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# MASTER THESIS

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Evaluation and comparison of drilling parameters and hardware used to improve cuttings transport and limit the thickness of cuttings accumulations in high angle and horizontal well bore sections

A thesis  
submitted to the Mining University of Leoben  
in partial fulfilment of the requirements for the  
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By  
Trésor SONWA LONTSI B.Sc

**Supervised by:** Univ.-Prof.-Dipl.-Ing. -Dr.-mont. Gerhard THONHAUSER  
Dipl.-Ing. Johann SPRINGER

**Approval date:** June 2008

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# AFFIDAVIT

I declare herewith that this thesis is entirely my own work and that where any material could be construed as the work of others, it is fully quoted and referenced.

Tresor Sonwa Lontsi

Leoben, June 2008/ Austri

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# **DEDICATION**

This Thesis is dedicated to my parents LONTSI Emmanuel and SOKING Pauline and my brothers and sister for all their support and encouragement throughout the years. And this thesis is dedicated also to my fiancée, Cathy PETEGA.

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# 1 Abstract

The increase in the demand of energy worldwide has resulted in the expansion of the drilling activities, particularly in deviated and extended reach wells. One of the major challenge while drilling these type of wells is the transport of cuttings in inclined section of the annulus when angle exceeds 30° (degrees) of inclination. Inefficient hole cleaning will cause cuttings bed formation, which if not handle lead to problems such as premature bit wear, high torque and drag, high non-productive time and drilling cost, stuck pipe, lost of the well.

In the inclined wells, cuttings settle vertically due to the gravitational force, but the fluid velocity has a reduced vertical component. Drilled cuttings settle than quickly in the low side of annulus and have less distance to travel before they hit the borehole wall. Here the velocities are negligible and particles tend to deposit in the annulus leading to the formation of cuttings bed. The first approach when faced with such a situation is to optimize the controllable drilling parameters such as flow rate or annular velocity, wellbore inclination, mud properties, drill string rotation and rate of penetration. It is showed in this work that for the same drilling condition, the directional wells require significantly higher flow rate which is the most important operating parameter than the vertical ones in order to remove or prevent the cuttings bed formation. However for many cases the required flow rates are not always practically achievable due to pump limitations and borehole washouts. The positive effect of drill pipe rotation on the cuttings transport is not always applicable because of the sliding mode while drilling which make things more complex. Theoretically, the rate of penetration is usually kept on the highest possible value mostly because of economics reasons

The second part of this thesis deals with the economic evaluation and performance analysis of wells drilled with specific drill strings components such as Hydroclean (HDP) in comparison to the Standard Drill Pipe (SDP). Two sections, 12 ¼” and 8 ½” of three wells (well P, well G, well H) drilled with SDP and one well C drilled with HDP were analyzed. The well G and H shows a significant high NPT due to poor hole cleaning which increase the drilling cost and the well C shows less NPT. The result led to the conclusion that with good drilling practice and HDP, the drilling time and cost in deviated can be reduced but not for all the wells. Alternative mechanical cuttings removal aids such as Cuttings Bed Impellers, Helical Drill Pipe and their characteristics were also highlighted in this work.

## Zusammenfassung

Der Anstieg des weltweiten Energiebedarfs hat zu einer erheblichen Zunahme der Bohraktivitäten im allgemeinen und von geneigten und weitreichenden horizontalen Bohrungen im besonderen geführt.

Beim Abteufen dieser Bohrungen ist es relativ schwierig, den Bohrkleinaustrag in mehr als dreißig Grad gegen die Vertikale geneigten Bohrlochsabschnitten sicherzustellen. Wird die Lösung dieser Aufgabe nicht ernst genug genommen, kann es infolge nicht ausreichender Bohrlochsreinigung zur Ausbildung von "Cuttingsbett" genannten Ablagerung von Bohrgut an der Bohrlochsunterseite kommen, die ohne rasche und zielführende Gegenmassnahmen zu Problemen wie vorzeitigem Meißelverschleiß, einem hohen Anteil an nicht produktiver Zeit und dadurch erhöhten Bohrkosten, hohen Drehmomenten und Zuglasten, Festwerden des Bohrstranges und zum Verlust eines bereits durchteuften Bohrabschnitts oder im Extremfall der ganzen Bohrung führen.

In geneigten Bohrungen sinkt das Bohrklein unter den Einfluß der Schwerkraft vertikal ab, während die Vertikalkomponente des Bohrspülungsströmungsgeschwindigkeit abfällt. Cuttings erreichen sich schon nach einer kurzen Wegstrecke die Bohrlochsunterseite. Zwischen Bohrlochswand und Bohrstrang, wo die Geschwindigkeit der Bohrspülung gegen null sinkt wird das sich ablagernde Bohrgut nicht mehr weiterbewegt und bildet ein sogenanntes "Cuttingsbett". Seit diesem Zusammenhang erkannt wurde, versucht man verschiedenen Einflußgrößen derart zu verändern, daß dadurch der Cuttistransport verbessert wird. Gelegentlich wurde der Bohrlochsverlauf geändert um nicht in den Bereich kritischer Bohrlochsneigungen zu gelangen. Es wurden Pumpraten und damit die Ringraumströmungsgeschwindigkeiten erhöht, die Spülungseigenschaften verändert, die Drehzahl des Bohrstranges angehoben und / oder der Bohrfortschritt reduziert um die je Zeiteinheit anfallende Bohrgutmenge in beherrschbaren Grenzen zu halten.

Höhere Fließgeschwindigkeiten der Bohrspülung erodieren abgelagerte oder sich ablagernde Cuttingsbette und stellen somit die wichtigste Einflußgröße zur Verbesserung des Bohrkleinaustrags in stark geneigten Bohrabschnitten dar. Die erforderlichen Fließgeschwindigkeiten sind aber, wie in dieser Arbeit aufgezeigt wird, wesentlich höher als sie für vertikale Bohrlochsabschnitte erforderlich wären. In vielen Fällen kommen diese Pumpraten wegen Limitationen der vorhandenen Spülpumpen oder wegen des Risikos von

BohrlochsAuswaschungen nicht in Frage. Der positive Einfluss der erhöhten Bohrstrangdrehzahl kommt z.B. während des Gleidmodus von Richtbohrungen mit Spülungsmotoren nicht zum Tragen. Aus wirtschaftlichen Gründen wäre es außerdem wünschenswert den Bohrfortschritt nicht zu reduzieren sondern so schnell wie möglich zu bohren.

Der zweite Teil dieser Diplomarbeit beschäftigt sich mit der technischen und wirtschaftlichen Bewertung von in geneigten Bohrlochsabschnitten eingestezten speziellen Bohrstrangkomponenten wie das von Vallourec Mannesmann angebotene HydroClean im Vergleich zu herkömmlichem Bohrgestänge.

Die 12-1/4" und 8-1/2" Abschnitte dreier mit konventionellem Bohrgestänge abgeteuften Bohrungen ("well P", "well G", "well H"), und die unter Verwendung von HydroClean gebohrten Bohrung "well C" wurden miteinander verglichen. Als Folge schlechter Bohrlochsreinigung hatten die Bohrungen ("well G", "well H") einen signifikant höheren Anteil an nicht produktiver Zeit (NPT) als die Bohrung "well C". Das Ergebniss meiner Diplomarbeit führte zum Schluß dass mit guter Bohren-Praxis und HDP, der bohrenden Zeit und kosten in geneigten Bohrungen kann reduziert werden aber nicht für alle Bohrlöcher.

Auf alternative mechanische Hilfsmittel zur Verbesserung des Bohrgutaustrags wie "Cuttings Bed Impeller" und spiralig verformtes Bohrgesänge und deren Charakteristik wurde in diesem Werk ebenfalls hingewiesen.

## 2 Introduction

As the need for directional and horizontal well has increased, the interest in cuttings transport has changed from the vertical to the inclined and horizontal well geometries during the last decades. When a well is drilled, it is always necessary to transport the cuttings up to the surface. With increasing measured depths and horizontal displacements in deviated wells, good hole cleaning remains one of the major challenges in the Oil and Gas Industry. To this end, fluid is pumped down through the centre of the drill pipe, through nozzles in the drill bit, and back up to the surface through the annular gap between the drill pipe and the drilled hole. The drilling fluid is viscous, non-Newtonian (shear-thinning), and will typically have a gel strength. The flow up the annulus might be laminar, or it might be turbulent, depending on the situation.

It has been recognized from researchers and from laboratories test<sup>2,14,16,23</sup> that removal of the cuttings during drilling of high inclined wells in the range of 30-60° and horizontal wells presents special problems which affect the cost, time, and the quality of the directional drilled wells drastically. Poor hole cleaning can result to expensive problems like stuck pipe, lost circulation, slow rate of penetration, high torque and drag, poor cement jobs and some other effects. If the situation is not handled at the right time and properly, these problems can lead to a loss of a well. Brandley et al. stated that the combined stuck pipe cost of the industry is in a range between 100 to more than 500 millions dollars per year<sup>3</sup>. Usually, to avoid this problem in the field, drilling operators often include such practice as “washing and reaming” wherein the drilling fluid is circulated and the drill string is rotated as the bit is lowered into the wellbore, and “back-reaming” wherein the drilling fluid is circulated and the drill string is rotated as the bit is pull out of hole. Others Operations like “wiper trips” and pumping out of the hole are often performed to attempt to control the cuttings accumulation in the wellbore. All these operations required time and can significantly increased the cost of the drilling in deviated and horizontal wells.

As a result, the search for more effective drill string components like Hydroclean, Cuttings Bed Impellers, Helical Drill Pipe are needed to improve directional and horizontal borehole cleaning. These drill string components will maximize the mechanical cuttings agitation process of the cuttings bed which will probably increase the cuttings transport.

Having understood the drilling parameters and their interactions, the aim of this thesis will be to establish an economic and technical comparison of the mechanical removal cuttings aids used to limit the thickness of cuttings accumulation in deviated and horizontal wells.

## 3 Objectives and structure of the Thesis

### 3.1 Objectives

The objectives of this thesis are the following:

Determine from literature the major operating parameters influencing the transport of the cuttings while drilling deviated and horizontal wellbore.

Determine from previous work, the section of cuttings bed problems in the wellbore and estimate based on mathematical equation the minimum flow rate required to keep the wellbore clean during the drilling operation.

Estimate based on the end of the well drilling report the non-productive time due to poor hole cleaning while drilling with Standard Drill Pipe in deviated part of the wellbore above 30° of inclination.

Having given the features of the Hydroclean Drill Pipe, the non-productive time due to poor hole cleaning while drilling with this hardware will be determine and analyse.

Based on real field data of four wells, an economic evaluation while drilling with both drill pipes will be made and compared.

Alternative mechanical cuttings transport aids to overcome cuttings accumulation in high inclined and horizontal wells such as Cuttings Bed Impellers and Helical Drill Pipe (still not commercial) will be mentioned and developed in this work.

## 3.2 Structure of the thesis

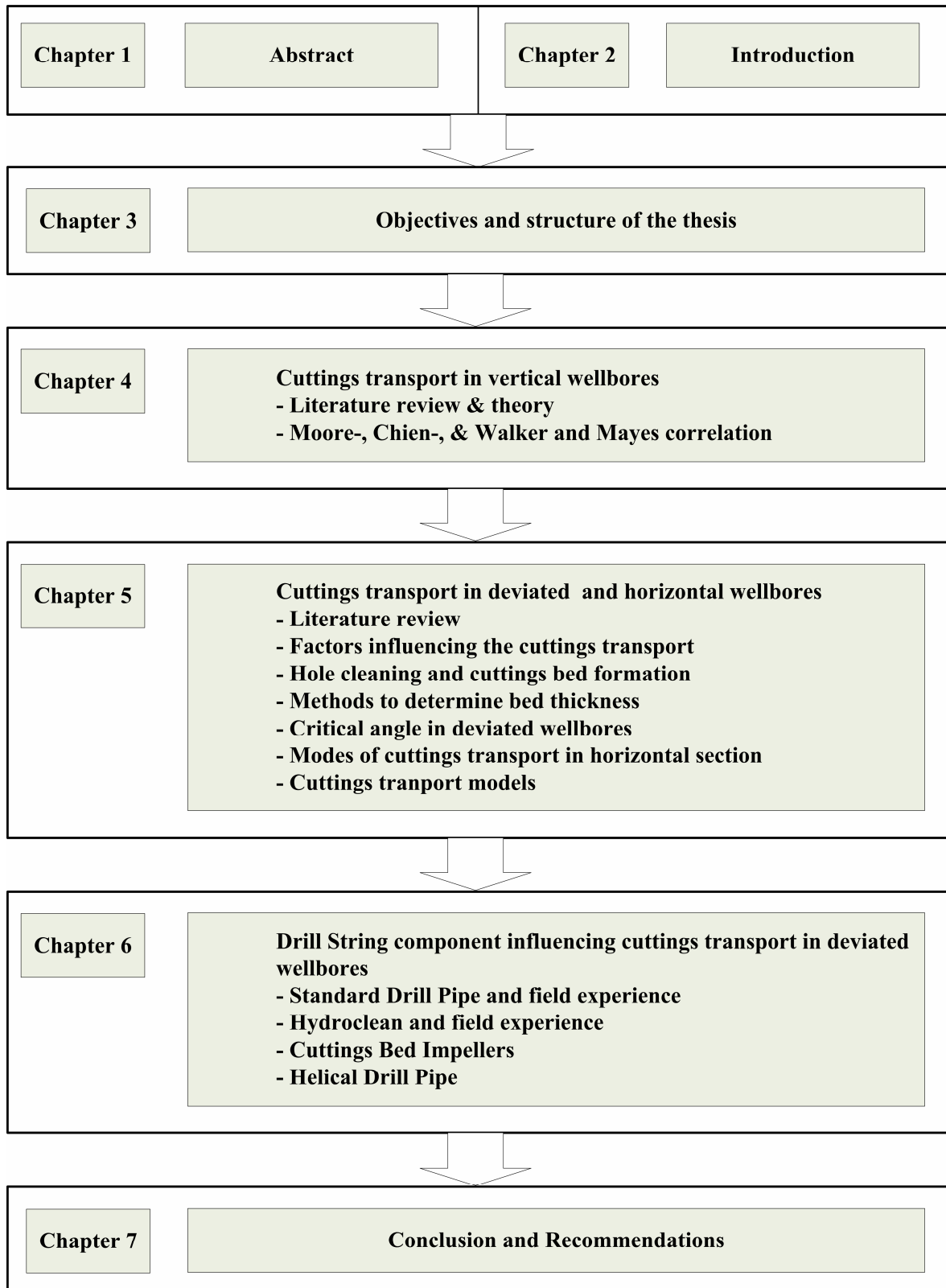


Figure 1: Structure of the thesis



## 4 Cuttings transport in vertical wellbores

Cleaning the hole is one of the most important objectives of the drilling fluid during the drilling process. This problem is since the early seventy a topic for researchers in the oilfield industries and at universities.

### 4.1 Literature Review

Zeidler et al (1972) conducted one of the pioneering studies in cutting transport. A laboratory setup consisting of 15 feet long, 3.5 inches inner diameter glass tube was employed to study and correlate the settling velocity of particles based on measurable properties. This correlation was based on the drag coefficient-Reynolds number plots. He derives correlations for drilled particle recovery fractions and studies the effects of various parameters such as flow rate, fluid viscosity and inner pipe rotation on transport mechanisms. It was observed by the author that turbulent flow and drill pipe rotation increased the cutting transport rate.

### 4.2 Theory behind the cuttings transport in vertical wells

In vertical and near vertical wells from  $0^\circ$  to  $30^\circ$  inclination<sup>1,8,22</sup>, the transport of the cuttings generated at the bit is not very complex. In this case the cuttings particles generally remain in suspension the whole time they are in the wellbore. The drilling fluid rising from the bottom of the well must carry the drilled cuttings to the surface. Under the influence of the gravity, these cuttings tend to settle. This phenomenon is defined as the slip velocity. Slip velocity depends upon the density and the viscosity of the mud. It is necessary to analyze the cuttings transport mechanism and the factors that affect cuttings transport in the wellbore such as: fluid velocity in the annulus as function of annular area and pumping rate, rate of penetration of the drill bit, drill pipe rotation speed, hole geometry, drilling fluid rheology, and average cutting diameter, to increase the cuttings removal.

There are mainly three effects which result from the cuttings transport in the vertical section of the well, namely:

- The slip velocity  $V_{slip}$ , the critical velocity wherein cuttings start to be deposited
- The cuttings transport velocity  $V_{cut}$ , is the velocity of fallen cuttings
- The minimum velocity  $V_{min}$  is the sum of the slip velocity and cuttings transport velocity where cuttings can be lifted to the surface.

The annular velocity, the cuttings size, and the viscosity of the drilling fluid are the most important parameters when drilling a vertical well. A drilled cutting that must be carried out have four forces acting on it:

- A downward gravitational force
- An upward buoyant force due to the cutting being immersed in the drilling fluid
- A drag force parallel to the direction of the mud flow due to the mud flowing around the cuttings particle
- A lift force perpendicular to the direction of the mud flow also due to the mud flowing around the cutting particle.

Many hole problems in the verticals wells occur due to excessive ROP (Rate of Penetration) overloading the annulus. Overloading the annulus with cuttings can lead to a number of problems. In deepwater, where the fracture gradients are typically low, a high ROP and large concentration of cuttings can result in an Equivalent Circulating Density (ECD) greater than the fracture gradient, leading to formation breakdown and loss of fluid. A second problem that can be associated with high ROP is cuttings settling around the BHA (Bottom Hole Assembly) during the connections. If the concentration of cuttings is high, the settled cuttings can lead to pack-off around the BHA during the connection and subsequent breakdown the formation when drilling start.

#### **4.2.1 Particle settling mechanisms**

The hole cleaning process must counteract gravitational forces acting on cuttings settling during both the dynamic and static periods. In the vertical wells the basic settling mechanism can occur, a process called free settling.

Free settling occurs when the particle falls through a fluid without interference of other particles or container walls. The “terminal settling velocity” depends on the density difference between fluid and particle, fluid rheology, particle size and shape, and the flow regime around the particle. But in case of a turbulent flow, the settling velocity is

independent of the rheology of the fluid. In laminar flow around the particle, Stokes' law applies for free settling, and was developed for spherical particles, Newtonian fluid and non-Newtonian fluid.

Stokes' law<sup>1</sup> can be used for the Newtonian fluid and the equation is expressed as follow:

$$V_{slip} = \frac{g \times D_s^2 (\rho_s - \rho_L)}{46.3\mu} \quad (\text{Eq.1})$$

Where:

$V_{slip}$  : Slip or settling velocity in ft/sec

$g$  : Gravitational constant in ft/sec<sup>2</sup>

$D_s$  : Diameter of the solid in inches

$\rho_s$  : Density of the solid in lb/gal

$\rho_L$  : Density of the liquid in lb/gal

$\mu$  : Viscosity of the liquid in cp

This equation is a mathematical expression of events commonly observed, and can be summarize as follow:

- The larger the difference between the density of the liquid ( $\rho_s - \rho_L$ ), the faster the solid will settle
- The larger the particle is, the faster the solid will settle
- The lower the liquid's viscosity, the faster the settling rate will be.

Understanding free settling is important because its form the basis for the relationships which apply to vertical hole cleaning. Generally, Stokes' law is modified to incorporate equivalent viscosity for circulating Non-Newtonian fluids and non-spherical cuttings. The term of settling velocity under free settling is called slip velocity.

Besides Stokes' law, slip velocity can be calculated with other correlations like Moore correlation, Chien correlation, and also Walkers and Mayer correlations mostly used for non-Newtonian fluid will be briefly described in this chapter.

### 4.3 Moore Correlation<sup>1</sup>

According to Moore's correlation<sup>1</sup>, the slip velocity can be approximated by the following three equations which depend on the particle Reynolds number.

$$V_{slip} = \frac{498 \times D_p^2 (\rho_p - \rho_{mud})}{\mu} \quad \text{for } N_{RE} < 1 \quad (\text{Eq.2})$$

$$V_{slip} = \frac{175 \times D_p \times (\rho_p - \rho_{mud})^{0.667}}{\rho_{mud}^{0.333} \mu^{0.333}} \quad \text{for } N_{RE} = 10 \text{ to } 100 \quad (\text{Eq.3})$$

$$V_{slip} = 113.4 \left[ \frac{D_p (\rho_p - \rho_{mud})}{1.5 \rho_{mud}} \right]^{1/2} \quad \text{for } N_{RE} > 200 \quad (\text{Eq.4})$$

And the Reynolds number is calculated as follow:

$$N_{RE} = \frac{15.45 \times \rho_{mud} \times v \times D_p}{\mu} \quad (\text{Eq.5})$$

$$\mu = \left[ \frac{2.4v}{(D_{hole} - D_{pipe})} \frac{2n+1}{3n} \right]^n \left[ \frac{200K(D_{hole} - D_{pipe})}{v} \right] \quad (\text{Eq.6})$$

$$\text{With } n = 3.32 \log \frac{\theta_{600}}{\theta_{300}} \quad (\text{Eq.7})$$

$$\text{And } K = \frac{\theta_{300}}{511^n} \quad (\text{Eq.8})$$

Where:

$\mu$  = the mud viscosity at shear rate in flow stream in cp

$V_{slip}$  = slip velocity, ft/min.

$v$  = annular velocity, ft/min

$\rho_{mud}$  = mud weight, ppg

$\rho_p$  = particle density, ppg

$n$  = derived parameter of mud, dimensionless

$K$  = derived parameter of mud, dimensionless

$\theta_{300}$  = 300 viscometer dial reading

$\theta_{600}$  = 600 viscometer dial reading

$\theta_{300} = PV + YP$

$\theta_{600} = \theta_{300} + PV$

$PV$  = plastic viscosity of mud, cps

$YP$  = yield point of mud, lb/100ft<sup>2</sup>

$D_{hole}$  = hole diameter, inches

$D_{pipe}$  = drill pipe outer diameter, inches

$D_p$  = particle diameter, inches

The first equation applies only to very slow rates of settling or slips velocity in laminar flow. The third applies to cases where the flow is turbulent around the particles and the second one applies to the transition range between laminar and turbulent. When there is a doubt about which equation to use, the one giving the lowest slip velocity should be used.

For the fluid to lift cuttings to the surface, the fluid annular average velocity ( $V_{ann}$ ), must be in excess of the cuttings average slip velocity ( $V_{slip}$ ). The relative velocity between  $V_{ann}$  and  $V_{slip}$  is termed as the average cutting transport (rise) velocity  $V_t$ , that is:

$$V_t = V_{ann} - V_{slip} \quad \text{and} \quad \frac{V_t}{V_{ann}} = 1 - \frac{V_{slip}}{V_{ann}} = R_t \quad (\text{Eq.9})$$

Where,  $R_t$  is the cuttings transport ratio as defined by Siffermann<sup>22</sup> et al.

And the sum of this slip velocity and the cutting velocity ( $V_{cut}$ ) give you the Minimum velocity ( $V_{min}$ ) needed to carry the cuttings out in the vertical section:

$$V_{min} = V_{cut} + V_{slip} \quad (\text{Eq.10})$$

## Conclusion:

This equation is the most used in the oil industry nowadays for the calculation of the slip velocity in the vertical wells. Most of software is relay on these equations. In this method, the YP and PV of the drilling fluid must be adjusted to in order to increase or decrease the carrying capacity of the mud.

## 4.4 Chien Correlation<sup>1</sup>

Chien correlation<sup>1</sup> involves calculation of the Reynolds number using the apparent viscosity of the fluid. For the mixture of bentonite and water, the plastic viscosity can be used as apparent viscosity, while for the polymer type drilling fluid, the apparent viscosity is calculated as follows:

$$\mu_a = \mu_p + 5 \frac{\tau_y d_s}{v_{ann}}$$

(Eq.11)

The Reynolds number is then calculated like in Moore correlation, and if the above 100, the slip velocity becomes:

$$V_{slip} = 0.0075 \left( \frac{\mu_a}{\rho_f d_s} \right) \left[ \left( \frac{36800 d_s (\rho_s - \rho_f)}{\rho_f} + 1 \right) - 1 \right] \quad (\text{Eq.12})$$

However for the lower Reynolds number, the slip velocity can be calculated as:

$$V_{slip} = 1.44 \sqrt{d_s \frac{(\rho_s - \rho_f)}{\rho_f}} \quad (\text{Eq.13})$$

Where,

$\tau_y$  = shear stress in lbf/sqft

$\rho_s$  = solid density in ppg

$\rho_f$  = fluid density in ppg

$\mu_a$  = apparent fluid viscosity in cp

$v_{ann}$  = annular velocity in ft/min

$d_s$  = solid diameter in inch

### Conclusion

In this correlation the author doesn't take the transitional flow regime into consideration. He assumes the flow regime to be either laminar or turbulent which make the correlation less accurate but more easy to use.

