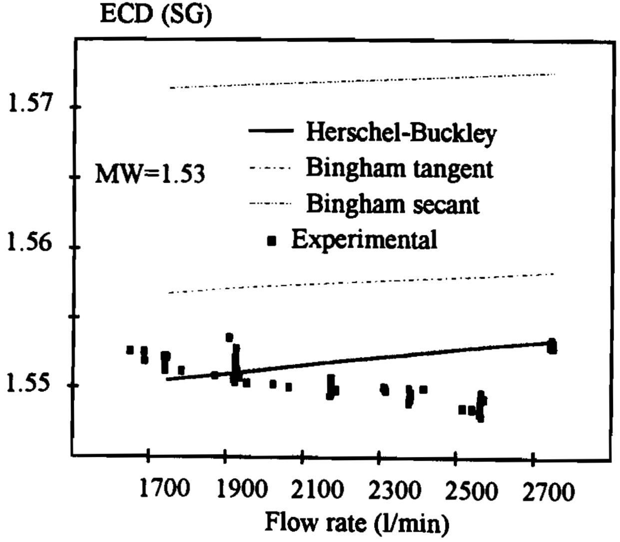
Fig. 2 - Comparison of static mud density issued from PWD and those calculated from DFG program a. 12 1/4" phase and b. 8 1/2" phase.



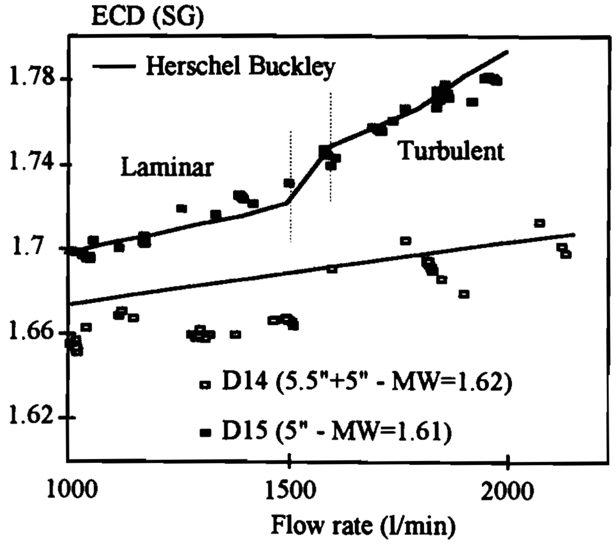
a.

b.

Fig. 3 - a Newtonian, Bingham and power law.
b. Example of rheogram obtained with a coaxial viscometer (POBM- XP07)



a.



b.

Fig. 4 - Comparaison of measured and calculatedECDs
a. 12 1/4" phase
b. 8 1/2" phase