## 4.5 Walker and Mayes correlation<sup>1</sup>

For Walker and Mayes, the apparent viscosity is determined by using an empirical relation for shear stress due to particle slip. The corresponding equation for apparent viscosity is:

$$\mu_a = 479 \frac{\tau_s}{\gamma_s} \quad (\text{Eq.14})$$

Where,

$\tau_s$  is the shear stress in lbf/sqft

$\gamma_s$  is the shear rate in 1/sec.

For particles Reynolds number bigger than 100, the slip velocity can be computed as:

$$V_{slip} = 2.19 \sqrt{d_s \frac{(\rho_s - \rho_f)}{\rho_f}} \quad (\text{Eq.15})$$

While for the lower Reynolds number, it is reduced to:

$$V_{slip} = 0.0203 \tau_s \sqrt{\frac{d_s \gamma_s}{\rho_f}} \quad (\text{Eq.16})$$

### Conclusion

As already mentioned in the Chien correlation, the flow regime is not taken into consideration but also the wellbore geometry is not taking into account for the calculation of the slip velocity. All this failed parameters make the correlation less accurate and less used.

## 5 Cuttings transport in deviated and horizontal wellbores

### 5.1 Literature Review

On the commissioning of various flow loops, a significant amount of experimental data was collected on the effect of different parameters on cuttings transport under various conditions. The observations made and subsequent analysis of the data collected provided the basis for the work towards formulating correlations and models. Meanwhile, field experiences and drilling data of inclined and horizontal wells provided practical operational guidelines and the necessary basis for evaluation and improvement of the laboratory and theory based models.

#### 5.1.1 *First experimental studies*

Tomren et al (1986) performed a comprehensive study of steady state cutting transportation in inclined wells by means of a flow loop. The study was conducted with a 5 inch and 40 feet long transparent section. He investigated numerous angles of inclination, flow rates, drill pipe rotations and pipe hole eccentricities. He identified visually the occurrence of cutting or sliding beds based on various parameters. It was reported that the major factors that should be considered in directional wells are fluid velocity, hole inclination, and mud and rheological properties.

Okranjni and Azar (1986) studied specifically the effects of field measured mud rheological properties like apparent viscosity, plastic viscosity, yield value and gel strength in inclined wells. Since different muds could have the same rheological property, a ratio of yield point (YP) to plastic viscosity (PV) was additionally used to distinguish the mud. The study was done on the same flow loop as Tomren et al. (1986) using 15 different types of mud systems including water. They noted that in the turbulent regime, the transport capacity of mud was found to be independent of its rheological properties. The transport is affected most by momentum forces which are mainly a function of mud density. Also in horizontal wells, it was deduced that the turbulence would be a positive factor in the cleaning of the annulus while the rotation of the drillpipe didn't actually contribute to the cleaning of the



bed, but it inhibited the formation of the bed. They lastly provided some field guidelines for directional well drilling.

Sifferman and Becker (1992) performed experiments using an 8 inch 60 foot long flow loop. They studied the effects of annular velocity, mud density, mud rheology, mud type, cutting size, ROP, drill pipe rotary speed, drill pipe eccentricity, drill pipe diameter, and hole angles ( $45^{\circ}$  to  $90^{\circ}$  versus the vertical). The experiment was split into three phases to be able to conduct a statistical analysis of the drilling parameters and validate the existence of interactions between them. They found that cuttings size, mud weight have moderate influence on the cuttings transport and showed that the transport ratio increases rapidly with increase in annular mud flow rate then begins to level out or increase more slowly in the mud flow rate range of 200 to 400 gpm.

Belavadi and Chukwu (1994) used an experimental flow loop with transparent acrylic casing drill pipe annulus. Four different weights of bentonite mud samples 8.9 ppg, 9.3 ppg, 12 ppg, and 13 ppg with cutting chips of graded sizes small, medium and large were introduced into the annular column from the bottom section of the transparent acrylic pipe. They used a non-dimensional approach and observed that an increase in the flow rate at higher fluid densities greatly increase the transport ratio i.e. the ratio of the net cutting velocity and the average fluid annular velocity. This effect is almost negligible when using low density fluids to transport large size cuttings. They reported that the fluid density to viscosity ratio concept can be applied to control drilling through sensitive formations. A small increase in the fluid density to viscosity ratio results to a rapid decrease in the transport ratio. Similarly, a small increase in the drag coefficient on the cuttings results to a large increase in the transport ratio.

Kenny et al (1996) defined a lift factor that they used as an indicator of cuttings transport performance. The lift factor is a combination of the fluid velocity in the lower part of the annulus and the mud settling velocity. A flow loop of 8 in wellbore simulator, 100 ft long, with a 4 in. drill pipe, was used in their study. The variables considered in this work were drill pipe rotary speed, hole inclination, mud rheology, cuttings size, and mud flow rate. Results have shown that the drill pipe rotation has an effect on hole cleaning in directional well drilling. The level of enhancement in cuttings removal as a result of rotary speed is a function of the combination of mud rheology, cuttings size, mud flow rate, and the manner in

which the drill string behaves dynamically. They found out that, smaller cuttings are more difficult to transport. However, with high rotary speed and high viscosity mud, small cuttings become easier to transport. Low viscosity mud in the hole cleans better than high viscosity mud with no pipe rotation.

Sanchez et al (1999), investigated the effect of drill pipe rotation on hole cleaning during directional-well drilling. For his study, an 8 in. diameter wellbore simulator, 100 ft long, with a 4 1/2 in. drill pipe was used. The variables considered in this experimental work were: pipe rotation, hole inclination, mud rheology, cuttings size, and mud flow rate. Over 600 tests were conducted. The rotary speed was varied from 0 to 175 rpm. High viscosity and low viscosity bentonite muds and polymer muds were used with 1/4 in. crushed limestone and 1/10 in. river gravel cuttings. Four hole inclinations were considered: 40°, 65°, 80°, and 90° from vertical. His results show that drill pipe rotation has a significant effect on hole cleaning during directional-well drilling if the pipe is freedom to spin around the hole axis. This result is contrary to what has been published by previous researchers who forced the drill pipe to rotate about its own axis. The level of enhancement due to pipe rotation is a function of the simultaneous combination of mud rheology, cuttings size, and mud flow rate. Also it was observed that the dynamic behaviour of the drillpipe plays a significant role in the improvement of hole cleaning.

### **5.1.2 Theoretical studies**

Gavignet and Sobey (1989) presented a two-layer cutting transport model on slurry transport. They assumed that the cuttings had fallen to the lower part of the inclined wellbore, and had formed a bed that slides up the annulus. Above this bed, a second layer exists of pure mud. Eccentricity is taken into account in the geometrical calculations of wetted perimeters and an apparent viscosity can be calculated for Non-Newtonian muds using a rheogram written in polynomial form.

Sharma (1990) extended Gavignet and Sobey's work modelling approach by separating the particle into two separate layers. This allows having both a stationary and sliding bed at the same time, and a bed sliding up inside the annulus on top and a bed sliding down at the bottom.

Martins and Santana (1992) presented a two layer model that is more versatile than Gavignet and Sobey's model because it allows particle to be in suspension in the upper layer. The mean particle concentration in this layer is calculated from a concentration profile that has been obtained from solving a diffusion equation.

Clark and Bickham (1994) developed a mechanistic model to describe hole cleaning. Their model considers the various mechanisms involved in the transport of cuttings out of a well i.e. rolling, lift and particle settling. Their publication concurs with industry opinion in classifying flow rate as the most important factor in hole cleaning, and it considers fluid density and rheology as the most important drilling fluid properties that affect hole cleaning. The Herschel-Bulkley rheological model is also used, with the fluid yield stress being dominant factor. But the influences of other rheological parameters like consistency index and flow index are unclear.

Larsen et al (1997) developed a new mathematical model for estimating the minimum fluid transport velocity for system with the inclination between  $55^\circ$  and  $90^\circ$ . They found that the model worked fairly well within inclination  $55^\circ$  to  $90^\circ$ , and there were no correction factors yet for the inclination less than  $55^\circ$ . From Larsen method it was known that there are three parameters which affect the determination of minimum fluid annular velocity for inclined hole: (1) inclination, (2) ROP and (3) mud density.

Kamp and Rivero (1999) developed a two-layered model for near horizontal wellbores. The model consisted of a stationary or a moving bed below a layer of heterogeneous cuttings suspension. They assumed that there was no significant slip velocity difference between the particles and the mud. They took into account cuttings settling and re-suspension, but not the vertical motion of the particles in the liquid. This simplified the model by assuming the liquid and cuttings had the same density hence not taking into account the pressure and the temperature effects. The model predicted thickness of the uniform bed as a function of mud flow rate, cuttings diameter, mud viscosity, pipe eccentricity and other properties of the flow. The results of the model were compared to a previous correlation based model. The closure terms in the model were based on the experimental results. And Kamp et al.(1999) suggested possible improvements to the model including solving separate momentum equations for the solids and mud suspension layer.

Pilehvari et al (1999) carried out a review of cuttings transport in horizontal wells. The advancement in cutting transportation research was summarized and suggestions were made for much more work on turbulent flows of non-Newtonian fluids, effects of drill pipe

rotation, comprehensive solid-liquid flow model and the development of a hole cleaning monitoring system that receives all the available relevant data in real time for quick analysis and determining the borehole status.

Hyun et al. (2000), formulated a mathematical three layer model to predict and interpret the cuttings transport in deviated wellbore from vertical to horizontal. The model considered the following layers: (1) a stationary bed of cuttings in low side of the borehole, (2) moving bed layer above the stationary one, (3) a heterogeneous suspension layer at the top. They modelled three segments to deal with the well deviation: horizontal segment from 60° to 90°, transient segment from 30° to 60°, and a vertical segment from 0 to 30°. For every segment they set up continuity equations and momentum equations. They analyzed the interface interaction using the correlations. They reported effects of annular velocity, fluid rheology, and angle of inclination on cuttings transport. The model predictions based on the simulation are in good agreement with the experimental data published by other.

## 5.2 Factors influencing the cuttings transport

They are several factors that affect the transport of the cuttings while drilling deviated wells. Cuttings transport is affected by several interrelated mud, cuttings and drilling parameters, as shown in the table below. For the hole cleaning, annular and mud viscosity are generally considered to be the most important parameters.

Well profile and geometry	<ul style="list-style-type: none"> <li>• Hole inclination angle and doglegs</li> <li>• Casing/hole and drill pipe diameters</li> <li>• Drillstring eccentricity</li> </ul>
Cuttings and cuttings bed characteristics	<ul style="list-style-type: none"> <li>• Specific gravity</li> <li>• Particle size and shape</li> <li>• Reactivity with mud</li> <li>• Mud properties</li> </ul>
Flow characteristics	<ul style="list-style-type: none"> <li>• Annular velocity</li> <li>• Annular velocity profile</li> <li>• Flow regime</li> </ul>

Mud properties	<ul style="list-style-type: none"> <li>• Mud weight</li> <li>• Viscosity, especially at low shear rates</li> <li>• Gel strengths</li> <li>• Inhibitiveness</li> </ul>
Drilling parameters	<ul style="list-style-type: none"> <li>• Bit type</li> <li>• Penetration rate</li> <li>• Differential pressure</li> <li>• Pipe rotation</li> </ul>

Table 1: Drilling parameters influencing the cuttings removal

### **5.2.1 Annular velocity**

In case of an inclined annulus, the axial component of particle slip velocity play a less important role, and one could conclude that to have satisfactory transport, the annular mud velocity in this case may be lower than in the vertical annulus. This however is a misleading conclusion. The increasing radial component of the particle slip velocity pushes the particle toward the lower wall of the annulus, causing a cuttings bed to form as already mentioned. Consequently, the annular mud velocity has to be sufficient to avoid the bed formation. It is expected that an increase in flow rate will always cause more efficient removal of the drilled cuttings out of the annular space. However, an upper limit of the flow rate is dictated by:

- Rig hydraulic power
- Equivalent Circulation Density
- Susceptibility of the open hole section to hydraulic erosion

### **5.2.2 Wellbore Inclination angle**

It has been well established from previous laboratories work that as hole angle increases from zero to about 65 degrees from vertical, hole cleaning becomes more difficult and hydraulic requirements increase, likewise. The flow rate requirements peak around hole angles between 65°-75° (degrees) from vertical and slightly decrease toward the horizontal. Also, it has been shown that at angles between 30°-60° (degrees) from vertical, a sudden pump shut-down causes sloughing of accumulated cuttings bed to bottom and may cause a serious problem of pipe sticking. Although, hole inclination causes difficulties in hole cleaning, its choice is mandated by the anticipated geological conditions and by field

development company objectives. Reservoir inaccessibility, offshore drilling, avoiding troublesome formations, and horizontal drilling into the reservoir are some of the geological conditions that dictate hole angle. Company objectives in the total development of a field, such as primary production objectives, secondary production objectives, economic objectives, environmental objectives, etc., are also governing factors in hole angle selection. But in order to reduce the inclination effect the planning of the wellbore trajectory must be as straight as possible.

### **5.2.3 Mud Properties**

The functions of the drilling mud are many and have competing influences. These include

- cleaning the bottom hole and annulus
- wellbore stabilization (mechanical and chemical)
- cooling and lubrication of the drill string
- formation evaluation
- Prevention of formation intrusion into the wellbore during conventional drilling (i.e., over-balanced).

Generally speaking, different drilling fluid types provide similar cuttings transport if their downhole properties also are similar. However, selection of optimum properties requires careful consideration of all related parameters. Clearly, mud properties must be maintained within certain limits to be effective without being destructive or counter-productive. Properties of particular interest to hole cleaning include mud weight, viscosity, gel strengths and level of inhibition.

*1). Mud weight* helps buoy cuttings and slow their settling rate<sup>1</sup> (as shown by Stokes' law in the first chapter), but it is really not used to improve hole cleaning. Instead, mud weights should be adjusted based only on pore pressure, fracture gradient and wellbore-stability requirements. Vertical wells drilled with heavy muds normally have adequate hole cleaning as compared to highly deviated directional wells drilled with low-density fluids.

Wellbore instability is a special case where mud weight clearly targets the cause, rather than the symptoms, of hole-cleaning problems. As a rule, formations drilled directionally require higher mud weights to prevent bore-hole failure and sloughing into the annulus. What can appear as a hole-cleaning problem at the surface, in fact, can be a stress-related

problem which should be corrected by increasing the mud weight? Alternative actions to improve cuttings transport may help but will not eliminate the basic problem.

2). *Mud viscosity* helps determine carrying capacity<sup>1</sup>. For vertical wells, yield point historically has been used as the key parameter which was thought to affect hole cleaning. More recently, evidence concludes that Fann 6- and 3-RPM (Rotation per Minute) values are better indicators of carrying capacity (even in vertical wells). These values are more representative of the LSRV (Low-Shear Rate Viscosity)<sup>4</sup> which affects hole cleaning in marginal situations. Coincidentally, most viscosifiers (clays, for example) added to increase yield point also increase 6- and 3-RPM values. One common rule of thumb is to maintain the 3-RPM value so that it is greater than the hole size (expressed in inches) in high-angle wells. The Low-Shear Yield Point (LSYP)<sup>4</sup>, calculated from 6- and 3-RPM values, has also gained broad acceptance for quantifying LSRV:

$$\text{LSYP} = (2 \times \theta_{3rpm}) - \theta_{6rpm} \quad (\text{Eq.17})$$

LSYP can play an even more important hole-cleaning role in directional wells, if it is applied in accordance with the specific well conditions. For example, in laminar flow, there is a clear correlation between improved hole-cleaning performance and elevated LSYP, especially in conjunction with the rotation of eccentric pipe. On the other hand, low LSYP values are preferred for turbulent-flow hole cleaning, because turbulence could be achieved at lower flow rates. Elevated LSRVs make it possible to achieve superb hole cleaning at much lower flow rates than conventional systems.

3). *Gel strengths* provide suspension under both static and low-shear-rate conditions. Although closely related to viscosity, gel strengths sometimes are overlooked with regard to their effects on hole cleaning. Quickly developing gels which are easily broken can be of significant help. Excessively high and/or progressive gels, on the other hand, should be avoided because they can cause or exacerbate a number of serious drilling problems.

### 5.2.4 Drill String Rotation

It has been demonstrated in laboratory studies and reported in field cases, that drill string rotation with the induced modes of vibrations (torsional, longitudinal, and lateral) has moderate to significant effects on hole cleaning in directional wells. The level of enhancement in drilled cuttings removal due to drill string rotation is a function of the combination of mud rheology, cuttings size, flow rate, and the dynamic behavior of the

string. It is believed that the whirling motion of the string as it rotates is the major contributor to the cleaning process. Mechanical agitation of the cuttings bed and its exposure to higher fluid velocities are the beneficiaries of this motion.

Although there is a definite gain in hole cleaning due to drill pipe rotation, it must be recognized also that there are limitations that may have to be imposed as well. For example, pipe rotation cannot be activated during the sliding mode while building hole angle. Also, pipe rotation induces cyclic stresses that can accelerate pipe failure due to fatigue, causes excessive casing wear and in some cases mechanical destruction of the walls of open hole sections. Additionally, in slim-hole drilling (hole diameter less than 6"), high pipe rotation may cause an increase in the annular friction pressure losses and therefore an increasing in ECD. Also very important to highlight that all the changes of such parameters as RPM must be done according to the capacity of the tools used like, motor, RSS, MWD and LWD tools.

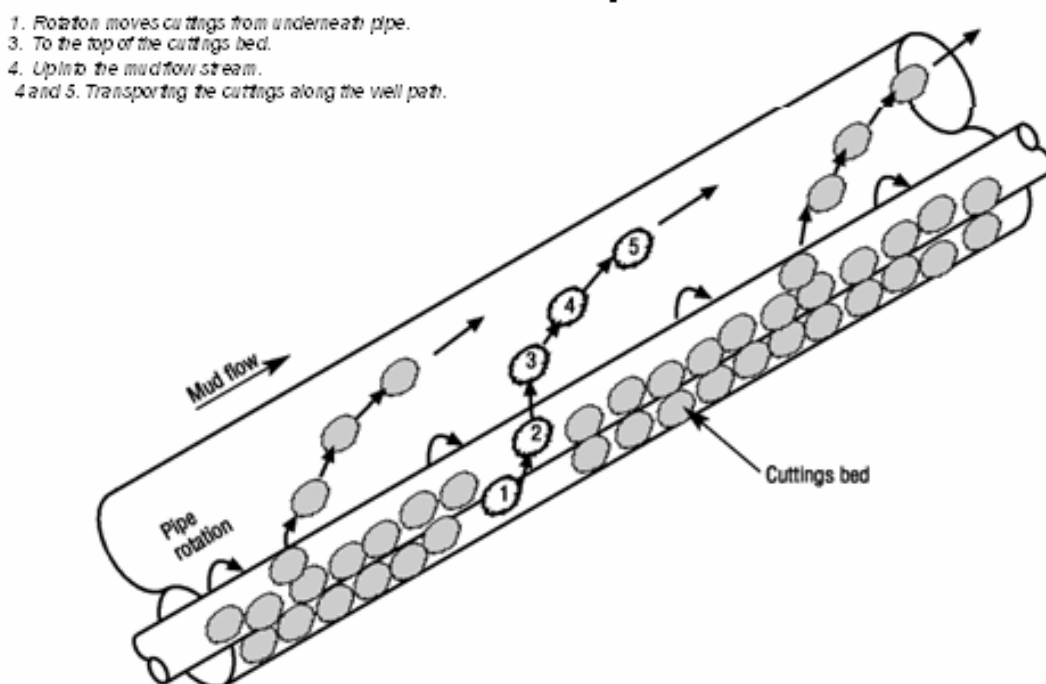


Figure 2: Lifting of the cuttings due to pipe rotation<sup>10</sup>

### 5.2.5 Drilled Cuttings Properties

The size, the shape, and the specific gravity of drilled cuttings are what affect their dynamic behavior in a flowing media. The specific gravity of most rocks that are drilled is on the average of about 2.6 and therefore, can be assumed to be known. However, the



cuttings size and shape are functions of the type of bit groups that are being used (drag bits, roller cone bits), the regrinding that may take place beneath the bit after they are generated, and their bombardment and further breakage by the rotating drill string. Thus, it is impossible to control their size and shape even if the right bit is selected to generate a specific geometry. In directional wells, it is documented that generally smaller cuttings are more difficult to transport to the surface. Although, when drilling with some fluid viscosity and then rotated the pipe, finer particles seem to stay in suspension in the mud<sup>8</sup>.

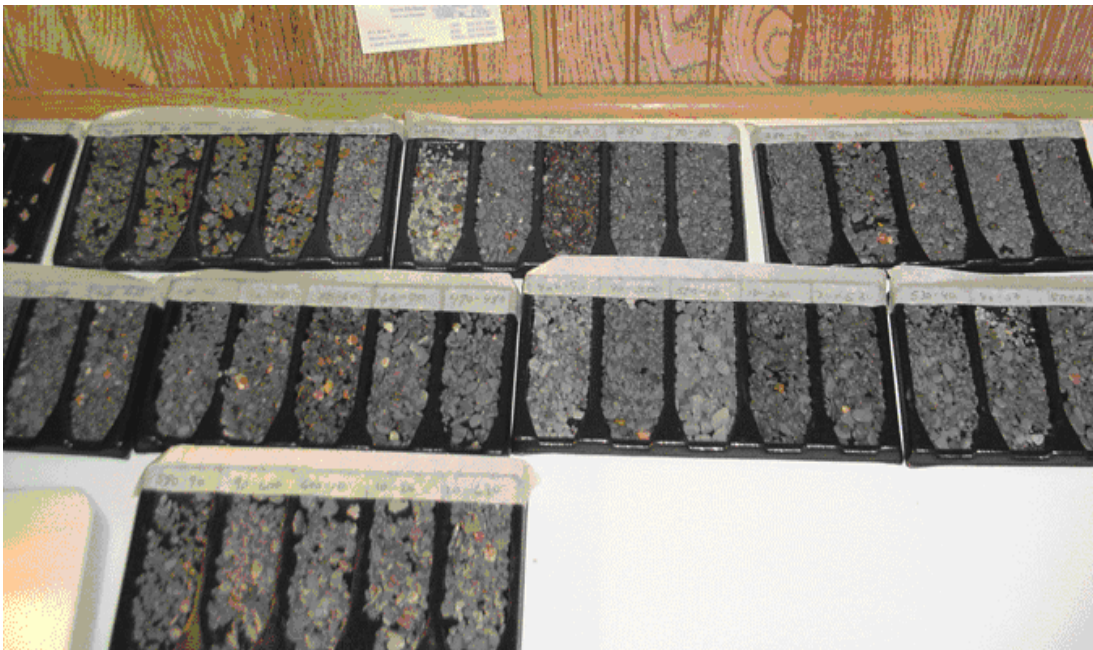


Figure 3: Picture of some dry cuttings<sup>8</sup>

### **5.2.6 Drill String Eccentricity**

The position of the drill string in the inclined portion of the hole has a dramatic effect on the drilling mud efficiency in the removal of drilled cuttings in the annulus space. Due to the nature of gravity, the string always has a tendency to be on the low side of the hole especially in the sliding mode. Unfortunately, this is the worst position (so called positive eccentricity) which causes very low fluid velocities in the narrow gap below the drill string where most of the cuttings are, and higher velocities in the widened gap above the string. The problem worsens as mud viscosity increases due to the increase in fluid flow divergence from the narrow gap to the wider portion. This is the main reason to why low viscosity mud, in general, perform better in directional hole cleaning than

high viscosity mud. Since eccentricity is governed by the pre-selected wellbore trajectory and the dynamic behavior of the drill string, its adverse impact on hole cleaning is unavoidable.

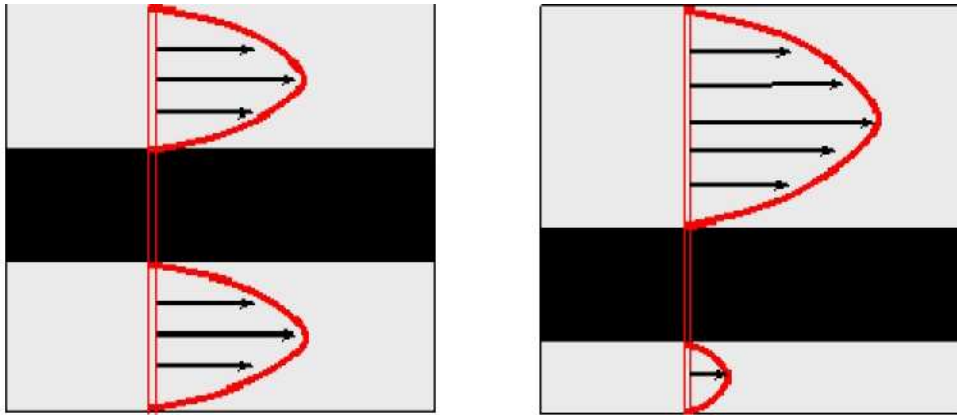


Figure 4: Comparison between concentric (left) and eccentric (right) drill pipe annular flow distribution<sup>8</sup>

### 5.2.7 Rate of Penetration

Under equal conditions, an increase in ROP causes an increase in the drilled cuttings concentration in the annulus. Therefore, to maintain an acceptable and effective hole cleaning, other controllable variables such as hydraulics and rotary speed must be adjusted. If the limits of these variables have been reached then the only alternative is to decrease the rate of penetration. Although, a decrease in ROP will have a negative impact on well cost, the benefits of avoiding drilling problems such as pipe sticking and excessive torque and drag can outweigh the losses.

## 5.3 Hole cleaning and cuttings bed formation

Based on laboratory researches and on field experiences, deviated and horizontal wellbores lead to some of the most troublesome hole cleaning problem. Removing cuttings from the deviated part of the wellbore trajectory (see Figure 5) is a big challenge and will be discussed in details in this chapter.

### 5.3.1 Cuttings bed formation

This graph gives a general idea of where the cuttings start to accumulate in the inclined wellbore trajectory.

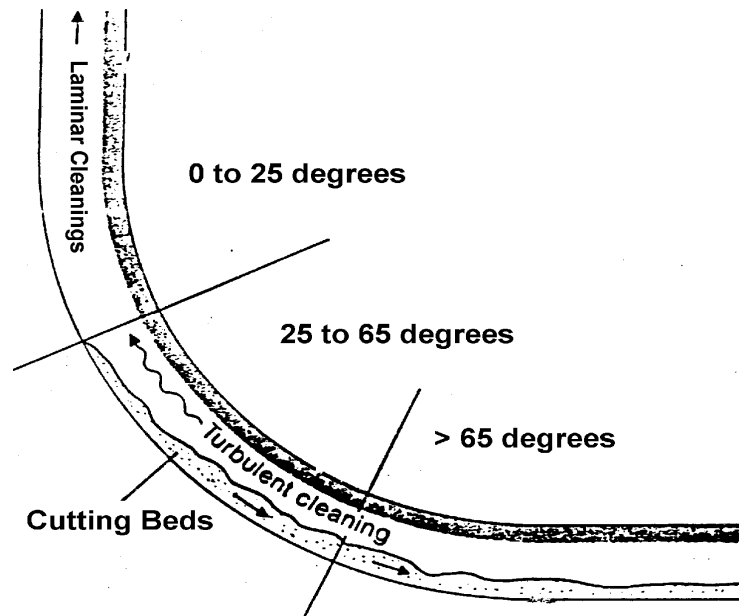


Figure 5: Well trajectory in directional drilling

During the drilling of the deviated part of the hole, the directional driller must slide for changes in direction and/or inclination, and rotate to drill the hold part. The sliding is the worst operation because the drill pipe lies against the low side of the hole which increases hole cleaning problem. The flow of the cuttings in the annulus is a dynamic process and is subject to many forces that were already mentioned in the previous chapter for the vertical section. The forces and the velocity components acting on a cutting are shown in the figure below in the figure 6 and 7.

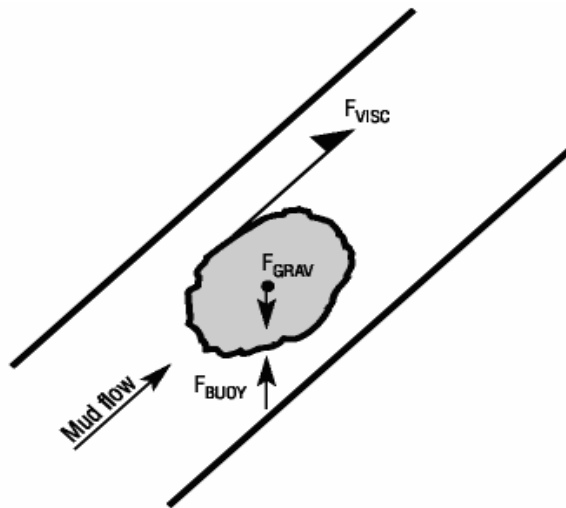


Figure 6: Force component acting on a cutting

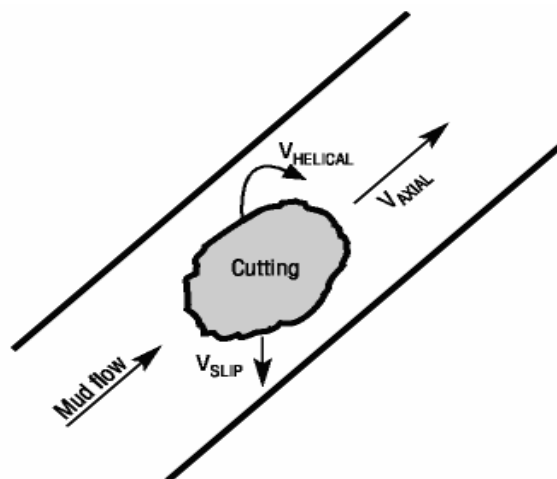


Figure 7: Velocity components acting on a cutting

The proper hole cleaning depends on two aspects:

- Optimizing the drilling parameters and their interaction
- Optimizing the quality of the downhole drilling equipment used.

In this chapter we will focus on the drilling parameters influencing the cuttings transport, on the cuttings bed formation, and on the description of some models used to describe the cuttings transport.

One more common type of carrying capacity problem is the ability of the fluid to lift the cuttings or slough and to carry them out of the hole. If the hole is beginning to slough, the amount of shale coming across the shaker may appear to be normal, while large amounts are

being collecting in the hole. Sometimes the appearance of the cuttings will indicate poor hole cleaning. If the cuttings are rounded, it may indicate that they have spent an undue amount of time in the hole. The condition of the hole is usually one of the best indicators of the hole cleaning difficulty. Fill on bottom after a trip is an indicator of inadequate hole cleaning. However, the absence of the fill doesn't mean that there is not a cleaning problem. Large amounts of cuttings may be accumulating in washed out places zones in the borehole. Drag while pulling the drill string to make a connection may also indicate inadequate cleaning. When the pipe is moved upward, the swab effect may be sufficient to dislodge cuttings packed into a washed-out section of the hole. The sudden dumping of even a small amount a material is often enough to cause severe drag or sticking.

The ability of the fluid to lift a piece of rock is affected first by the difference of density of the rock and the fluid. If there is no difference in densities, the rock will be suspended in the fluid and will move on a flow stream at the same velocity as the fluid. As the density of the fluid is decreased, the weight of the rock in the fluid is increased and it will tend to settle. The shear stress of the fluid moving by the surface of the rock will tend to drag the rock with the fluid. The velocity of the rock will be somewhat less than the velocity of the fluid. As already mentioned before, the difference in velocities is usually referred to as slip velocity. The shear stress that is supplying the drag force is a function of shear rate of the fluid at the surface of the rock and the viscosity of the mud at this shear rate. A number of others factors as wall effects, inter-particle interference, pipe eccentricity, hole angle and the turbulent flow around the particles make exact calculations of the slip velocity impossible.

When drilling in an inclined annulus at an angle  $\theta$  from the vertical, there will be two components for the slip velocity:

$$V_{slip.a} = V_{slip} \cos \theta \quad (\text{Eq.18})$$

$$V_{slip.t} = V_{slip} \sin \theta \quad (\text{Eq.19})$$

Where,  $V_{slip.a}$ ,  $V_{slip.t}$  are the axial and radial components of the average slip velocity, respectively as shown in the Figure 8 below.

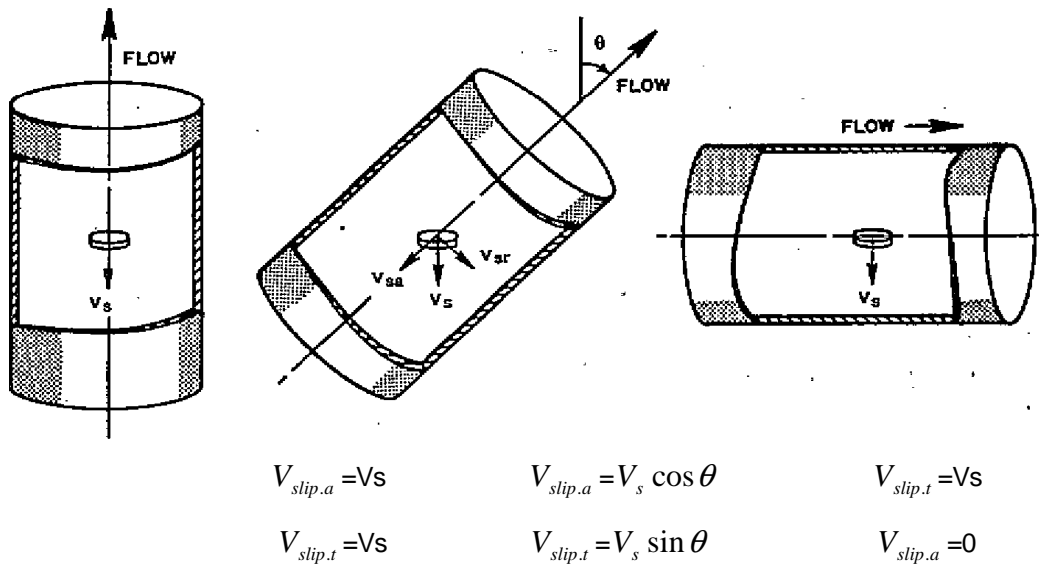


Figure 8: Particle settling velocity in an inclined annulus from TOMREN<sup>14</sup>

When the angle of inclination is increased, the axial component of the slip velocity decreases, reaching zero value at the horizontal position of the annulus. When these conditions are taken into account, all factors that may lead to improved cuttings transport by a reduction of the particle slip velocity will have a diminishing effect while angle of inclination is increasing. When reaching the hole section with an inclination between 30 and 60 degrees, the cuttings accumulation in the annulus adds a further problem to the drilling process. An equilibrium between cuttings bed erosion and cuttings settling at the low side of the hole results in a “stable” cuttings bed until the mud circulation is interrupted e.g. when making a connection. As soon as the dragging forces of the flowing mud discontinue, cuttings beds may slide down the low side of the hole like an avalanche leading to mechanical sticking at the lower portion of the drill string (see Figure 9).

Cuttings accumulations can be difficult to erode or re-suspend, so mud properties and drilling practices which minimize their formation should be emphasized. Clearly, cuttings which remain in the flow stream do not become part of a bed or accumulation. Mud suspension properties are important, especially at low flow rates and under static conditions. Cuttings beds, such as those formed in directional wells, can take on a wide range of characteristics that impact hole-cleaning performance. For example, clean sand drilled with clear brine will form unconsolidated beds which tend to roll rather than slide

downwards, and are conducive to hydraulic and mechanical erosion. On the other hand, reactive shale drilled with a water-base mud can form thick filter-cake-like beds which are very difficult to remove without aggressive hydrodynamic and mechanical action.

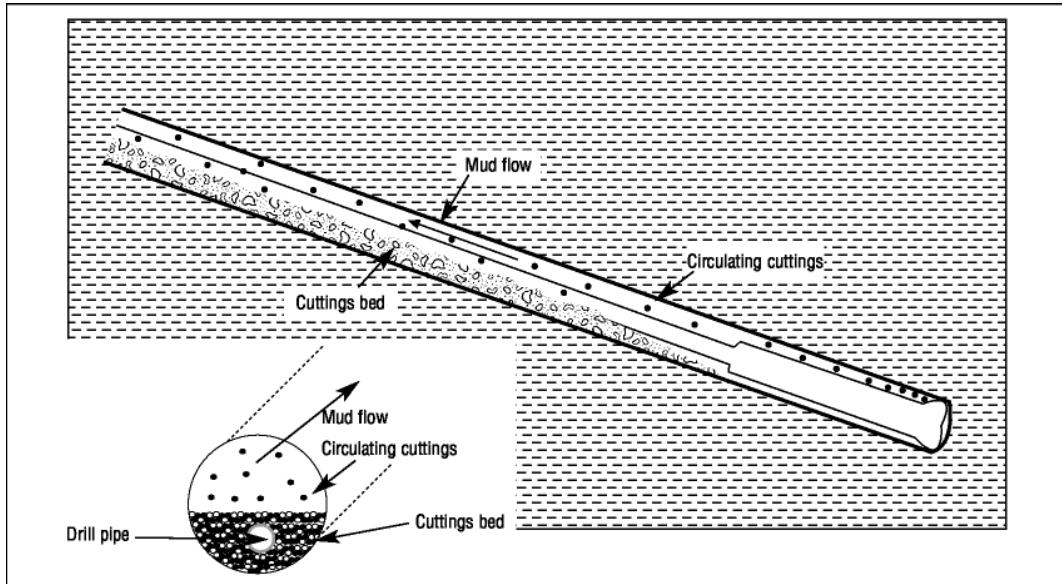


Figure 9: Cuttings bed in highly inclined well<sup>11</sup>

In horizontal sections, the particles settle into a bed and do not move from that position until drill string rotation is reapplied. The slip velocity in this interval is perpendicular to the flow direction of the drilling fluid. One important point must be recognized, to have a horizontal interval one must have drilled a build section, and thus the same challenges and potential dangers still exist higher up the well. The transport efficiency or solids removal rate is still low in horizontal section. Drill pipe rotation and adequate flow rate like already mentioned in the previous chapter are also essential parameters for transporting the cuttings in the horizontal sections.

In this section of the hole we have the following flow patterns:

**Stationary bed flow:** when the total flow rates does not generated the fluid velocities required for the transport of the cuttings, the cuttings particles start to accumulate at the bottom of the hole and create a “stationary cuttings bed” as shown in the Figure below. The equilibrium bed height is reached when the fluid viscosity become strong enough to transport the cuttings downstream, not allowing further accumulation.

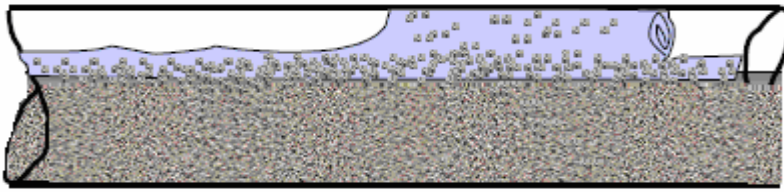


Figure 10: Stationary cuttings bed

Moving bed flow: When increasing the volumetric flow rates, there is a point which the cuttings break into a slowly moving cuttings bed as shown in the Figure below.

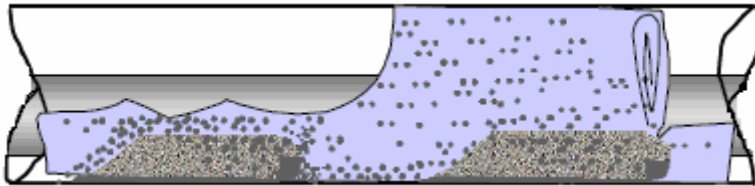


Figure 11: Moving cuttings bed

Dispersed bed flow: The dispersed bed flow normally occurs when the total volumetric flow rate high enough to suspend all the solids particles in the liquid as you can see in the figure below.

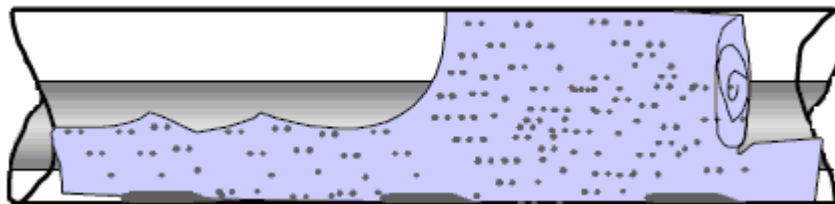


Figure 12: Dispersed cuttings bed

Although particles cannot avalanche in the horizontal sections, pack-offs can still be induced if the drill pipe is moved axially in the interval with a cuttings bed present. Hole cleaning should be performed prior to tripping out of the hole so that the drill string isn't dragged through a cuttings bed or the cuttings are not pushed up into the build section where avalanching can occur. Drill pipe pulled through a cuttings bed will act like a "bulldozer", accumulating cuttings across tool joints, the BHA or at the bit.

The Figure 13 below illustrated the pack-off effect that appears when tripping out of the hole in the horizontal section:



Figure 13: Pack-off while pulling the BHA out of the hole



### **5.3.2 Hole cleaning during the drilling operations**

Hole cleaning problems start when the employed operating parameters fail to efficiently circulate cuttings to surface. Experience has shown that this can occur whether with rotary drilling or drilling with motors is employed. The problems have further been identified in both the drilling phase and the tripping phase.

These two modes represent two different configurations of cuttings bed build up processes and hole cleaning practices in the wellbore.

#### Drilling phase

During the drilling phase, there is an equilibrium cuttings bed height that can be used as an indication of the efficiency of the hole cleaning by measuring the amount of cuttings at surface versus the calculated volume of cuttings expected to be generated when drilling out the formation. During this mode even though the bed reaches a steady state (provided parameters remain unchanged) the cuttings bed height is not necessarily regularly distributed along the drill string. For example, the section directly above the BHA encounters high volumes of cuttings as the smaller annular clearance in the BHA generates high mud velocity and therefore avoids cuttings accumulation but this effect is greatly reduced in the drill pipe section resulting in the immediate settling of the cuttings into beds or dunes.

For this mode then, the hole cleaning performance corresponds directly to the final equilibrium bed height (provided parameters remain unchanged).

#### Tripping phase

During tripping phase, cuttings can build-up under several conditions:

- Natural sedimentation of solid particles when mud flow stops
- Dragging of the drill string through the existing cuttings bed creates localized “dunes” of cuttings
- Avalanching of the cuttings when the bed is established in the critical angle section (30 - 60 degrees) of the well

For this mode, the hole cleaning performance is related to the speed at which the system decays the cuttings and to the final cuttings bed height

## 5.4 Some methods to determine the bed thickness

Two methods are presented in this thesis to highlight the determination of the cuttings bed thickness in the wellbore. The first method is the empirical correlations and the second one is the method of Artificial Neural Networks developed by Ozbayoglu et al (2002). In order to develop a more general empirical correlation, which will be valid for a wide range of conditions, it is essential to describe the variables in dimensionless form. Thus a dimensional analysis is conducted. It is generally believed that the height of a cuttings bed is the essential information for controlling hole cleaning performance and a successful drilling operation<sup>6,12</sup>. Major independent drilling variables, which control the development of a cuttings bed in a wellbore, considered in these methods are inclination angle, feed cuttings concentration, fluid density, a term representing the apparent fluid viscosity, average velocity and dimensions of the pipe and wellbore.

A dimensional analysis is conducted by using those independent variables in order to develop dimensionless groups that can be correlated for estimating bed height. After applying the Buckingham -  $\pi$  Theorem which is a key theorem in dimensional analysis, five dimensionless groups are developed and defined as:

$$\pi_1 = C_c = \text{volume of cuttings/volume of annulus}$$

$$\pi_2 = \alpha \tag{Eq.20}$$

$$\pi_3 = \frac{A_{bed}}{A_w} \tag{Eq.21}$$

$$\pi_4 = \frac{\rho v D}{\mu} = N_{Re} \tag{Eq.22}$$

$$\pi_5 = \frac{g D}{v^2} = \frac{1}{N_{Re}} \tag{Eq.23}$$

### 5.4.1 Empirical correlation using Least Square Method

The relation between the dimensionless bed area and the rest of the dimensionless groups can be written as:

$$\frac{A_{bed}}{A_w} = f(C_c, \alpha, N_{Re}, N_{Fr}) \tag{Eq.24}$$

Where:

$A_{bed}$  Cross-section flow area of the cutting bed in sqft

$A_w$  Cross-section flow area of the wellbore in sqft

$C_c$  Feed cuttings concentration

$\alpha$  Angle in degree versus vertical

$N_{Re}$  Reynolds number

$N_{Fr}$  Froude number

The relation between each dimensionless group and the dimensionless bed area is presented in the Figure 14<sup>16</sup>.

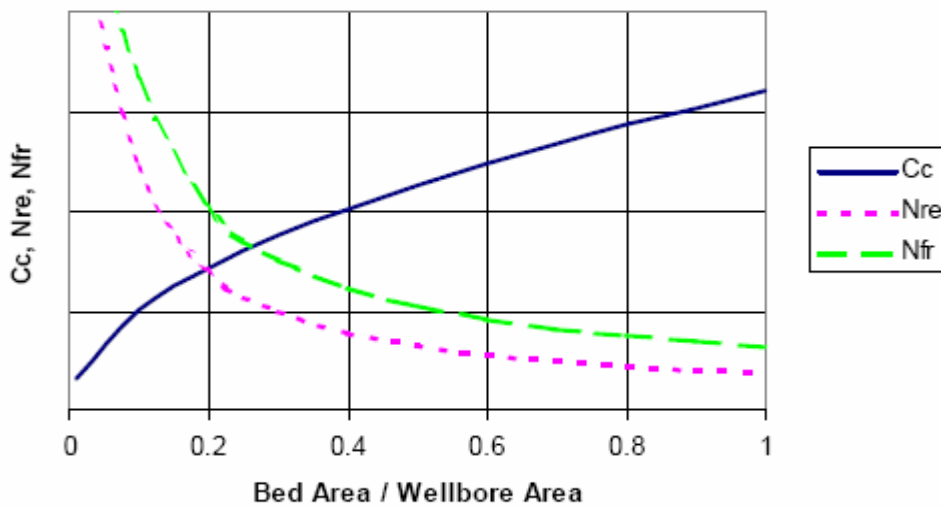


Figure 14: Change of each dimensionless group with the dimensionless cuttings bed area

Flow loop experiments with a simulated drill-string have shown that the inclinations up to 65° degrees do not affect the bed height. Thus, inclination angle  $\alpha$  is removed from the equation above. From the analysis (see Figure 14), it is observed that a possible relationship among these dimensionless group is the multiplication form. Thus, a general representation of the dimensionless bed area is expressed as:

$$\frac{A_{bed}}{A_w} = k_1 (C_c)^{k_2} (N_{Re})^{k_3} (N_{Fr})^{k_4} \quad (\text{Eq.25})$$

In order to determine the coefficient,  $k_1$  experimental data collected at the Tulsa University flow loop are used. Information established from the cuttings experiments with different muds was analyzed. A set of empirical correlations was developed using multivariate regression (Statistica<sup>TM</sup>). The least square method is used during this analysis.

The following equations are obtained:

For  $N \geq 0.9$

$$\frac{A_{bed}}{A_w} = 4.1232(C_C)^{0.0035} (N_{Re})^{-0.2198} (N_{Fr})^{-0.2164} \quad (\text{Eq.26})$$

For  $0.6 < N < 0.9$

$$\frac{A_{bed}}{A_w} = 0.7115(C_C)^{0.0697} (N_{Re})^{-0.0374} (N_{Fr})^{-0.0681} \quad (\text{Eq.27})$$

For  $N \leq 0.6$

$$\frac{A_{bed}}{A_w} = 1.0484(C_C)^{0.0024} (N_{Re})^{-0.1502} (N_{Fr})^{-0.0646} \quad (\text{Eq.28})$$

The correlation coefficients ( $R^2 = \text{estimated variation/ total variation}$ ) for these equations are 0.8612, 0.9318 and 0.7966 respectively with the perfect match if  $R^2 = 1$ . The result of the experimental results and the empirical correlation is compared in the graph (Figure 15) below, which shows is less accuracy at  $N > 0,9$ .