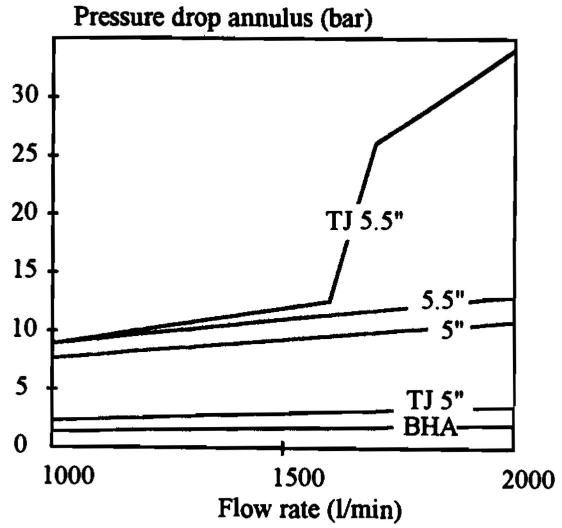
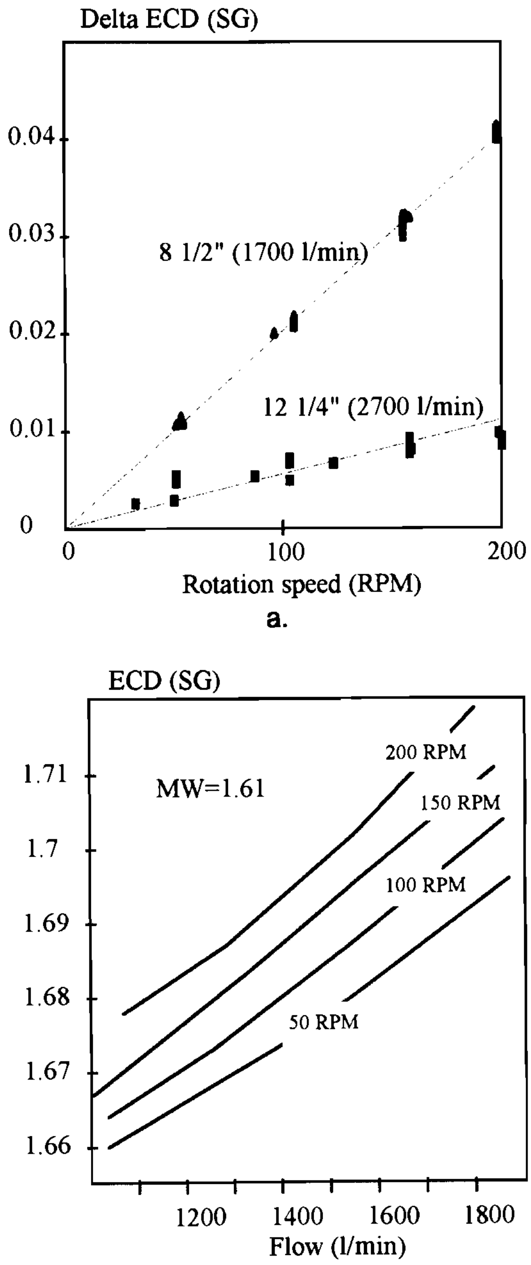


Fig. 5 - Effect of 5 1/2" tool joints on the ECD (8 1/2" section - Test 1).



a.

b.

Fig. 6 - Effect of rotation on ECD
a. Comparaison between 12 1/4" and 8 1/2" hole b. Combined effect rotation/flow rate.

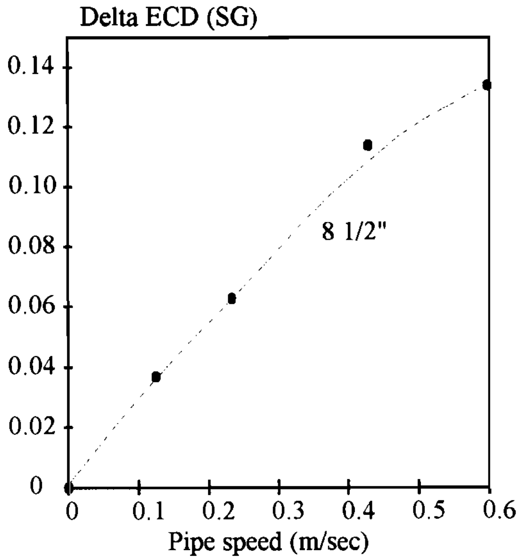


Fig 7 - Excess of ECD due to reciprocation (8 1/2" phase only)