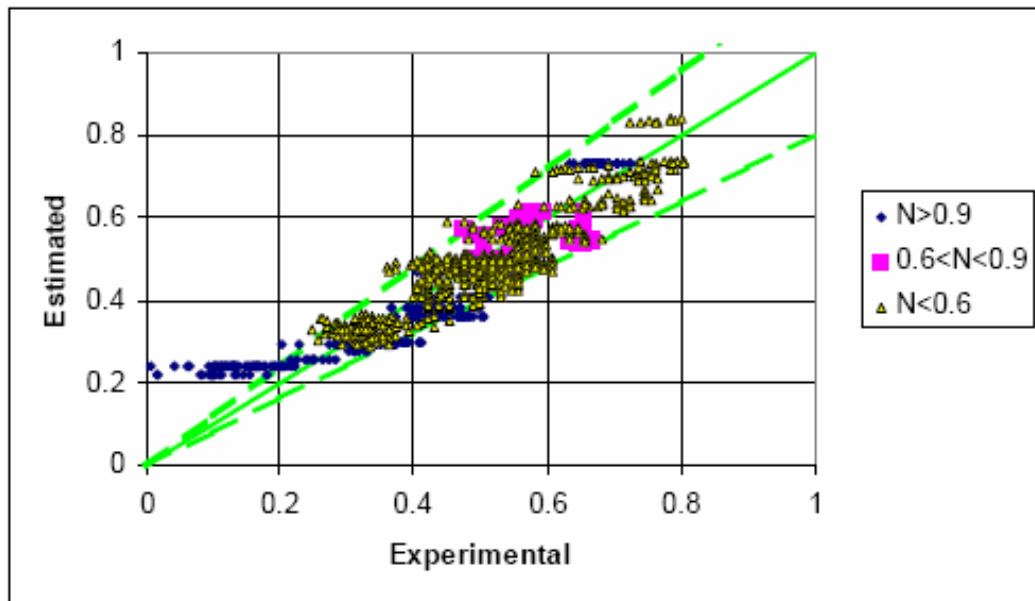


Figure 15: Experimental results versus empirical correlation results<sup>16</sup>

#### 5.4.2 Artificial Neural Network (ANN)<sup>16</sup>

Another method used to estimate the cuttings bed height is using the ANN. The popularity of ANN is increasing due to its wide range of possible applications, and its capability of handling the nonlinearities that cannot be described by conventional mathematical functions<sup>16</sup>. A neural network has a parallel distributed architecture with

a large number of nodes and connections<sup>16</sup>. Connection points are connected from one node to another and are associated with a weight. A simple view of the network structure and behaviour is given in Figure 16.

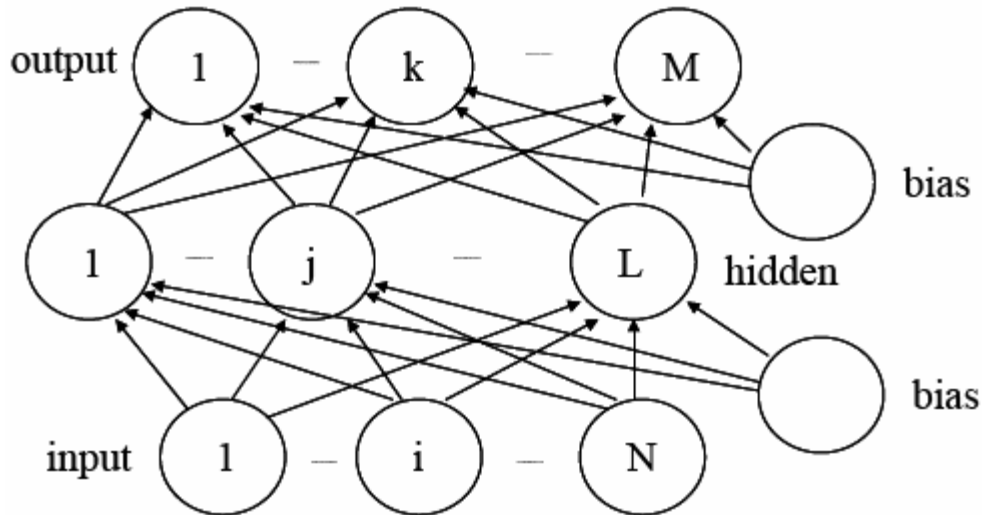


Figure 16: Schematic view of a basic Neural Network System

#### Network layers

*The input layer:* the nodes in this layer are called input units, which encode the instance presented to the network for processing. For example, each input unit may be designated by an attribute value possessed by the instance. In this study, the inputs are feed cuttings concentration, Reynolds Number and Froude Number; thus, there are three input nodes.

*The hidden layer:* The nodes in this layer are called hidden units, which are not directly observable and hence hidden. They provide nonlinearities for the network. In this study, a single hidden layer is used with ten hidden nodes. The number of hidden layers and nodes are determined by trial and error.

*The output layer:* the nodes in this layer are called output units, which encode possible concepts or values to be assigned to the instance under consideration. Here, the only output is the cuttings bed area; thus, there is only one output node.

#### Backpropagation

The backpropagation network is a technique that is probably the most well known and widely used among the current types of neural network systems available<sup>16</sup>. A backpropagation network is a multi-layer feed forward network with a different

transfer function in the artificial neuron and more powerful learning rule. The learning rule is known as backpropagation, which is a kind of gradient descent technique with backward error propagation. The training instance set for the network must be presented many times in order for the interconnection weights between the neurons to settle into a state for correct classification on input patterns. While the network can recognize patterns similar to those they have learned they do not have the ability to recognize new patterns. This is true for all supervised learning networks. In order to recognize new patterns, the network needs to be retrained with these patterns along with previously known patterns. If only new patterns are provided for retraining, then old patterns may be forgotten. In this way, learning is not incremental over time. This is a major limitation for supervised learning of networks.

Reynolds number, Froude number, feed concentration are used as inputs for training the network. The network determines dimensionless bed area using the weight functions obtained during training.

Comparison done by Ozbayoglu et al (2002) between both methods describe shown that ANN estimates the cuttings bed thickness more accurately than the empirical methods at lower bed thickness. As it is shown in the Figure 17 below the ANN estimation follow the perfect match from zero to the high value of the ration between the bed area and the total wellbore area.

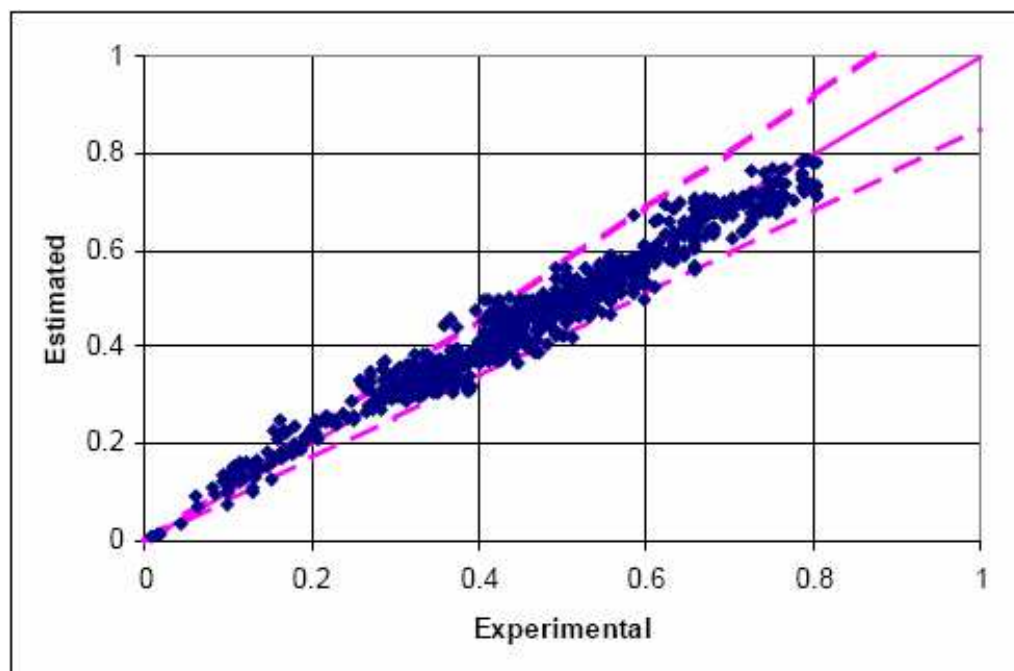


Figure 17: Experimental results versus ANN results<sup>16</sup>

## 5.5 Critical angle in deviated wellbores

Range	Angle in degrees
Near-vertical I	0-10
Low II	10-30
Intermediate III	30-60
High IV	60-90

Table 2: range based on hole angle

Their keys of consequences are listed here according to angle range:

- Near-vertical and low ranges: cuttings concentrations are little and there is not cuttings bed formation.
- Intermediate range: cuttings concentration, bed thickness and property for slumping.
- High range: bed thickness and physical characteristics.

The limits of each range should be considered only as guidelines, since all are affected by bed stability, borehole roughness, cuttings characteristics and drilling fluid properties, among others. Figure 8 illustrates relative hole-cleaning difficulty based on angle. In vertical and near-vertical wells, cuttings beds do not form, but failure to properly transport and suspend cuttings can cause fill on bottom or bridging in doglegs. In directional wells, the build section in the intermediate range typically is the most difficult to clean, because cuttings beds can slide or “slump” opposite the direction of flow. Boycott settling which is explaining on the next page can exacerbate the problem. Sliding tendencies start dissipating at angles greater than about 60°, due to the corresponding decrease in the gravitational force vector.

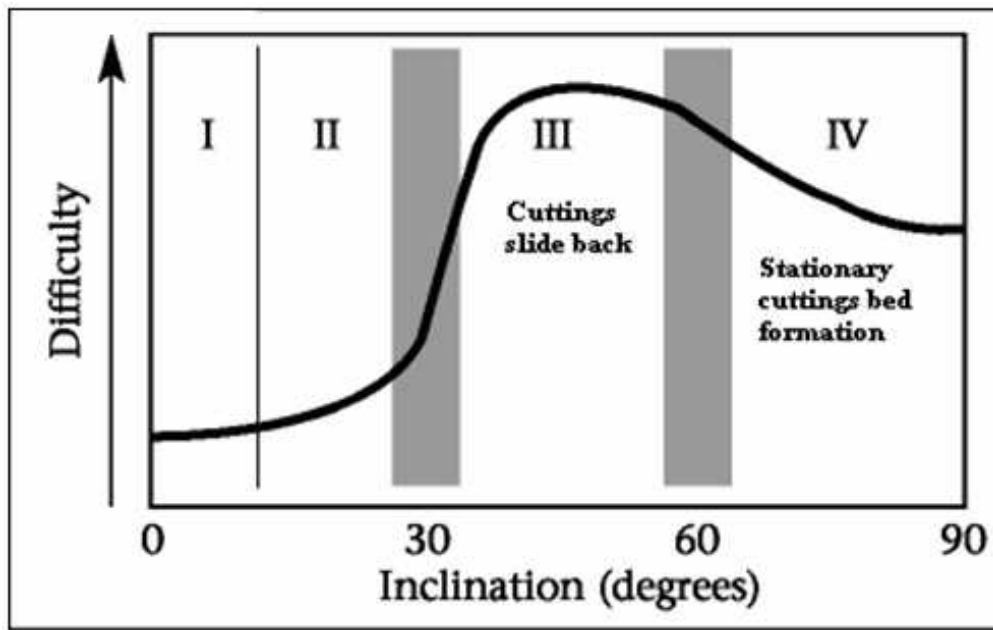
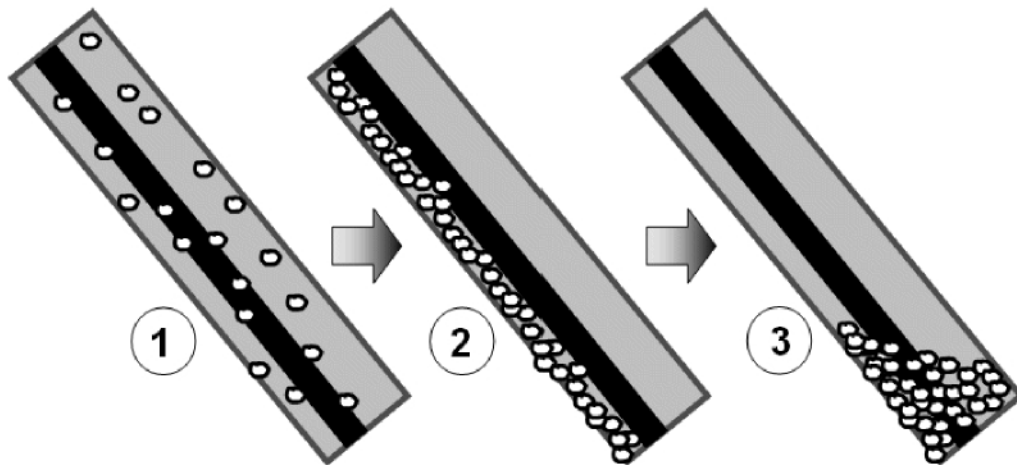


Figure 18: Hole cleaning difficulty versus inclination<sup>8</sup>

All four ranges may co-exist in the same directional well. For most cases, fluid properties and drilling practices should strive to minimize problems in the most critical interval. Hole-cleaning factors considered optimum for one interval may be inadequate in another. For example, requirements differ for large-diameter casing (which severely limits annular velocity), the build interval (which promotes cuttings-bed formation and sliding) and the production formation drilled horizontally (which may be shear sensitive and tend to wash out).

**Boycott settling<sup>8</sup>**, an accelerated settling pattern which can occur in inclined wellbores, is named after the physician who first reported that particles in inclined test tubes settle 3 to 5 times faster than in vertical ones. Boycott settling is the consequence of rapid settling adjacent to the high (top) and low (bottom) sides of inclined well-bores. This causes a pressure imbalance which drives the lighter, upper fluid upwards and any cuttings beds on the low side downwards. Angles from 40 to 60° are particularly troublesome. At relatively low flow rates, mud flows mainly along the high side and accelerate or enhance the Boycott effect. High flow rates and pipe rotation can disrupt the pattern and improve hole cleaning.





Boycott Settling Effects, 1) Cuttings particles are suspended when drilling with pipe rotation. 2) Once circulation and drill pipe rotation stop, cuttings begin to settle to the low side of the annulus. 3) Once a critical mass has been exceeded the cuttings avalanche, leading to a pack-off.

Figure 19: Illustration of the Boycott Settling Effects in the range of 40 to 60° inclination<sup>8</sup>

## 5.6 Modes of Cuttings Transport in horizontal section

Based on visual observations of the laboratory experiments done in the past work, the transport process can be categorized while assuming a perfect concentricity of the pipe into the following flow patterns as shown in the Figure 20 below :

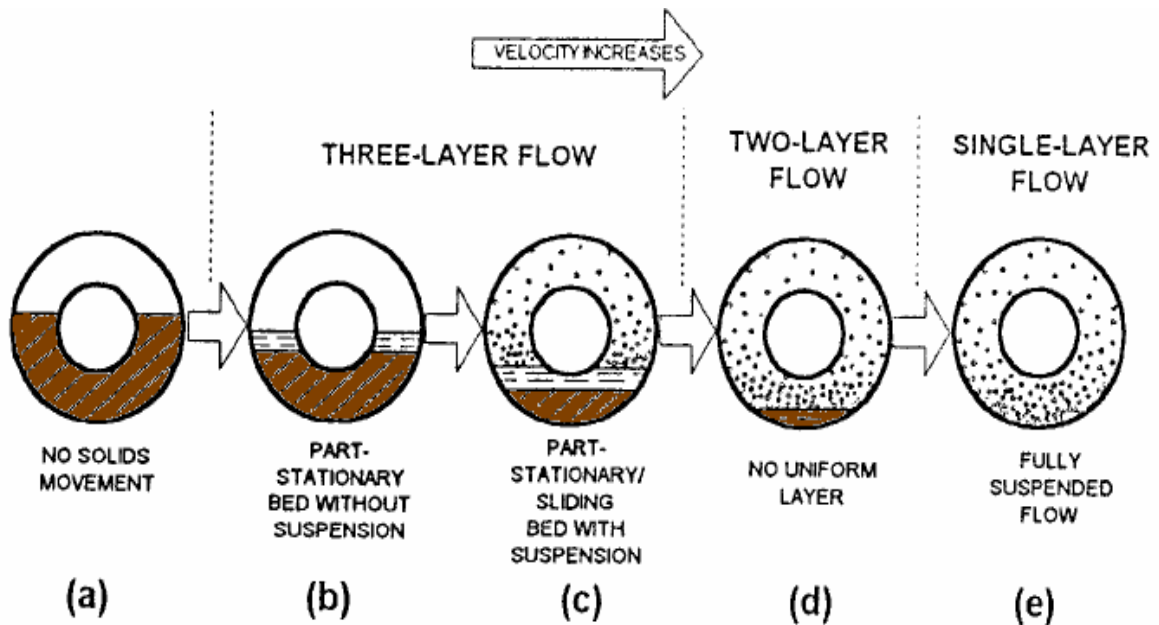


Figure 20: Schematic representation of different modes of transport<sup>13</sup>

At high flow velocity, mobile particles on the uppermost layer of the bend tend to glide forward on the top of a stationary bed forming a dilated dispersed layer; thus, we have a three-layer-flow pattern: a stationary bed of particles of uniform concentration, a dispersed layer in which particle concentration is varied, and an essentially clear fluid flow region on top as shown in the Figure 20(b). As the flow velocity is increased, the intensity of turbulent eddies grows in strength and eventually reaches a stage at which these turbulent eddies are strong enough to lift the topmost particles of the dispersed layer into the fluid flow region and carry them in a turbulent suspension mode. At this stage, we also have a three layer flow pattern but with a slightly different composition than that shown in Figure 20(b). The figure 20(c) shows a heterogeneous suspension layer on the top of a dispersed layer and a uniform concentration bed that can either be stationary or moving in a kind of “bloc”<sup>21</sup>. As more and more particles are picked up by turbulent eddies as the flow velocity further increases, the bed will get thinner and eventually the bed will disappear, leaving behind a dispersed layer and a heterogeneous suspension layer. This flow pattern is hereafter referred as two layer flow pattern as we can see in the Figure 20(d). Finally, with further increases in the annular flow velocity, all particles will be transported in the heterogeneous or homogeneous turbulent suspension mode. This flow pattern is hereafter referred as a single layer flow pattern as illustrated in the Figure 20(e).

### ***5.6.1 Wellbore geometry in horizontal interval***

In order to solve the equations for the determination of the bed height in the borehole, the area and contact surfaces for each layer are required. All possible wellbore configurations can be categorized into six major cases as shown in the Figure 21. For each layer case, the area, contact surfaces, etc can be determined by using basic trigonometry and geometry equations. The cases 4-6 can normally not happen in the horizontal section because we assume that the pipe will be almost every time at the low side of the borehole wall. The symbol “e” in the graph below represents the eccentricity. Eccentricity can be positive if “e” bigger than zero or negative if “e” smaller than zero.

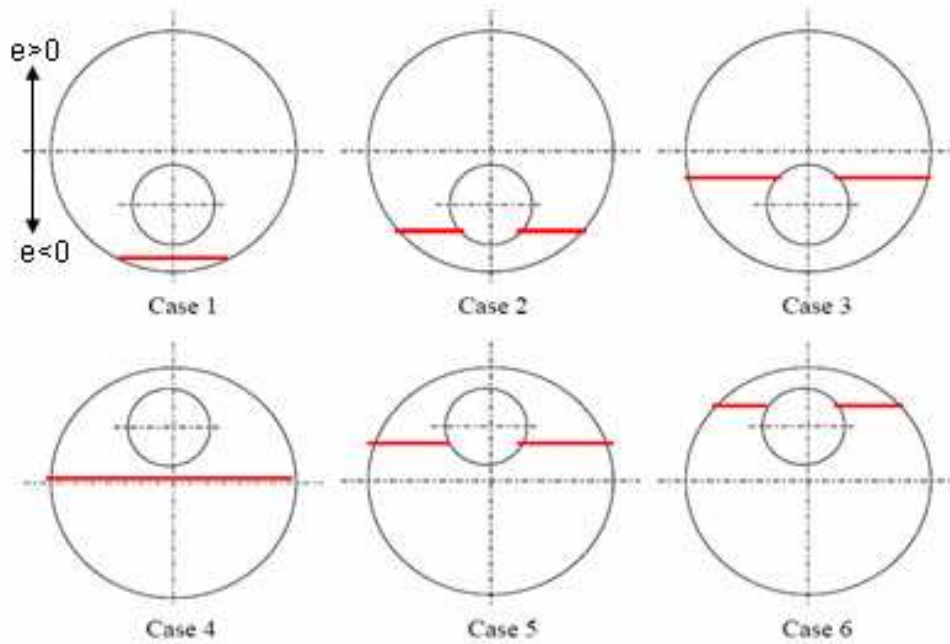


Figure 21: Possible wellbore configurations in horizontal interval<sup>14</sup>

## 5.7 Transport Models used to describe cuttings phenomena

### 5.7.1 Model for the prediction of the minimum transport velocity

This model basically developed by Larsen et al (1997) and updated by Mirhaj et al (2007) describes the calculation of the minimum transport velocity required to ensure efficient hole cleaning in highly deviated wells.

#### Experimental setup and procedure

The correlations that have been developed are based on experimental study in 5 in. full scale flow loop, which was 35 ft long with a 2.375 in. rotating inner drill pipe. All the drilling parameters were taken into consideration. Three cuttings sizes 0.275 in. (large), 0.175 in. (medium), 0.09 in. (small) and three cuttings bed porosities 41, 36, and 39% were used. The drillpipe eccentricity varied from negative (-62%) to positive (+62%) and the three cuttings injection rates of 10, 20, 30 lbm/min, which correspond to a ROP of 27, 54, and 81ft/hr were investigated. At the end the model was compared with the experimental results giving a good match.

**Cuttings velocity<sup>5</sup>**

A simple mass balance is assume, where,

Mass of cuttings generated at the bit is equal the mass of cuttings transported to the surface.

$$\rho_{cut} \cdot q_{inj} = V_{cut} \cdot A_{hole} \cdot C_{conc} \cdot \rho_{cut} \quad (\text{Eq.29})$$

From this equation, we can derive the cutting velocity ( $V_{cut}$ ) as a function of the ROP.

$$V_{cut} = \frac{ROP}{\left[1 - \left(\frac{A_{pipe}}{A_{hole}}\right)^2\right] 36 \times C_{conc}} \quad (\text{Eq.30})$$

And the same equation can be calculated by inserting in the equation 25 by the pipe and hole diameter. So, the new equation<sup>5</sup> will be:

$$V_{cut} = \frac{ROP}{\left[1 - \left(\frac{D_{pipe}}{D_{hole}}\right)^2\right] 36 \times C_{conc}} \quad (\text{Eq.31})$$

Based on the regression analysis a relation was fund to calculate the cuttings generated as a function of the ROP<sup>5</sup>. Figure 10 can be expressed in terms of cuttings concentration and ROP by the equation<sup>5</sup>:

$$C_{conc} = 0.01902 \times ROP + 0.495 \quad (\text{Eq.32})$$

The cuttings velocity can now be expressed by inserting the equation 27 into the equation 26 as:

$$V_{cut} = \frac{1}{\left[1 - \left(\frac{D_{pipe}}{D_{hole}}\right)^2\right] \left(0.685 + \frac{17.82}{ROP}\right)} \quad (\text{Eq.33})$$

Where,

$V_{cut}$  is the minimum cuttings transport velocity in ft/min

$D_{hole}$  is the hole diameter in inches

$D_{pipe}$  is the pipe diameter in inches

*ROP* is the rate of penetration in ft/min

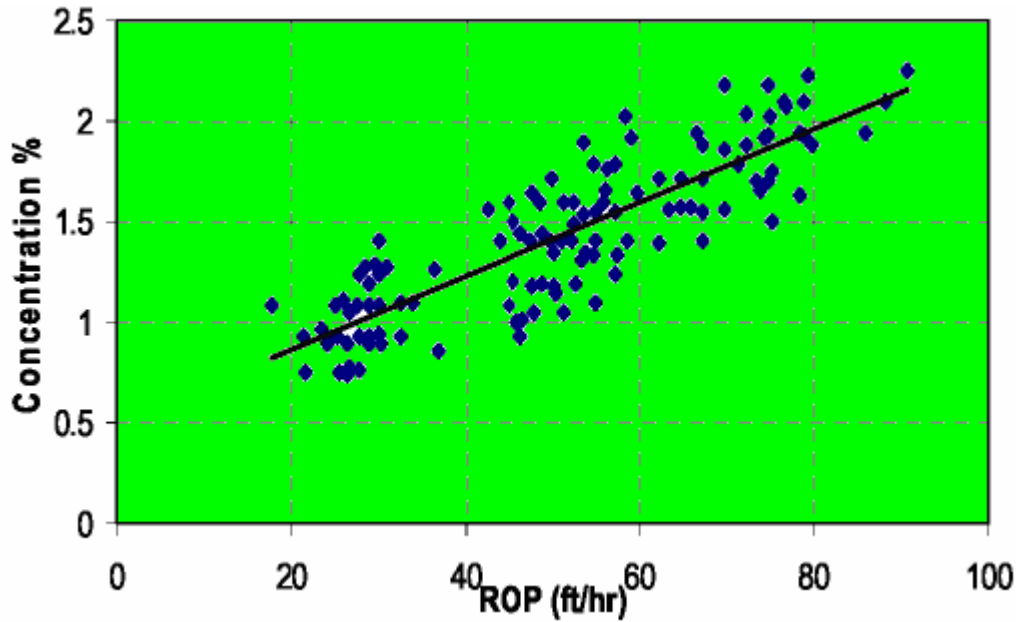


Figure 22: Cuttings Concentration vs Rate of Penetration at the Minimum Transport Velocity with Positive Eccentricity<sup>5</sup> (+62%)<sup>5</sup>.

This equation confirms that the experimental tests were performed according to the definition of the minimum fluid velocity required to maintain cuttings movement. This equation confirms that the experimental tests were performed according to the definition of the minimum fluid velocity required to maintain cuttings movement. That is the reason for the interdependence of the mud rheology, the mud weight, and the angle of inclination between 55 and 90°.

### Equivalent slip velocity (ESV) and its corrections factors

Using a linear regression of the figure below, the ESV can be represented by:

$$ESV = 0.0052 \times \mu_a + 3.10 \quad \text{for } \mu_a < 55 \text{ cp} \quad (\text{Eq.34})$$

$$ESV = 0.025 \times \mu_a + 3.26 \quad \text{for } \mu_a > 55 \text{ cp} \quad (\text{Eq.35})$$

And the apparent viscosity is given by:

$$\mu_a = PV + \frac{5.YP.(D_{hole} - D_{pipe})}{V_{min}} \quad (\text{Eq.36})$$

Where

$V_{min}$  is the minimum transport velocity in ft/sec

$PV$  is the plastic viscosity of mud, cps

$YP$  is the yield point of mud, lb/100ft<sup>2</sup>

This equation is not a general equation for different mud weights, cuttings sizes and angle of inclinations. So for this reason the correction factors for these parameters have been introduced.

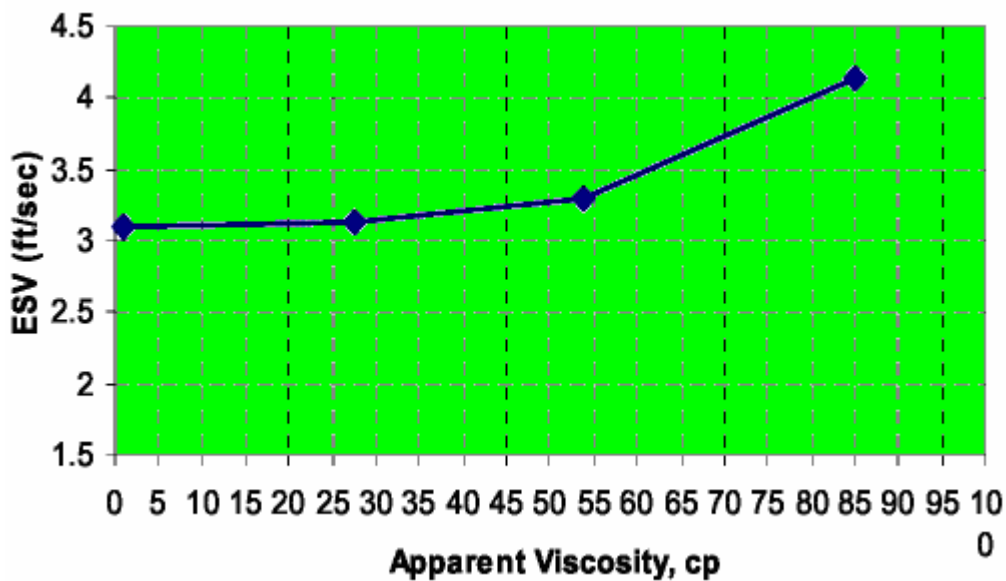


Figure 23: Equivalent slip velocity vs. apparent viscosity, average of 55, 65, 75, and 90°. <sup>5</sup>

### Correction factor for inclination angle

The angle of inclination correction factor was found by dividing the experimental Minimum Transport Velocity mean for the individual angles (90, 75, 65, and 55°) by the average of all angles, as shown in Figure 24 (which shows that angles ranging from 65 to 80° are slightly harder to clean) or the equation:

$$C_{ang} = 0.0365 \times \theta_{ang} - 0.0002 \times \theta_{ang}^2 - 0.20 \quad (\text{Eq.36})$$

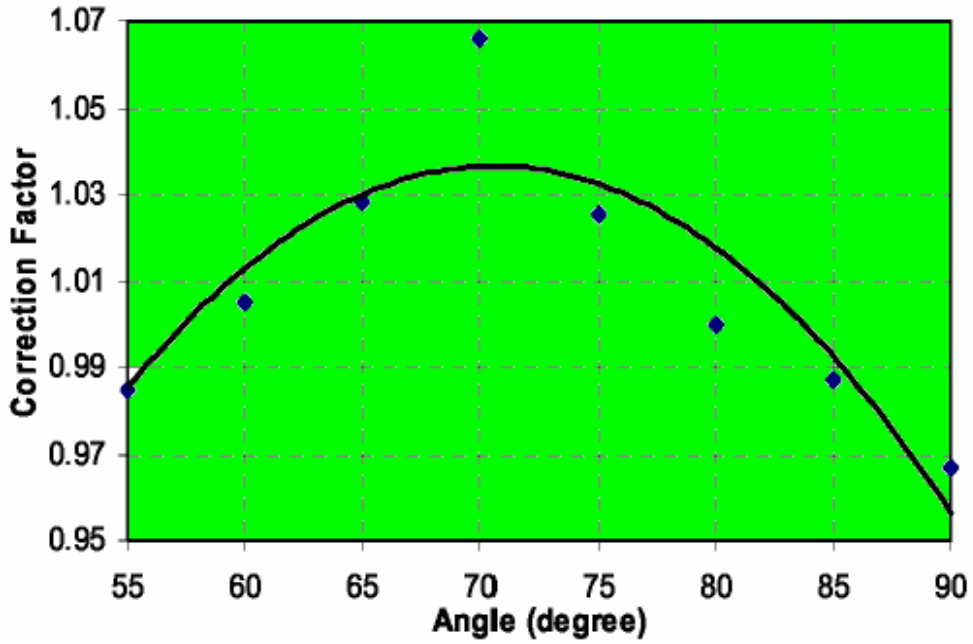


Figure 24: Correction factor in inclination angle<sup>5</sup>

**Cuttings size correction factor**

The cuttings-size correction factor, shown in Figure 25, is generated by dividing the average results of large, medium, and small cuttings by that of the large cuttings. It is also represented by the equation:

$$C_{size} = -1.02 \times D50_{cut} + 1.27 \tag{Eq.37}$$

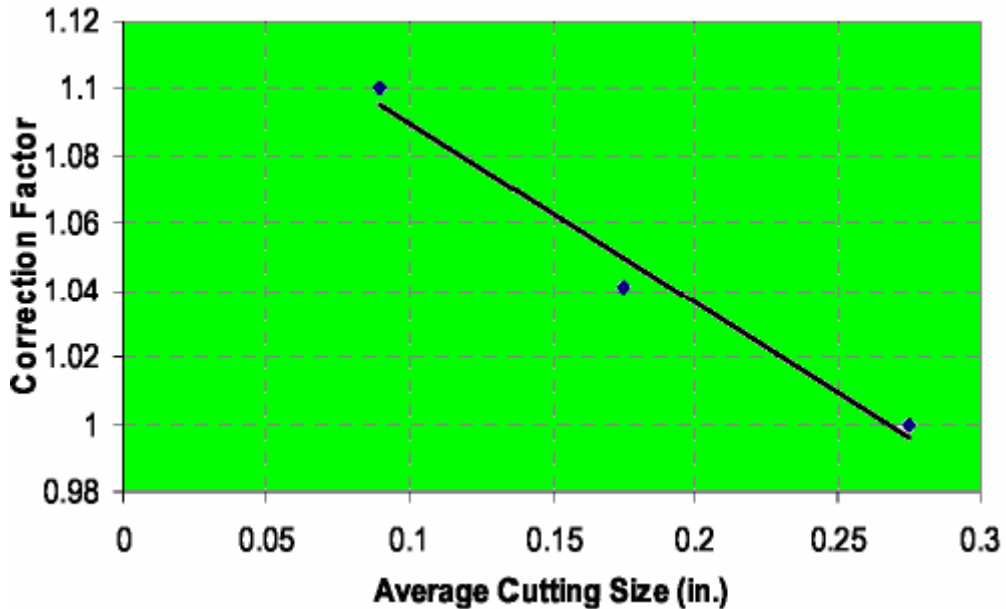


Figure 25: Correction factor for cuttings size<sup>5</sup>

### Mud weight correction factor

The correction for mud weight has been based on mud 2 (8.65 lbm/gal) and 4 (11.0 lbm/gal). The test results for mud 5 (15.0 lbm/gal) were not incorporated into this correction factor since the plastic viscosity ( $\mu_p$ ) could not be kept at 14 cp, as the case was for the two other mud, but rather rose to 28 cp. Thus, the effect of density was not totally isolated. Figure 26 below can be used to find the correction factor for mud weight, as can the equations:

$$C_{MW} = 1 - 0.333 \times (\rho_{mud} - 8.65) \text{ for } \rho_{mud} > 8.65 \quad (\text{Eq.38})$$

$$C_{MW} = 1.0 \text{ for } \rho_{mud} < 8.65 \quad (\text{Eq.39})$$

The general equation of the equivalent slip velocity will be expressed as:

$$V_{slip} = ESV \cdot C_{ang} \cdot C_{size} \cdot C_{MW} \quad (\text{Eq.40})$$

Therefore the minimum transport velocity can be found by adding the cuttings transport velocity and the equivalent slip velocity.

$$V_{min} = V_{cut} + V_{slip} \quad (\text{Eq.41})$$

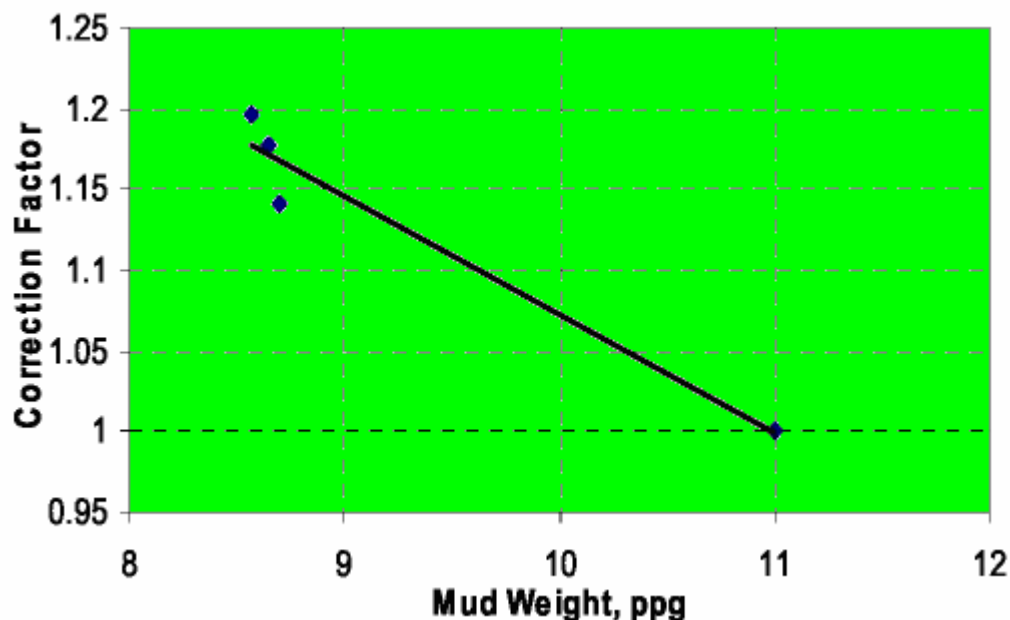


Figure 26: Correction factor of the mud weight<sup>5</sup>



## Results and conclusion

Prediction of the model versus the experimental results is examined and the effect the variables are as follow:

- A higher viscosity requires a larger flow rate to reach the minimum transport velocity
- To reach minimum transport velocity a higher velocity is needed for an increase in ROP
- An increase in mud weight will improve cuttings transport

Based on an extensive experimental testing program, gathered in a full-scale flow loop, simple empirical correlations have been developed for predictions of  $V_{cut}$  and  $V_{min}$ .

A sample for the calculation minimum transport velocity can be found in the Appendix B.

### 5.7.2 New cuttings lifting equation Model

To match the previous work of Larsen, the new equation for the calculation of the minimum transport velocity in the entire trajectory from 0 to 90° was developed by Rudi Rubiandi et al<sup>4</sup>. At angle bigger than  $\theta > 45^\circ$ , Larsen equation and the new equation of Rudi give the same result, but at the angle lower than  $\theta < 45^\circ$ , the new equation is more accurate than that of Larsen et al. This new equations take the pipe rotation into considerations.

By the linear regression of the dimensionless plotting, angle correction is obtained as expressed below, where  $C_i$  is the corrected angle:

$$\theta < 45^\circ, \quad C_i = \left(1 + \frac{2\theta}{45}\right) \quad (\text{Eq.42})$$

$$\theta > 45^\circ, \quad C_i = 2 \quad (\text{Eq.43})$$

Based on the dimensionless plotting between the slip velocity and the inclination for varied mud density, it is found that density correction factor can be expressed as:

$$C_{mw} = \frac{3 + \rho_{mud}}{15} \quad (\text{Eq.44})$$

Meanwhile, the RPM correction factor is determined from dimensionless plotting from between the slip velocity based on peden's method for varied RPM (rotation per minute) by linear regression. This correction factor is:

$$C_{RPM} = \left(\frac{600 - RPM}{600}\right) \quad (\text{Eq.45})$$

Minimum velocity  $V_{\min}$  for, vertical, horizontal and deviated well could be written as:

$$V_{\min} = V_{cut} + (1 + C_i \times C_{mw} \times C_{RPM})ESV \quad (\text{Eq.46})$$

Hence the new equation can be expressed as:

For  $\theta < 45^\circ$ ,

$$V_{\min} = V_{cut} + \left[ 1 + \frac{\theta \times (600 - RPM) \times (3 + \rho_{mud})}{202500} \right] ESV \quad (\text{Eq.47})$$

For  $\theta > 45^\circ$ ,

$$V_{\min} = V_{cut} + \left[ 1 + \frac{(600 - RPM) \times (3 + \rho_{mud})}{4500} \right] ESV \quad (\text{Eq.48})$$

### 5.7.3 Annular cuttings concentration prediction

For a given flow rate or operating flow rate, cuttings will start to deposit in the well bore. The cuttings accumulation, or cuttings bed, will grow until the open area to flow above the bed is restricted that the fluid is capable of transporting out all the cuttings from that area. Steady state is achieved whenever the cuttings bed will neither grow nor erode. Then, the velocity in the open area above the bed is assumed to be the same velocity corresponding to the minimum cuttings transport flow rate to keep the hole clean. By first neglecting the flow through the cuttings bed itself, the assumption can be made that:

$$V_{open} = V_{\min} \quad (\text{Eq.49})$$

Where,

$V_{open}$  is the average fluid velocity above the cuttings bed at steady state

$V_{\min}$  is the velocity at which the is no cuttings accumulation possible.

In terms of flow rate and the corresponding area open to flow, the above equation becomes:

$$\frac{Q_{pump}}{A_{open}} = \frac{Q_{\min}}{A_{ann}} \quad (\text{Eq.50})$$

Where,

$Q_{pump}$  is the pump or operating flow rate

$Q_{\min}$  is the flow rate at which the is no cuttings accumulation possible.

$A_{open}$  is the area open to flow above the cuttings bed

$A_{ann}$  is the total area of the annulus.

The area occupied by the cuttings ( $A_{cutt}$ ) can be calculated by the equation:

$$A_{cutt} = A_{ann} - A_{open} \quad (\text{Eq.51})$$

$$A_{cutt} = A_{ann} \left( 1 - \frac{Q_{pump}}{Q_{min}} \right) \quad (\text{Eq.52})$$

When taking the cuttings bed porosity ( $\phi$ ) into consideration the equation 46 becomes:

$$A_{cutt} = A_{ann} \left( 1 - \frac{Q_{pump}}{Q_{min}} \right) (1 - \phi) \quad (\text{Eq.53})$$

The cuttings bed concentration ( $\bar{C}_{cutt}$ ), or average cross-sectional area of the cuttings in the annulus can be estimated by the following equation:

$$\bar{C}_{cutt} = \frac{A_{cutt}}{A_{ann}} = \left( 1 - \frac{Q_{pump}}{Q_{min}} \right) (1 - \phi) \quad (\text{Eq.54})$$

This equation 49 is the basis for cuttings concentration calculations for any given fluid flow rate that corresponds to a velocity lower than the minimum transport velocity. A more accurate result can be obtained by incorporating a correction factor<sup>6</sup> from the linear regression analysis:

$$C_{CF-cutt} = 0,97 - 0,0023\mu_a \quad (\text{Eq.55})$$

So the cuttings bed concentration becomes:

$$C_{cutt} = \bar{C}_{cutt} \times C_{cor-cutt} \quad (\text{Eq.56})$$

The estimated how much of this cuttings are staying as a cuttings bed, we have to assume of percentage X of cuttings remaining. So,

$$C_{bed} = X \% \times C_{cutt} \quad (\text{Eq.57})$$

$$A_{bed} = \frac{C_{bed}}{(1 - \phi)} \times A_{ann} \quad (\text{Eq.58})$$

Having calculated the bed of the cuttings that will remain in the hole, the new hole area and the hole outer diameter in above the cuttings bed can be calculated as follow:

$$A_{ann-new} = A_{ann} - A_{bed}$$

$$A_{ann-new} = \frac{\pi(D_{new-hole}^2 - D_{pipe}^2)}{4} \quad (\text{Eq.59})$$

Based on the new hole diameter, we can calculate the velocity of the cuttings flowing above the cuttings bed and then estimate the minimum transport velocity in that area.

$$V_{cut-new} = \frac{(1 - X\%)ROP}{36 \left(1 - \frac{X\%}{1 - \phi}\right) \left[1 - \left(\frac{A_{pipe}}{A_{hole}}\right)^2\right] C_{conc}} \quad (\text{Eq.60})$$

The flow chart below (shown in Figure 27) summarizes the calculating steps needed for the estimation of the minimum transport velocity. The minimum flow rate in the wellbore to keep the hole free of cuttings and the flow rate above the cuttings bed in case of cuttings accumulation at the low side of the wellbore in the deviated part is also calculated. All these steps are summarized in the excel sheet in the Appendix A as a VBA program.

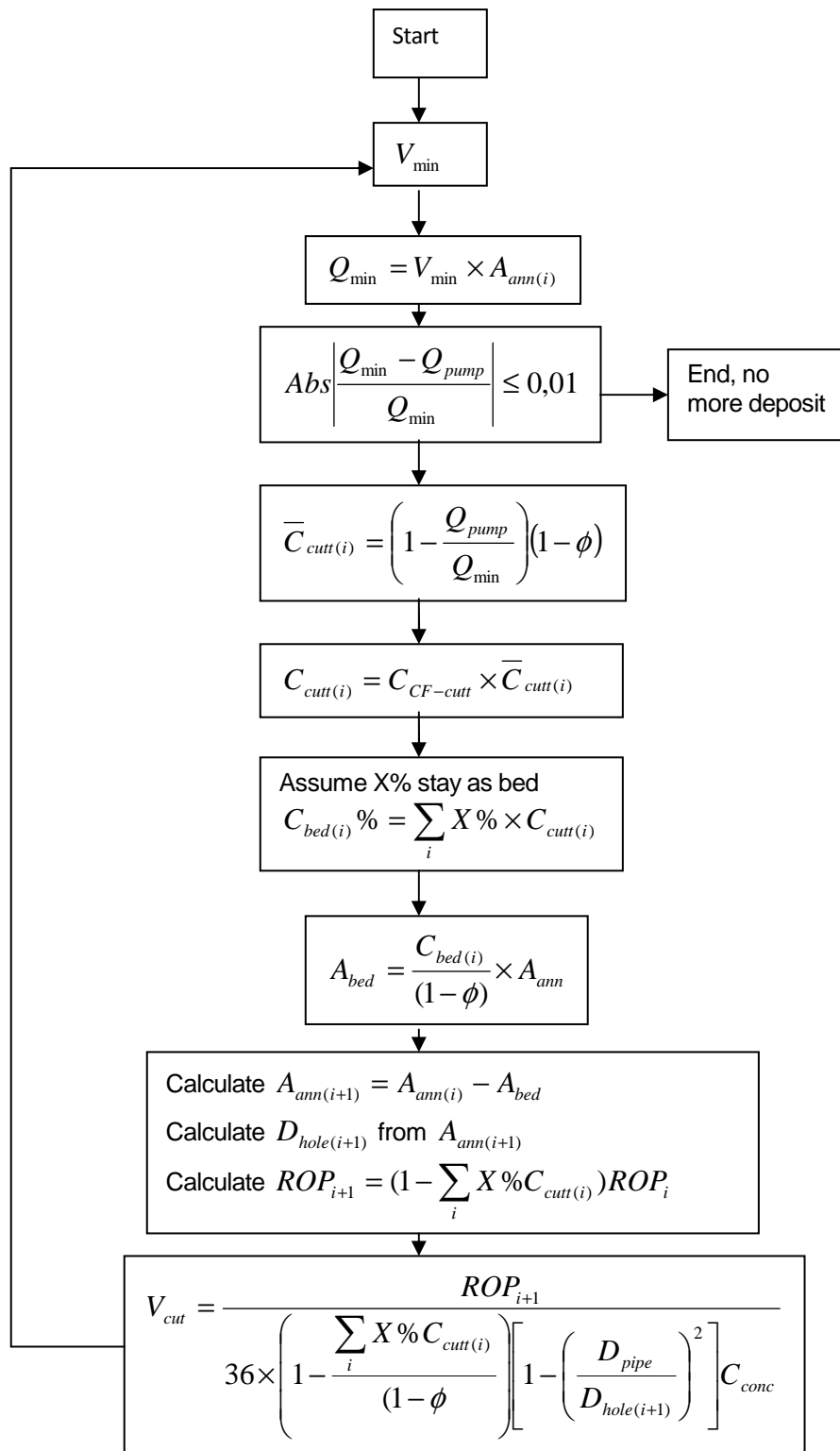


Figure 27: Flow chart of cuttings bed estimation

## 6 Drill String Component influencing Cuttings Removal in Deviated wellbore

In this work, three wells drilled with Standard Drill Pipe, and one well drilled with the Hydroclean Drill Pipe are analysed. Others use hardware like Cuttings Bed Impellers and Helical Drill Pipe will also be discussed.