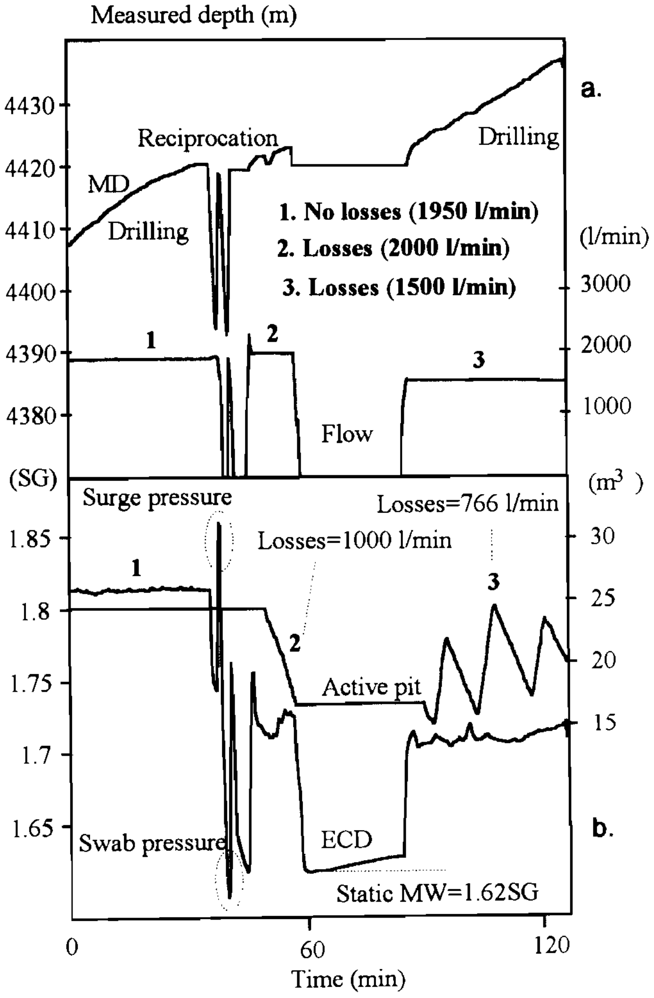


Fig. 8- Losses in the Brent (8 1/2" phase)

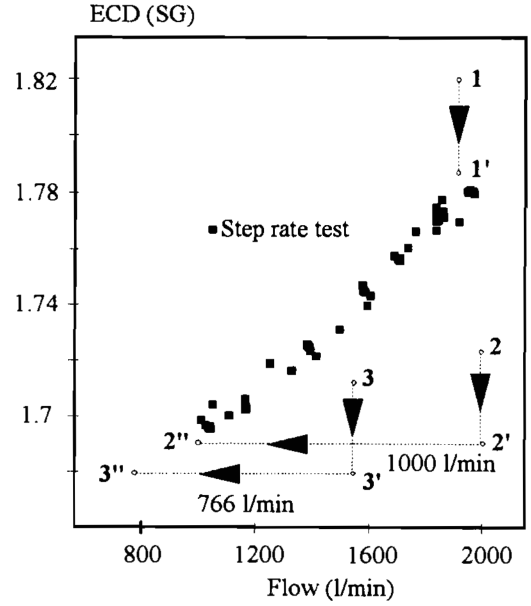


Fig 9 - Annulus flow diagram

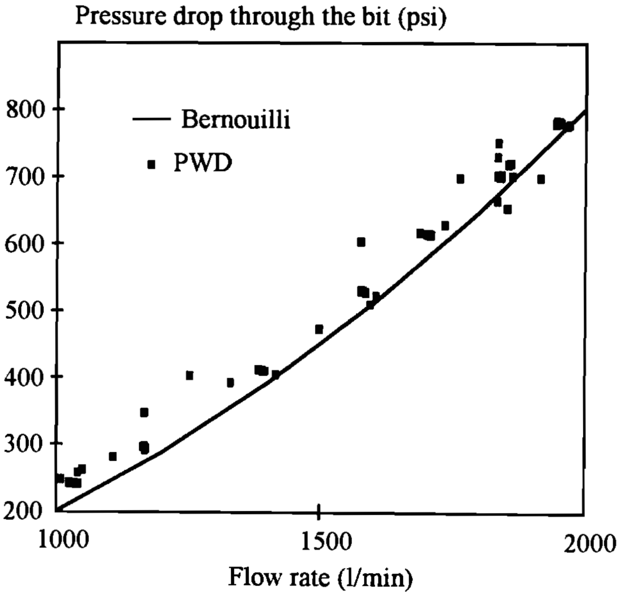


Fig. 10 Pressure drop through a QP19L (Security-DBS) bit (8 1/2" phase of a Dunbar well - North Sea).