### 6.1 Well drilled using Standard Drill Pipe

Drill pipe is arguably the most overlooked and taken for granted component in directional drilling. The drill string, made up of separate joints of pipe, is the link between the drill unit and down hole components. For the directional drilling, pipe must withstand tremendous forces generated during the drilling and pullback. Each length of the pipe must be steered effectively, yet has sufficient rigidity not to break or become permanently bent. Connections must be durable to resist wear from repeated used. The 5 inches and 5 1/2 inches outer drill pipe diameter are the most used. The properties of the 5" and 5 1/2" Standard Drill pipe in API/SI units are summarised in the table 3 and table 4 as:

5" Standard Drill Pipe				
DP	Grade	Weight	API Units Max. Tensile Load	Rated Load (80% Load)
(in)		(lbs/ft)	(lbs)	(lbs)
5	19.5	E-75	395,595	316,476
5	19.5	X-95	501,087	400,870
5	25.6	E-75	530,144	424,115
5	19.5	G-105	553,633	442,906
5	25.6	X-95	671,515	537,212
5	50.0	HWDP	690,750	552,600
5	19.5	S-135	712,070	569,656
5	25.6	G-105	742,201	593,761
5	25.6	S-135	954,259	763,407

Table 3: 5" Standard Drill Pipe specification in API Units

5" Standard Drill Pipe				
DP	Grade	Weight	API Units Max. Tensile Load	Rated Load (80% Load)
(mm)		(kg/m)	(daN)	(daN)
127	E-75	29	176,000	140,800
127	X-95	29	223,000	178,400
127	E-75	38	239,900	191,920
127	G-105	29	246,400	197,120
127	X-95	38	298,800	239,040
127	HWDP	74.4	307,000	245,600
127	S-135	29	316,900	245,600
127	G-105	38	330,300	253,520
127	S-135	38	424,600	339,680

Table 4: 5" Standard Drill Pipe specification in SI Units

### 6.1.1 Field experience

For the purpose of this thesis, four case studies are analysed to illustrate the effect of the poor hole cleaning on the Non-Productive Time (NPT). All these wells are deviated wellbore and one of them was drilled with Hydroclean Drill Pipe (HDP) and the three other with Standard Drill pipe. The directional drilling data, the operation company end of the well report were analysed in order to identify the problems related with the cuttings removal and calculated the Non-Productive Time (NPT) per day due to the poor hole cleaning. The NPT in these analyses are obtained from the directional daily drilling report by adding the back-reaming time, wiper trip time, sweeps utilization time, and all the lost time to get the drill string free in case of stuck pipe. And all the other drilling operations are summarized as the Productive time (PT) and are not of interest in this thesis. These wells are: Well P, Well H, and Well G. In these three wells, standard S135, and G105 drill pipes of 5 inches outer diameter were used from the top of the BHA to the surface.

#### *Well P*

The deviated part of the well P was drilled in two sections, the 12 ¼" section drilled from 450 meters to the measured depth of 1416 meters and the 8 ½" section drilled from 1416 meters to the Total Depth (TD) of 2245 meters. Five Bottom Hole Assemblies were run from top to bottom of the hole to reach the TD.

**First section:** 12 ¼” open hole section

- The trajectory of the wellbore is a build and hold type, and the section is drilled in sliding and rotating mode.
- The Standard Drill pipe of 5 inches, S 135 grade, 19, 5 ppg, 4, 276 ID and Heavy Weight Drill Pipe of 5 inches are used from the top of the BHA to the surface
- The Kick Of Point (KOP) is at the depth of about 400 meters
- The start drilled from vertical to end up with 79° of inclination at 1416 meters.
- At 500 meters, the hole inclination reach 30°. And the BHA composes of PDC bit, Motor, MWD tool, Drill Collar, and HWDP with a length of 330 meters were used for the section.
- The sliding time in this section is 181, 1 hours and the average sliding ROP is 7, 60 meter per hour. The section is drilled with a total 10 days.
- The maximum Torque on bottom reach while drilling this section is 16000 N-m.
- Flow rate vary from 2500 to 2800 liters per minute and the rotation is around 50 rpm.
- Mud type is a K<sub>2</sub>CO<sub>3</sub> polymer mud, with Specific Gravity between 1,13SG to 1,22SG, the PV of 20 cp, YP of 25 lb/100 sqft and the viscosity of 55 cp.
- The pump pressure on bottom varies between 185 to 205 bars.
- The maximum dogleg severity which represents the build/drop and turn rates was about 8°/30m and the average dogleg in the section at 5, 2°/30m.
- The formation in this well is mainly clay formation.

**Second section:** 8 ½” open hole section

- The section is drilled with a Rotary Steerable System (RSS) 1416 meters to the TD of 2245 meters.
- The Standard Drill pipe of 5 inches, S 135 grade, 19 ppg, 4, 276 ID and Heavy Weight Drill Pipe of 5 inches are used
- At about 2100 meters the well is horizontal, with the end inclination of 90°.



- The flow rate varies from 1700 to 2100 liters per minute which is less than the first section and the rotation of the Standard Drill Pipe is increased at 70 rpm.
- Back-reaming rotation speed is at 45 rpm
- The mud type is the same as for the first section and the specific gravity varies from 1, 10 to 1, 18 SG with a PV of 33 cp and YP of 16 lb/100sqft.
- The formation type in this second section is dominated by the clay formation
- The Torque on bottom varies 14000 N-m to 18000 N-m
- The dogleg severity which represents the build/drop and turn rates of this section was about 5, 96°/30m
- The section of this well is drilled in 10 days and only in the rotation mode.
- The BHA is composed of PDC bit, Motor, MWD tool, DP, and HWDP with the length of about 485 meters and three runs were used to drill to the TD.

## ***Well H***

The well H is drilled from 450 meters to 2550 meters with a KOP at 400 meters

- The 8 ½” section will be for interest, and start from 450 meters to 2100 meters
- The Standard Drill pipe of 5 inches, G 105 grade, 19 ppg, 4, 276 ID and heavy weight drill pipe of 5 inches are used in this section.
- The well start at 10° inclination at 450 meters and end up with 46° at the TD
- At 1100 meters, we reach 46° inclination, and which was held till the end of the well.
- At the measured depth of 500 meters we have an angle of about 30°.
- The flow rate is about 1800 to 2000 liters per minute and the rotation varies around a minimum of 40 rpm and a maximum of 60 rpm.
- The mud type is Oil Based Mud with the specific gravity varying from 1, 15 to 1, 22 SG and the PV of 24 cp and YP of 25 lb/100 spft.

- The formations are alternated between limestone, marl, shale and dense limestone in this section
- The pressure varies from 130 to 185 bars and the formation is a clay formation.
- The section is drilled in 9 days with 6 BHA runs with the length of 425 meters for each.
- The dogleg severity which represents the build/drop and turn rates of the section was about 6, 2°/30m
- The sliding time is about 170, 5 hours and the average sliding ROP is 4, 63 meter per hour.

## *Well G*

The well G is a geothermal well. The drilling data of this well are summarised as follow:

- The section is 12 ¼” open hole drilled from 1025 meters to 1725 meters with a KOP at approximately 700 meters.
- The wellbore trajectory is a build-hold-drop type, and at 1000 meters we reach an inclination angle of 30°. The maximum angle of about 46° is reached at 1500 meters which was held till the measured depth of 1625 meters.
- The Drill pipe of 5 inches, S 135 grade, 19 ppg, 4, 276 ID size is used form the BHA to the surface, and the BHA is about 415 meters length.
- Up 1625 meters, the inclination angle starts to drop and reach 29° of inclination at the TD.
- The torque on while drilling this section varies between 18100 Nm to 22000 Nm.
- The flow rate varies between 2300 liters per minute and 2800 liters per minute and the rotation varies between a minimum of 35 rpm and maximum of 80 rpm.
- The formations are alternated between limestone, marl, shale and dense limestone in this section
- A polymer mud with the specific gravity between 1, 02 to 1, 09 SG, PV of 15 cp and YP of 24 lb/100sqft are used.

- The average dogleg severity of the section which represents the build/drop and turn rates was about 8, 52°/30 m
- The sliding time is 92 hours and the average sliding ROP is 4, 90 meter per hour. This section is drilled within 17 days.

### **6.1.2 Most related problems with Standard Drill Pipe**

During the drilling process in the high deviated section, following problems are common while drilling with the standard drill pipe based on the field experiences and field observations:

- Poor hole cleaning at the lower part of the wellbore is common in the section higher than 30° inclination angle
- Poor agitation of the cuttings to the high side of the wellbore
- Reduction of the penetration rate after cuttings bed formation

### **6.1.3 Economic evaluation**

Based on the both daily drilling report and end of the well report of the operation company and the service company (Weatherford), many wells drilled with standard drill pipe were carefully analysed. In order to make the economic evaluation, a linear regression analysis of the Non-productive time (NPT) of all the data over the drilling depth were performs. The NPT in this analysis correspond to the back-reaming time, wiper trip time, sweeps utilization time, and all the lost time related to the poor hole cleaning like already mentioned. A safety margin of 20% is used in the correction of the calculated cumulative NPT to allow more accuracy of the results. The connection time and the survey time are for example considered as PT. In this thesis two sections of the wellbore were analyzed, the 12 ¼ inches section, and the 8 ½ inches sections. In each section, the daily NPT and PT are calculated per minute (per hours), for a daily meter depth drilled. Having calculated the NPT for each day, the total NPT for the section will be calculated and convert into cost in order to evaluate the losses (cost) due to the poor hole cleaning. As already mentioned into the previous chapter the depth below 30° of inclination from the vertical is considered to be trouble less, and without

cuttings accumulation problem. The section of interest for this performance analysis is between 30° to 90° inclination from the vertical.

**Well P:**

***12 ¼ inches section:***

The 12 ¼” section of the well P is drilled to the total depth (TD) of 1416 meters and the end inclination angle of 79° from the vertical. From 0 to 500 meters, the inclination is below 30° and from approximately 500 to the TD of 1416 meters the inclination exceeds 30°. The Figure 28 showed the change of the cumulative NPT versus cumulative drilled depth in the 12 ¼” section of the well P. The blue dotted are used in the graph to show the real NPT per cumulative depth. The pink line represents the predicted cumulative NPT over the cumulative depth after regression analysis. And the yellow line represents the corrected cumulative NPT which takes into the consideration the loss none related to the poor hole cleaning.

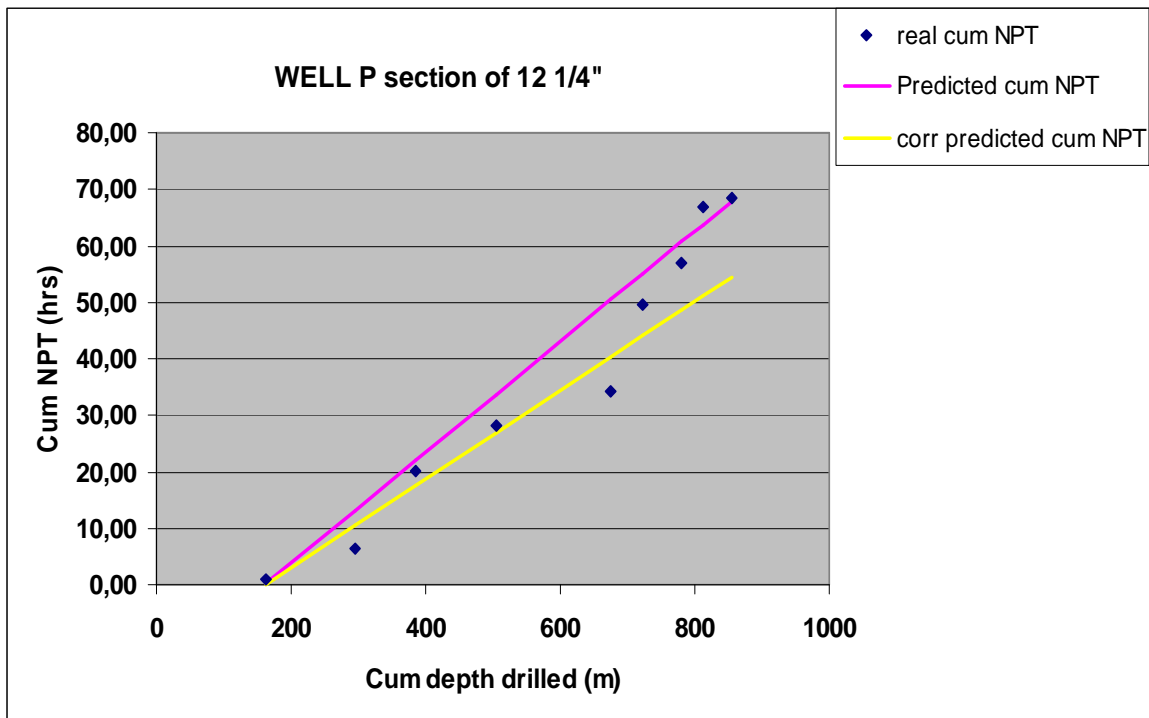


Figure 28: Cum NPT versus Cum depth drilled of the 12 ¼ “section of the well P

The x-axis represent the cumulative depth drilled above 30° of inclination, and the y-axis their cumulative daily NPT due to poor hole cleaning. At the end of the section the cumulative NPT after correction is about 53 hrs. This 20 % of safety factor are used to make

the analyse more accurate because not all the reported back-reaming, wiper trip, etc... are due to the poor hole cleaning.

The equation for the calculated pink line ( cumulative NPT) can be expressed as follows:

$$CumNPT(hrs) = 0,0979 * Cumdepth - 15,67 \tag{Eq.61}$$

And with the 20% safety factor the equation become:

$$CumNPT(hrs) = 0,0783 * Cumdepth - 12,54 \tag{Eq.62}$$

By comparing the factors that multiply the cumulative depth, we can be able to deduct the efficiency of the hole cleaning in the section. So if we have less NPT this means that we also have less hole cleaning problem, less time loss while drilling the section. And the figure below shows us the behaviour of the NPT per meter each day.

The figure 29 (below) shows how the NPT varies per meter in this section. The three first days we have an increase of the NPT/m, and which decrease again at the end of the section. So no conclusion can be taking actually with this section.

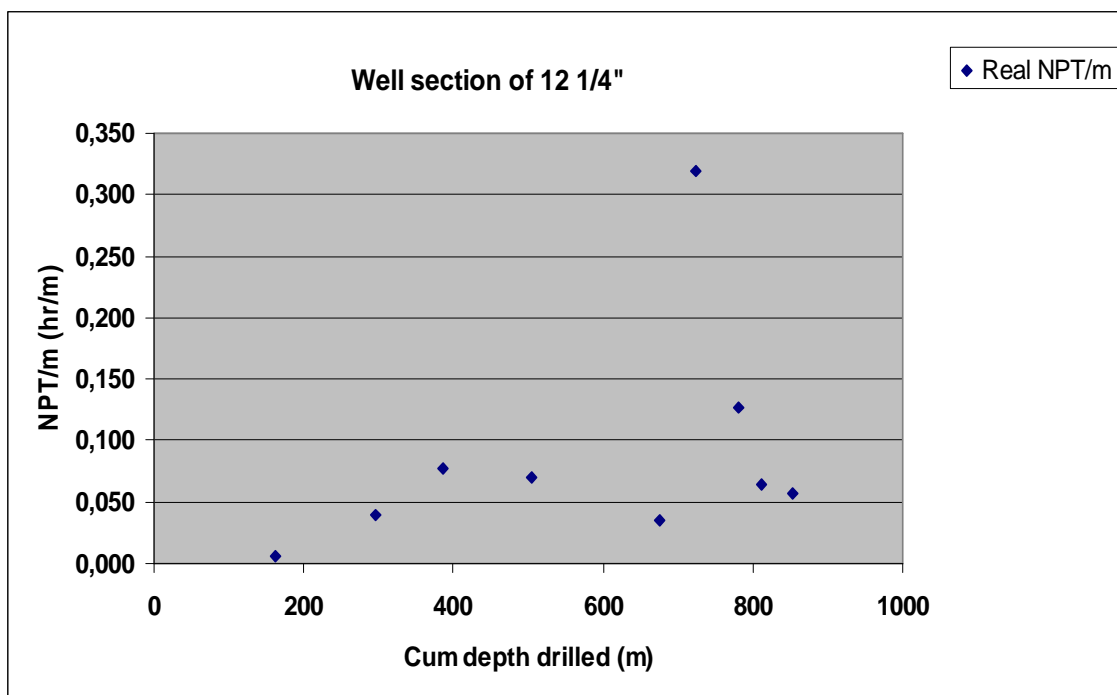


Figure 29: NPT per meter versus Cum depth drilled of the 12 1/4 “section of the well P

**Cost analysis:**

The following drilling cost due to the poor hole cleaning has been calculated for this critical 12 1/4” section, on the basis of well report time breakdown analysis for the well P.

The prices uses in the economic evaluation are not standard, but just assume for the purpose of this work. The 12 ¼” section of this well was drilled within a total of 9 days. The total NPT during the 9 days are calculation and evaluate in cost in the table 6 (below):

Rig rate per day: 40,000 \$/day

Daily production rate: 500 bbl/day

Days Drilled	NPT(hours)	NPT(days)	NPT Cost
9	54,38	2,26	90.400\$

Table 6: Cost of the NPT at the end of the section

The late oil production interest of the field must also be estimated in order to give a good idea about the total amount loss at end job by the operation company. The table 7 (below) give of summarize of the cost and days losses:

Actual price per Barrel	90,00 \$
Late production days	3,20
Production per day(bbl)	500
Loss production interest due to poor hole cleaning	144.000 \$
Late production interest (10%)	14.400 \$

Table 7: Total amount loss for the 12 ¼”section

The total amount loss at the end of this section of the well is about 104.800 \$ within 9 days which represent a huge amount of money.

**8 ½ inches section:**

This section of the well H is drilled from 1416 meters to the Total Depth (TD) 2245 meters, with 79° of inclination at the TD. The same linear regression analysis is made (i.e. the 12 ½” section) with the 8 ½” hole section and the Cum NPT curve can be generated with the equation:

$$Cum.NPT = 0,1306 * Cum.depth - 17,609 \tag{Eq.63}$$

And with the safety margin of 20 % the equation will be as follow:

$$Cum.NPT = 0,1045 * Cum.depth - 14,087 \tag{Eq.64}$$

Where,

*Cum.NPT* : represents the cumulative non-productive for a drilled interval cumulative

*Cum.depth* : represents the cumulative interval drilled

The analyze of this field data start at the interval drilled above 30° of inclination which in present situation is 143 meters. The graph in the figure 30 shows that at the end of the drilling section, the cumulative NPT in the field based on the analysis used is about 65 hours. The blue dotted are used in the graph to show the real NPT per cumulative depth. The pink line represents the predicted cumulative NPT over the cumulative depth. And the yellow line represents the corrected cumulative NPT which takes into the consideration the loss none related to the poor hole cleaning.

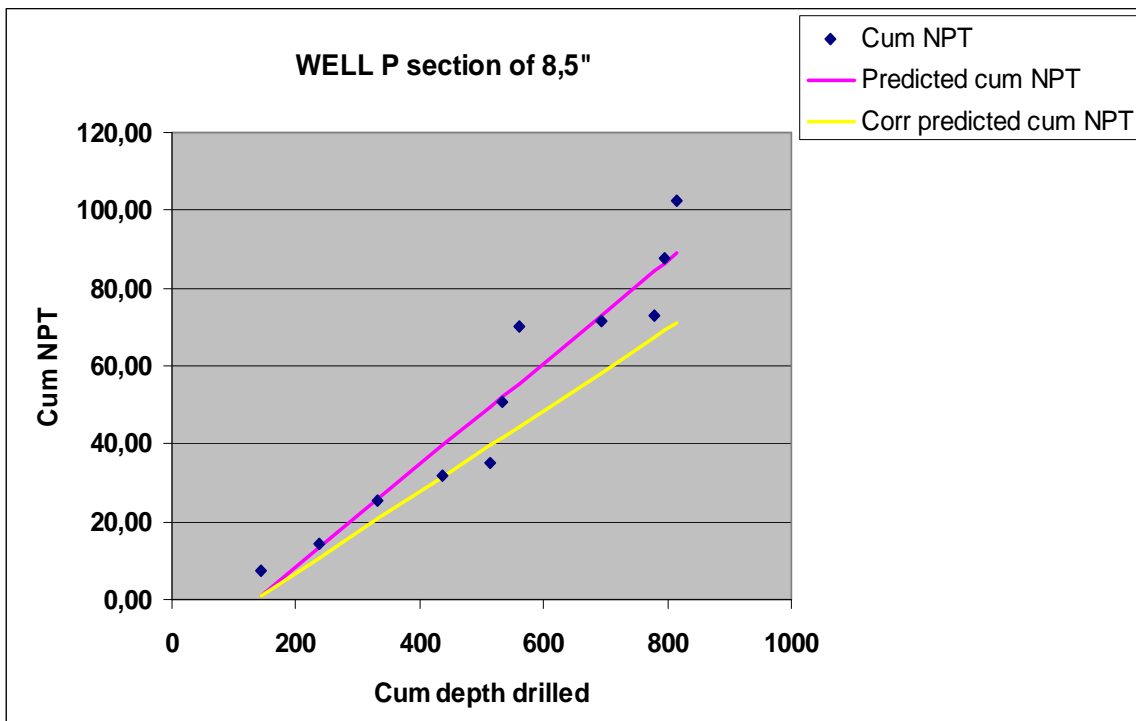


Figure 30: Cum NPT versus Cum depth drilled of the 8 ½ “section of the well P.

The figure 31 represents the NPT per meter of the section. The blue dotted points are the NPT/meter in each interval drilled per day. The minimum NPT/meter is about 0.03 m/h for the third day and 0.28 m/h reach in the 6 days.

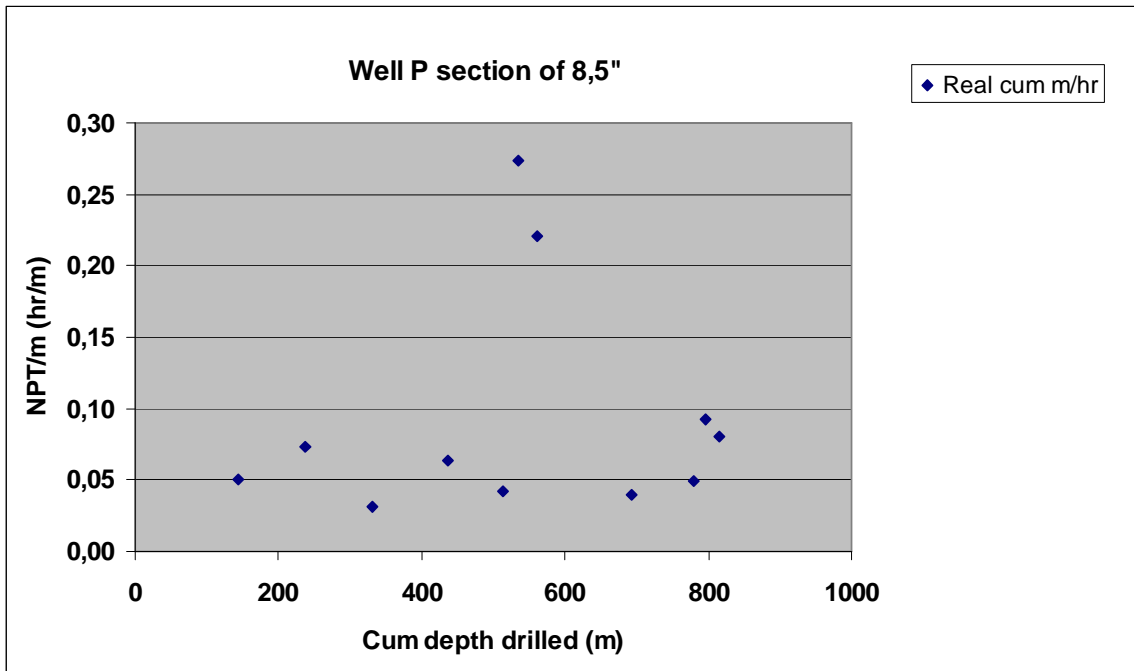


Figure 31: NPT per meter versus Cum depth drilled of the 8 ½ “section of the well P.

**Cost analysis**

For this section of the well, the job was done within 11 days.

The expenses due to the NPT are listed in the table 8 based on the same input as in the first section. The table 8 summarizes the only NPT related to the poor hole cleaning action on the rig site in 11 days drilled, and the corresponding additional rig cost.

Rig rate per day: 40,000 \$/day

Daily production rate: 500 bbl/day

Days Drilled	NPT(hours)	NPT(days)	NPT Cost
11	71,21	2,96	118.400 \$

Table 8: Cost of the NPT at the end of the 8 ½”section

The table 9 resumes the calculation of the total amount loss in this section of the well. Assuming the price of a barrel oil today at 90,00 \$, the late production interest after a certain years of production will be add to the rig cost time to give us and idea of the total losses.

Actual oil price per Barrels	90,00 \$
Late production days	3,28
Production per day(bbl)	500



Loss production interest due to poor hole cleaning	147.600 \$
Late production interest (10%)	14.760 \$

Table 9: Total amount loss for the 8 ½”section

The Total amount loss due to the hole cleaning and the late oil production interest of this 8 ½”section is 118.400 \$ for the 10 days required to drilled the section.

## **Well 2: well H**

### ***8 ½ inches section:***

The well H is a deviated well with a TD of 2550 meters and with 67° of inclination angle at the Total Depth. Only the 8 ½” section of this well is analysed because it is the section where we can have hole cleaning problems based on the offset well drilled in the region. The other sections of this well will not be of interest for the analysis. The daily NPT and the PT are calculated in the same manner as in the well H. Based on the regression analysis, the equation obtained can used for the 8 ½” section of this well. Per section, they are just one equation that can be applied for the calculation of the cumulative NPT. This predicted line obtained with the by plotting the cumulative NPT versus the cumulative interval depth drilled is a tool for the comparison of the cleaning efficiency of the well.

The equation obtain for the predicted cumulative NPT is the follow:

$$Cum.NPT = 0,0470 * Cum.depth - 7,345 \quad (Eq.65)$$

And with the safety margin of 20 % the equation will be as follow:

$$Cum.NPT = 0,0376 * Cum.depth - 5,876 \quad (Eq.66)$$

Where,

*Cum.NPT* : represents the cumulative non-productive for a drilled interval cumulative

*Cum.depth* : represents the cumulative interval drilled

From the equation (with 20% safety), with the cumulative metrage drilled of 2030 meters, the maximum NPT at the end of the section is about 70,44 hours. The blue dotted are used in the graph to show the real NPT per cumulative depth. The pink line represents the predicted cumulative NPT over the cumulative depth. And the yellow line represents the corrected cumulative NPT which takes into the consideration the loss none related to the poor hole cleaning.

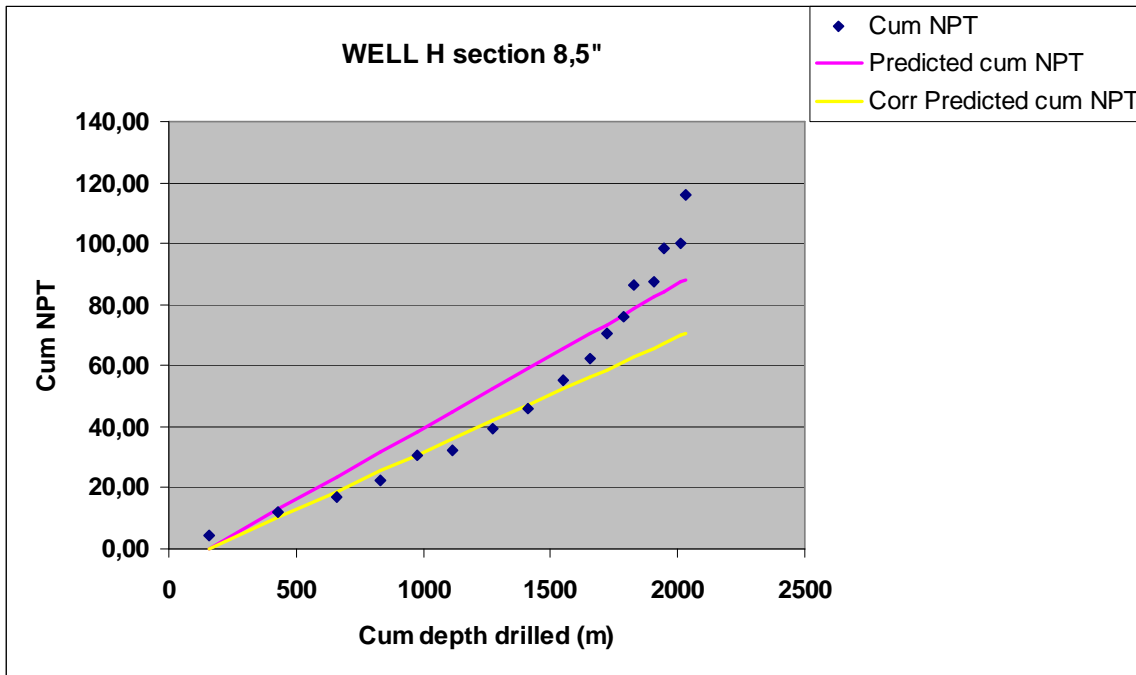


Figure 32: Cum NPT versus Cum depth drilled of the 8 1/2 "section of the well H

The graph of the figure 33 below represents the NPT per meter of this 8 1/2" section. The NPT/meter in this section is increasing with depth but varied depending of a lot of parameters like formations, drilling practice, and also poor hole cleaning. The dotted points represent the NPT/m drilled in each day. In this section the NPT/m has a tendency to increase with drilled depth and inclination.

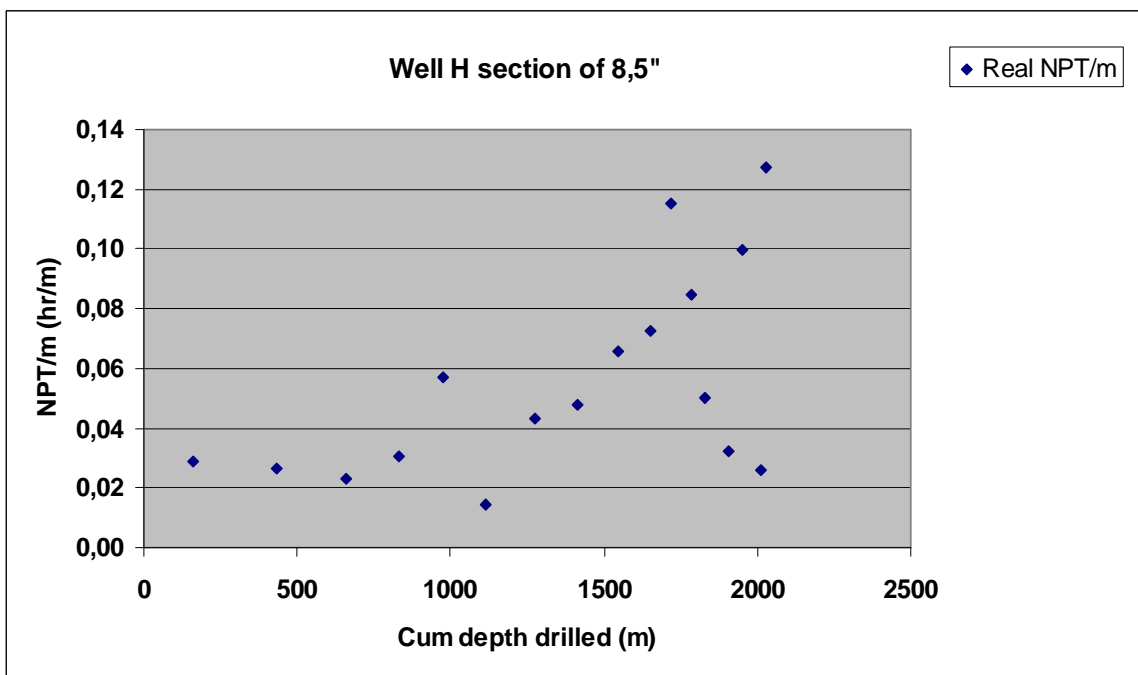


Figure 33: NPT per meter versus Cum depth drilled of the 8 1/2 "section of the well H

### Cost analysis

The 8 ½” open hole section of the oil well H was drilled in 17 days. The cumulative NPT is converted into cost to be able to estimate the economic impact of the poor hole cleaning. After having calculated the total NPT in this section of the wellbore, the total losses are calculated based on following data (See also table 10):

Rig rate per day: 40,000 \$/day  
Daily production rate: 500 bbl/day

Days Drilled	NPT(hours)	NPT(days)	NPT Cost
9	70,44	2,94	117.600 \$

Table 10: Cost of the NPT at the end of the 8 ½”section

They are addition cost due the late production of the well that must be taken into consideration, which can be estimated as in the table 11:

Oil price per Barrels	90,00 \$
Late production days(day)	2,40
Production per day(bbl)	500
Amount Loss due to poor hole cleaning	108.000 \$
Late production interest (10%)	10.800 \$

Table 11: Total amount loss for the 8 ½”section of the well H

The total amount loss due to poor hole cleaning and late production interest of this well is estimated at 128.400 \$.

### Well 3: Well G

The well G is drilled the starting depth of 1000 meters to the end at the TD of 1742 meters. The maximum angle of the well path is about 45° and the target is reached at 30° of inclination. The well in this section has a hole diameter of 12 ¼”, whereas the depth at about 1050 meters has 30° of inclination. The cumulative NPT is predicted based on the equation obtained from the regression analysis with the equation:

$$Cum.NPT = 0,084 * Cum.depth - 0,410 \quad (Eq.67)$$

And with the safety margin of 20 % the equation will be as follow:

$$Cum.NPT = 0,068 * Cum.depth - 0,328 \tag{Eq.68}$$

Where,

*Cum.NPT* : represents the cumulative non-productive for a drilled interval cumulative

*Cum.depth* : represents the cumulative interval drilled

The Figure 34 (below) shows the cumulative NPT, the predicted cumulative NPT and the corrected predicted cumulative NPT versus the cumulative depth drilled. The blue dotted are used in the graph to show the real NPT per cumulative depth. The pink line represents the predicted cumulative NPT over the cumulative depth. And the yellow line represents the corrected cumulative NPT which takes into the consideration the loss none related to the poor hole cleaning. These NPT are determined based on the drilling report and corrected by 20% of safety margin due to the less accuracy of the daily for such analysis. As already mentioned the NPT include all the losses time due to the poor hole cleaning in the section. In the analysis as already mentioned before, the problems that are not in the direct relation with the gaining metrage during the drilling operation like pump failure, top drive problem and others, are not consider as NPT. In this case we assume the some cases the working day (NPT plus PT) less than 24 hours. The total NPT here is about 48, 23 hours

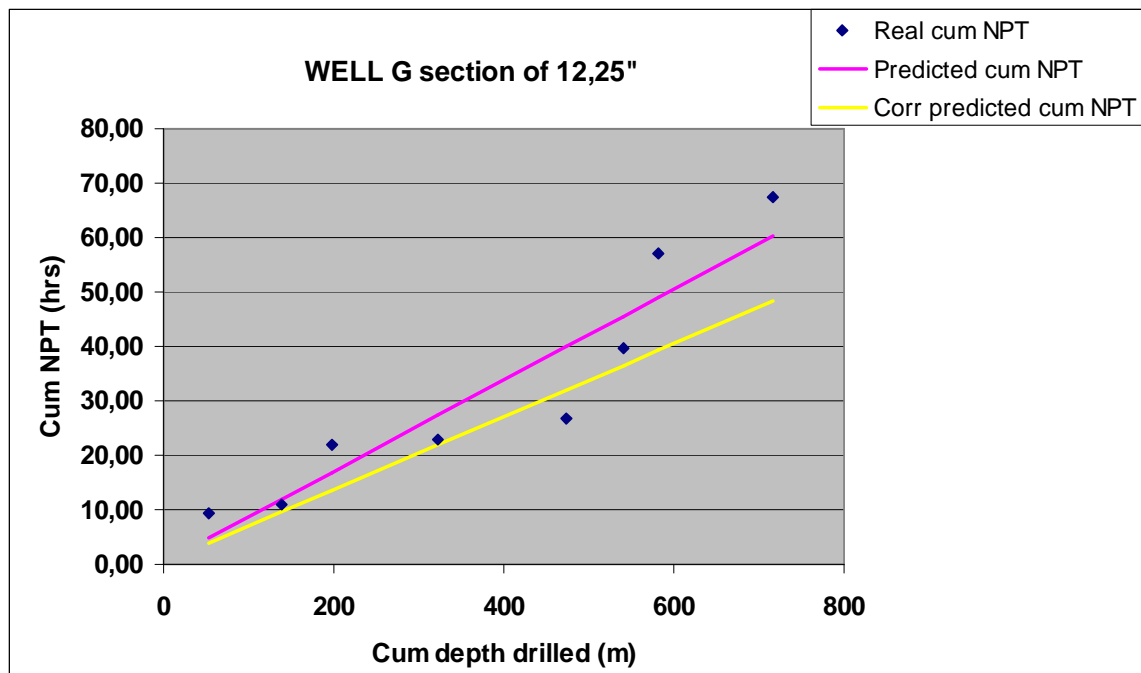


Figure 34: Cum NPT versus Cum depth drilled of the 12 ¼ “section of the well G

The blue dotted points represent the real cumulative NPT of this well. The pink line represents the predicted cumulative NPT above 30° of inclination and the yellow line represents the corrected predicted cumulative NPT. So we can see that the poor hole cleaning really affect and increase the amount of the cost.

The figure 35 (below) represents the NPT per meter of the section. The blue dotted points represent the NPT/m in each day. So in the first day, we have drilled almost 50 meters and have lost 0,04 hour per meter. This time loss is more related to the ROP than the inclination angle in this case. The maximum NPT/m is about 0,14 m/hr and the minimum at 0,02 m/hr. This NPT/meter doesn't increase with the depth and inclination in this section. The goal of this analyse is to finger out if the NPT/m will increase proportionally with the depth and inclination?

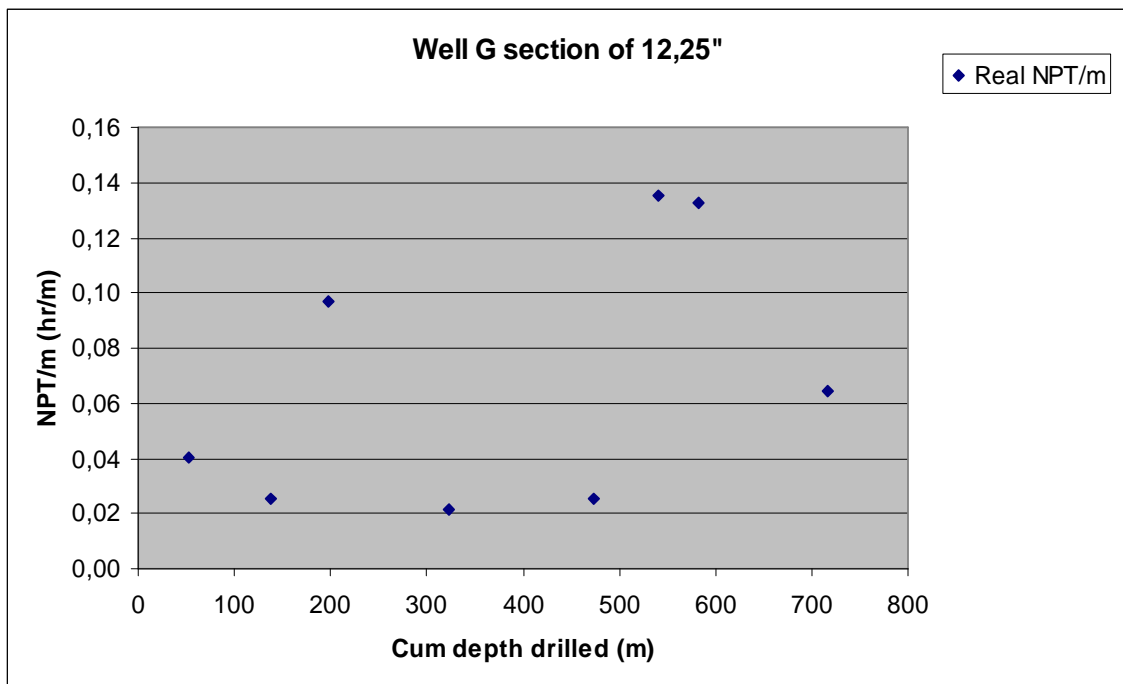


Figure 35: NPT per meter versus Cum depth drilled of the 12 ¼ “section of the well G

**Cost analysis:**

This well was a geothermal well, so just the rig time losses will be consider for the economic evaluation. The total NPT is also calculated and converted into cost. The table 12 shows the total amount losses after 8 days required to drill the section.

Rig rate per day: 40,000 \$/day

Days Drilled	NPT(hours)	NPT(days)	NPT Cost
8	48,23	2,01	80.400 \$

Table 12: Cost of the NPT at the end of the 12 ¼”section

The late production interest is not calculate in this well because is a geothermal well. The total lost due to the poor hole cleaning of this hole in the 12 ½” section is about 80.400 \$.

### **Result and conclusion:**

The total NPT of the each of these three wells analyse above 30° inclination for this work is significantly high. This result will increase the drilling cost and bring us to the question: if this high NPT is due to the drilling practice, to the down hole drill string component used, or both? After the economic evaluation of the three analysis in this thesis, it can be seen that the hole cleaning must be further analyse in order to reduced this huge amount of loss. For these reasons an alternative has to be found such as new drill string components to try to reduce the drilling cost and the daily NPT. For this purpose, in the next chapter an economic comparison between the losses due to the NPT while using Hydroclean Drill Pipe will be analysed in the same area as well G, and H.

## **6.2 Wells drilled using HydroClean Drill Pipe**

### **6.2.1 HydroClean**

In order to optimize the hole cleaning performance, Weatherford has brought into the industry a complete hole cleaning system. The improved system incorporates Hydroclean technology, a tool to maximize the mechanical cuttings recirculation system. The Hydroclean system has been developed in three different types, each integrating both the Hydro-mechanical Cleaning Zones and Hydro-dynamical Bearing Zones, or only the profile for hydro-mechanical cleaning. These tools are:

(1) Hydroclean Drill pipe which has the main functions as follows:

- Optimized the hole cleaning
- Reduced the differential sticking
- Reduced torque and drag
- Improved hydraulic performance

(2) Hydroclean Heavy weight Drill pipe with almost the same functions as the drill pipe to:

- Optimized the hole cleaning
- Reduced the differential sticking
- Reduced torque and drag

(3) and finally the Hydroclean Lo Torque Sub (will be not developed in this thesis) which,

- Reduced torque and drag
- Reduced the casing wear and can be used in cased or open hole

## **Design principles**

The Hydroclean profile is designed with two different zones, the Hydro-mechanical Cleaning Zone (HCZ) and the Hydrodynamic Bearing Zone (HBZ), which interact and provide the two basic effects of the profile; hole cleaning and reduction of friction factor between the bearing areas on the modified drilling equipment and the borewall.

By design principles, the Hydroclean profile is a combination of angles that work in harmony to provide a number of affects resulting in the cuttings being re-introduced into the flow stream.

There are two different alterations of flowing line patterns corresponding to the two different zones of the profile, where there is a hydro-mechanical cleaning effect and a hydrodynamic bearing effect. In order to have a better understanding of the effects developed by the profiles, the following will firstly describe the principles of the geometry.

### **Hydro-mechanical Cleaning Zone (HCZ)**

The profile at the hydro-mechanical cleaning zone features three construction angles,  $\alpha_{hc}$ ,  $\beta_{hc}$  and  $\gamma_{hc}$  angles. The geometry of this profile is composed of five grooves, making the  $\alpha_{hc}$  angle relative to the x-axis of the equipment as shown in the Figure below. These grooves are set at pre-determined angles to the axis of the drill pipe and are optimized for normal drilling rotational speed between 80 rpm and 120rpm. The grooves feature a  $\beta_{hc}$  negative angle, called negative leading edge angle, running in the direction of the rotational speed  $\Omega$ , while the opposite angle  $\gamma_{hc}$  creates a positive angle. The maximum outside diameter  $D_{hc}$  of the Hydro-mechanical Cleaning Zone (HCZ) is always smaller than the minimum diameter of the hydrodynamic bearing zone (HBZ). This will ensure that the hydro-mechanical zone will never be in contact with

the bore wall, as contact is at the larger diameter of the Hydrodynamic Bearing Zone (HBZ).

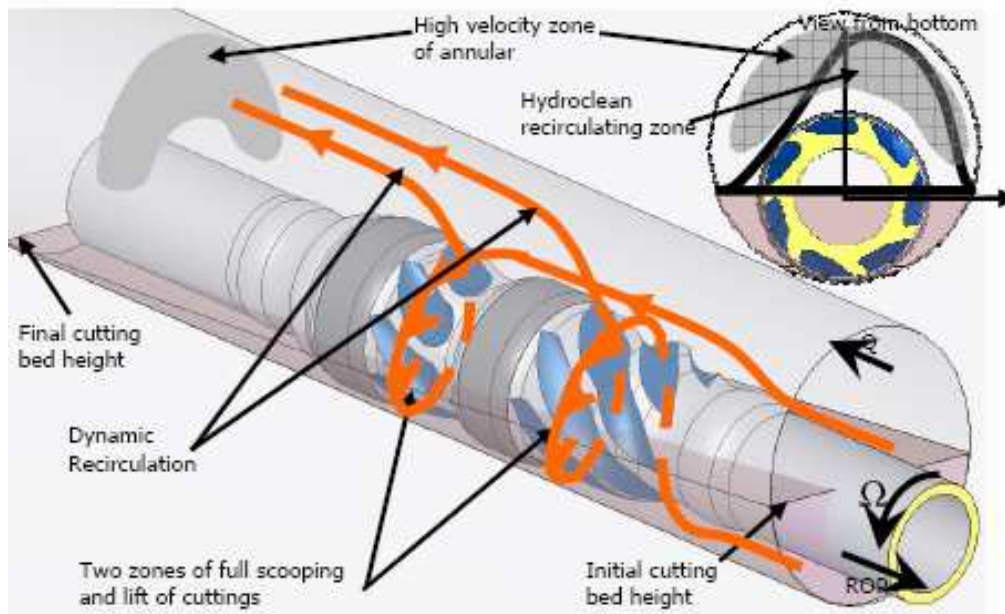


Figure 36: Hydroclean Cleaning Zone (HCZ)

### **Hydrodynamic Bearing Zones (HBZ)**

The profile of the Hydrodynamic Bearing Zone also has five grooves, which are aligned with the five grooves of the Hydro-mechanical Cleaning Zone (HCZ). The hydrodynamic bearing zone sections have positive edge angles  $\theta_1$  and  $\theta_2$  as also shown in the Figure 34. The depth  $d_{hb}$ , and width of the Hydrodynamic bearing zone grooves decreases from inlet to outlet, in order to provide a continuous decrease of the passage areas inside the grooves. The inlet groove on the hydrodynamic bearing zone is aligned with the outlet groove on the hydro-mechanical cleaning zone. External grooves, at inlet and outlet angles, enhance the geometric continuity between the external surfaces of the drilling equipment and the profile itself. The helix angle  $\alpha_{hc}$ , of the hydro-mechanical cleaning zone will be smaller than the helix angle  $\alpha_{hb}$  of the hydrodynamic bearing zone. In order to have a continuous axial bearing while rotating the inclination angle,  $\alpha_{hb}$ , of the profile ensures a ‘tight’ design configuration. This “nose coned” shaped design are just on the second generation of the hydroclean, and are used to decrease friction thanks to a fluid bearing effect between the pipe and the borehole.



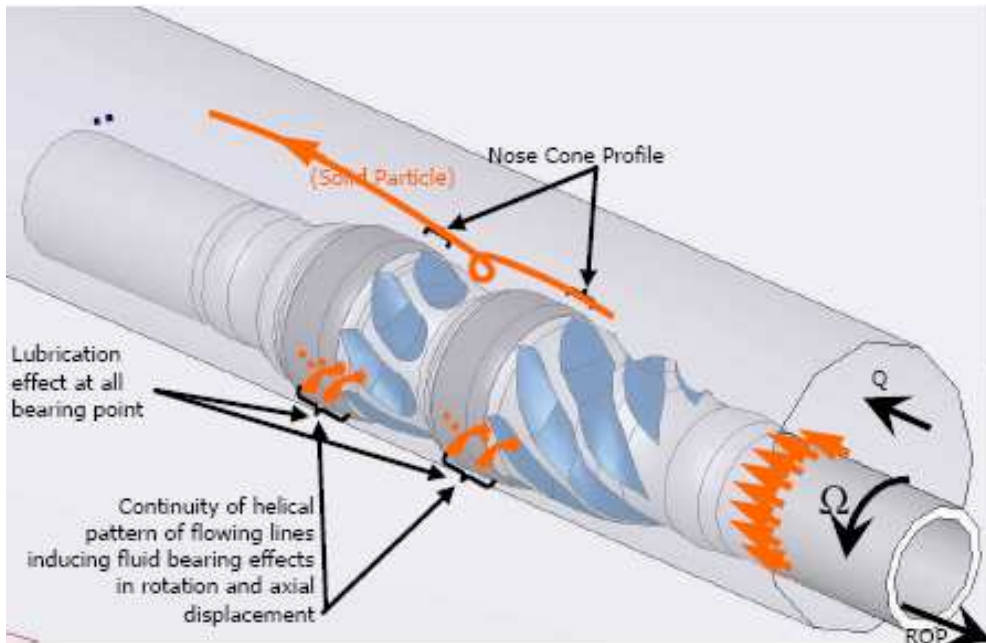


Figure 37: Hydrodynamic Bearing Zone (HBZ)

The two zones of the profile are usually machined together on the outside of drilling equipment, although separate utilization of each zone is possible depending on the primary function of the drilling tools. It should be noted however that the performance of the hydrodynamic bearing zone (HBZ) will be enhanced when it is used with the hydromechanical cleaning zone (HCZ), which will optimize the fluid charge at the HBZ. The Figure 37 below shows the combination of both HCZ and HBZ in a first generation HydroClean Drill Pipe and the different positive and negative angles mentioned before.

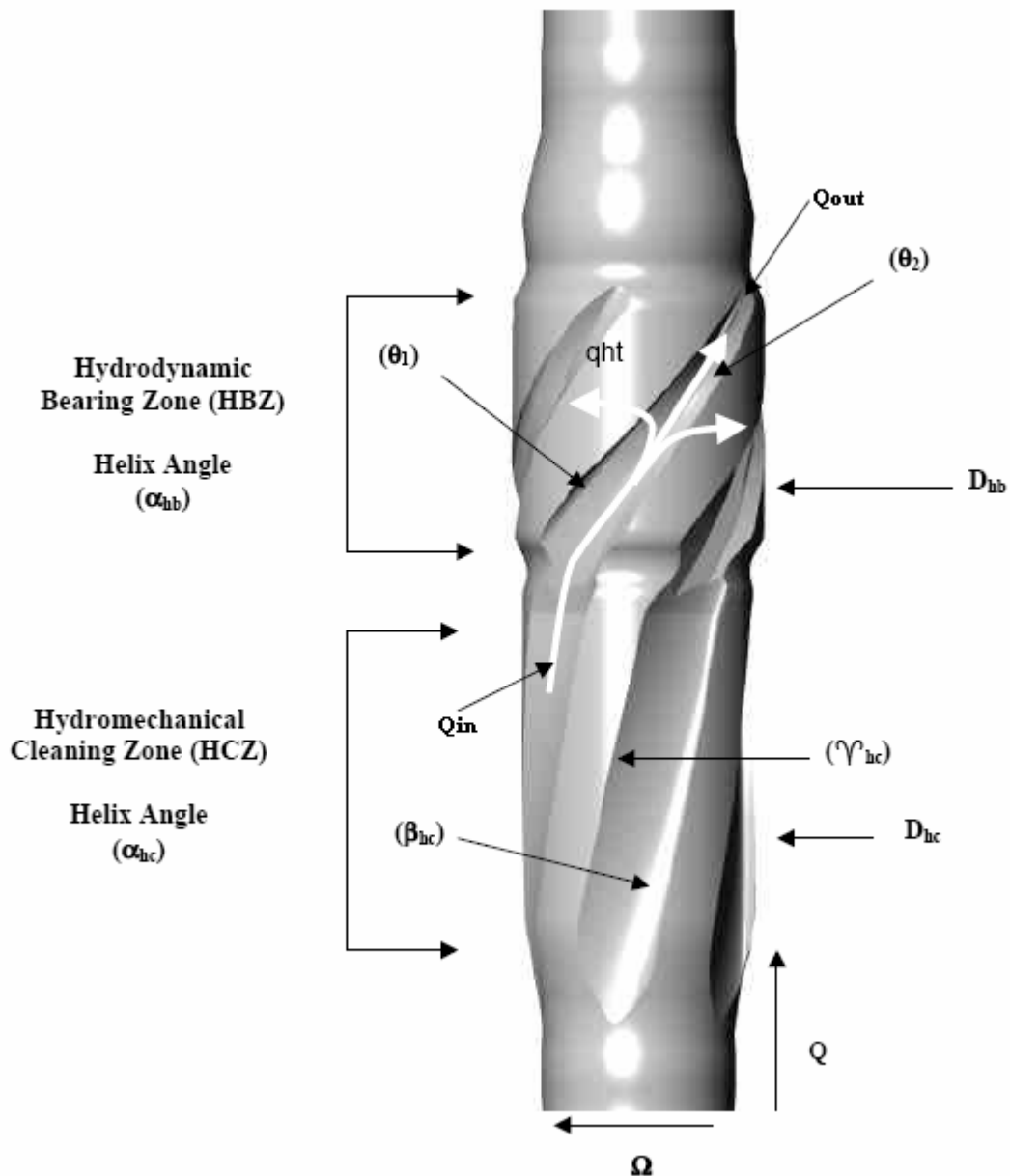


Figure 38: First generation HydroClean profile

### Effect of Hydroclean on solid particles

The combined action of the rotational speed, the flow rate and the features of the *HCZ* and *HBZ* will produce several effects on the cuttings lying on the low side of the wellbore like:

- **Lifting effect:** As the negative angle rotates over a solid particle, it is down up into the groove by the venture effect created by the leading angle as in the Figure 35.

The particles are then held in this vortex and remains inside the groove cavity due to the forces created by the vortex.



Figure 39: Lifting effect of a solid particle

- **Scoop effect:** Almost similar to the lifting effect, the scoop effect is a simple mechanical action where the negative angle digs into the bed and the particles are scooped up and held in place by the same venture affect. This phenomenon is illustrated in the Figure 40.

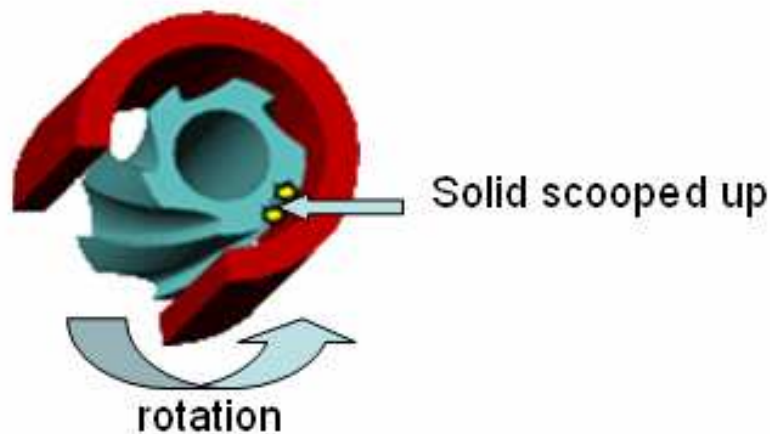


Figure 40: Scooped effect of a solid particle

- **Archimedian Screw Effect:** Once the particles have been held in place by the venture effect, the rotation of the drill pipe will drive them upward. This archimedian screw effect is enhanced as a result of working in combination with the negative angle and the angle at which the groove have been offset to the pipes XX axis otherwise the particles would simply settle back to the low side of the hole. This effect is also illustrated in the Figure 41 below.

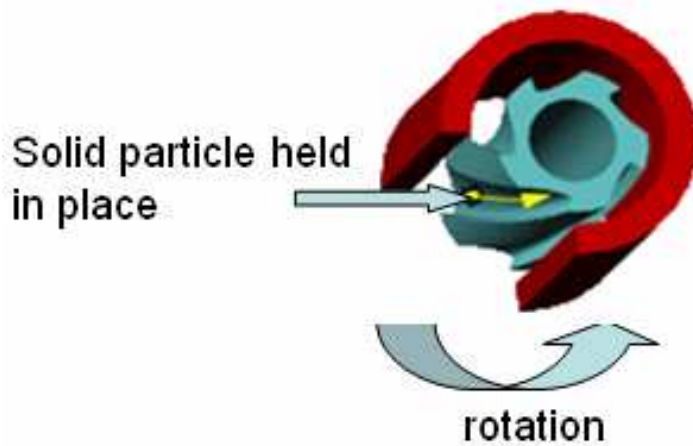


Figure 41: Archimedian screw effect of a solid particle

- **Particle Boosting and Re-circulating:** Here, the particles which are initially pulled into the groove, are accelerated along the profile while sliding to the opposite side where they are propelled and deflected back into circulation at an increased velocity as a result of the combination of the archimedian screw effect, the actual rotation of the drill pipe and the variable depth of the groove. This effect is illustrated in the figure 42(below).

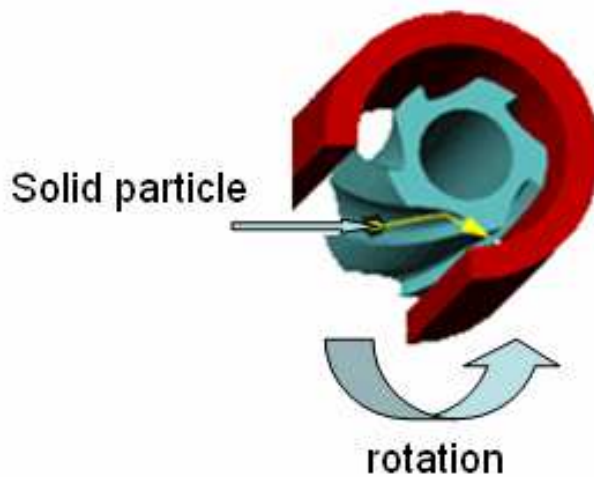


Figure 42: Re-circulation effect on a solid particle

## 6.2.2 Application of HydroClean

The Hydroclean Drill Pipe has been specially designed to run in conjunction with the standard drill pipe for use in extended reach well and other non –conventional wells. The tool can be run in cased as also open hole wells without considerably increasing the friction forces between the borehole wall and the pipe. The full length joint of 31 feet of the hydroclean drill pipe has three central upset and his mechanical strength meets or exceeds that of the S135 standard drill pipe. The hydroclean is suitable to be place one joint every 90 to 100 feet in problem area and in the inclination angle above 35 degrees from the vertical.

The heavy weight drill pipe hydroclean is also designed to be run along with conventional heavy weight and a full length joint is composed of two central upset. The rugged design of the two extended hydroclean sections makes it ideally suited to assist with hole cleaning in the BHA. Experience for the Weatherford crew has shown that placing hydroclean heavy weight as near as possible to the large outer diameter BHA components and one joint every 90 feet provides maximum hole cleaning performance.

### HydroClean specification data

The hydroclean drill pipes and hydroclean heavy weight drill pipes (shown in Figure 43) are constructed in different sizes, ranging from 3 ½ inches to 6-5/8 inches body outer diameter as illustrated in the table 13. These data are very important in the field to avoid fishing problem in case of a lost in the hole of one part of the hydroclean tool during the drilling process.

HYDROCLEAN DRILL PIPE						
Feature		Size				
		3 1/2 in	5 in	5 1/2 in	5 7/8 in	6 5/8 in
A	Body OD	3 1/2"	5"	5 1/2"	5 7/8"	6 5/8"
B	body ID	2 1/2"	4"	4 1/2"	4 3/4"	5 5/16"
C	Tool Joint OD	5"	6 5/8"	7"	7 1/4"	8"
D	Tool Joint ID (NC50)	2 1/4"	3"	3 1/2"	4 3/8"	4 1/4"
E	Dual OD	5 5/8"	7"	7 3/4"	8"	8 3/4"
F	Dual OD Length	6"	5 ½"	5 1/2"	5 1/2"	5 1/2"
G	Bearing Zone Length	8"	8"	8"	8"	8"
H	Bearing Zone OD	5 5/8"	7"	7 3/4"	8"	8 3/4"
I	Hydroclean Length	12"	12"	12"	12"	12"
J	Max. Hydroclean OD	5 1/8"	6 ½"	7 1/4"	7 1/2"	8 1/4"
K	Central Upset Spacing	7' 6"	7' 6"	7' 6"	7' 6"	7' 6"
L	Joint Length(ft)	31'	31'	31'	31'	31'

Table 13:HydroClean Drill Pipe specification

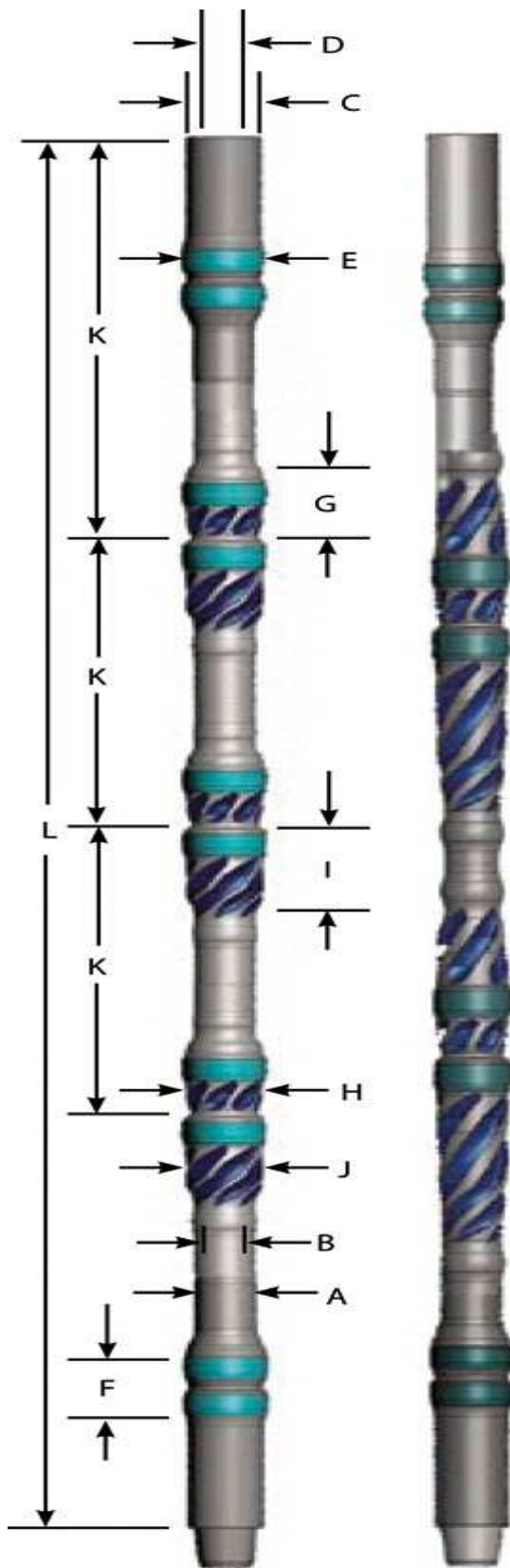


Figure 43: Left Hydroclean Drill Pipe and right Hydroclean Heavy Weight

And this table 14 is also represented the Hydroclean specification but in metric units.

<b>HYDROCLEAN DRILL PIPE</b>						
<b>(mm)</b>		3 1/2 in	5 in	5 1/2 in	5 7/8 in	6 5/8 in
A	Body OD	88.9	127	139.7	149.225	168.275
B	body ID	63.5	101.6	114.3	120.65	134.938
C	Tool Joint OD	127	168.275	177.8	184.15	203.2
D	Tool Joint ID (NC50)	57.15	76.2	88.9	111.125	107.95
E	Dual OD	142.875	177.8	196.85	203.2	222.25
F	Dual OD Length	152.4	139.7	139.7	139.7	139.7
G	Bearing Zone Length	203.2	203.2	203.2	203.2	203.2
H	Bearing Zone OD	142.875	177.8	196.85	203.2	222.25
I	Hydroclean Length	304.8	304.8	304.8	304.8	304.8
J	Max. Hydroclean OD	130.175	165.1	184.15	190.5	209.55
K	Central Upset Spacing	2286	2286	2286	2286	2286
L	Joint Length	9448.8	9448.8	9448.8	9448.8	9448.8

Table 14: HydroClean Drill Pipe specification in metric units

And the two others table 15 and table 16 represented the lists of the specifications of the HydroClean Heavy Weight Drill Pipe run in the drill string and mostly run in the BHA is used to increase the weight at the bit while drilling.

<b>HYDROCLEAN HEAVY WEIGHT</b>						
<b>Feature</b>	<b>Size</b>					
	3 1/2 in	3 1/2 in	5 in	5 1/2 in	5 1/2 in	6 5/8"
Nominal OD	3 1/2"	3 1/2"	5"	5 1/2"	5 1/2"	6 5/8"
Connection*	NC 38	WT 38	NC 50	FH DSTJ	HT 55	FH
Tube ID	2 1/16"	2 1/16"	3"	3 3/4"	3 3/4"	4 1/2"
Central Upset OD	5"	5"	6 5/8"	7"	7"	8"
Tool Joint OD	5"	5"	6 5/8"	7"	7"	8"
Tool Joint ID	2 1/16"	2 1/16"	3"	3 3/4"	3 3/4"	4 1/2"
Weight(lb/ft)	31.15	31.15	57.97	58.42	58.42	82.97
Length(ft)	31	31	31	31	31	31

Table 15: HydroClean Heavy Weight Drill Pipe specification in imperial units

<b>HYDROCLEAN HEAVY WEIGHT</b>						
Nominal OD	88.9	88.9	0	139.7	139.7	168.275
Connection*	NC 38	WT 38	NC 50	FH DSTJ	HT 55	FH
Tube ID	52.388	52.388	76.2	95.25	95.25	0
Central Upset OD	0	127	168.275	177.8	177.8	203.2
Tool Joint OD	127	127	168.275	177.8	177.8	203.2
Tool Joint ID	52.388	52.388	76.2	95.25	95.25	114.3
Weight(kg/mm)	0.045	0.045	0.082	0.084	0.084	0.119
Length	9448.8	9448.8	9448.8	9448.8	9448.8	9448.8

Table 16: HydroClean Heavy Weight Drill Pipe specification in metric units

### **6.2.3 Field data analysis and result**

One well drilled with HDP in the jungle of Peru in America was analysed to make a technical and economical comparison with the wells drilled with Standard Drill Pipe. This well was an oil field well and the characteristics of the well are as follow:

#### **WELL C**

The operator company of this well due to the experience of poor hole cleaning in the region decided to use the HDP to increase the cuttings removal. The well is drilled from the KOP 200 meters to the TD of 3522 meters by Weatherford.

- At 880 meters we have an angle of 47° inclination and this is constant to the TD.
- The trajectory of the wellbore is a build and hold type and the inclination of 30° is reach at 550 meters measured depth.
- The BHA was about 489 meters and with that BHA, the tangent section of 2952 meters MD was drilled.
- The flow rate was between 1700 and 2080 liters per minute and the rotation varied from 80 to 110 rpm.
- Oil Based Mud with the specific gravity of 1, 38 SG was used and the pressure on bottom was about 172 bars.



- The formations was alternated between limestone, marl, shale and dense limestone in this section
- The torque at the surface was between 19000 N-m and 22500 N-m.
- For drilling this well, 42 joints of 5” Hydroclean Drill Pipe (HDP) and 3 joints of Hydroclean Heavy Weight Drill Pipe (HHW) were added to the drill string.
- 3 HHW run in the BHA and 42 HDP run from the top of a BHA 1350 meters (from BHA) at a placement of 1 joint per stand.

**12 ¼” section:**

The 12 ¼” section was drilled from 200 meters to 2810 meters MD and the trajectory of the section is a build and hold type. And the HDP was introduced at the end of the section, because due to the poor hole cleaning, it was not possible to drill ahead with the same drill string. The HDP is then used from 2404 to 2810 meters.

**8 ½” section:**

The 8 ½” section was drilled from 2810 meters to the Total Depth of 3522 with Hydroclean Drill Pipe. The same BHA run as in the 12 ¼” section with 3 HHW was successfully used for the rest of the holding section. The formations are alternated between limestone, marl, shale and dense limestone in this section as in the well G an H. The figure 44 below shows the profile of the well path of the well C and clearly shows were the HDP and SDP was used in the wellbore.

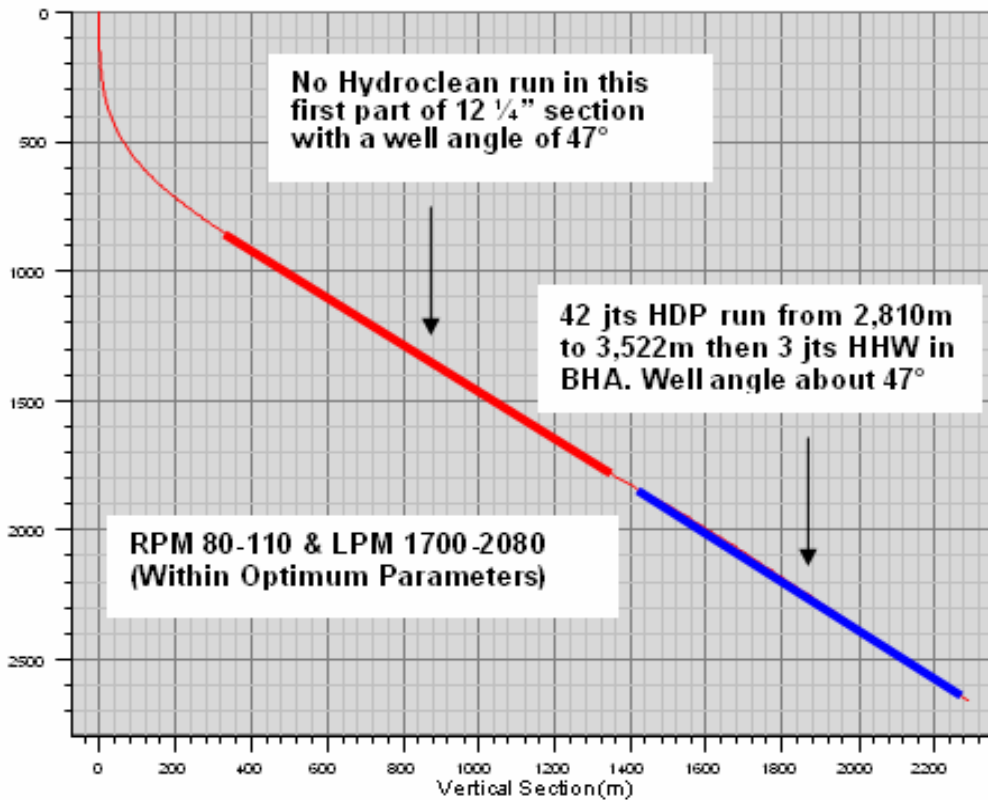


Figure 44: well profile of the WELL C

#### 6.2.4 Limitations of HydroClean

- The HDP is a very expensive tools and the price of one joint of Hydroclean is 16 time the price of a Standard Drill Pipe.
- The HDP can not be rented or purchased by all the service companies
- The crew must be specially trained in order to be able to use Hydroclean during the drilling process without problems.
- The placement of the Hydroclean joint in the Drill string increased the cuttings removal, so the placement must be carefully done by the engineers in charge.

#### 6.2.5 Economic Evaluation

Based on the drilling report and the drilling database of Weatherford, wells drilled with Hydroclean Drill Pipe were down to the last detail analysed. The wellbore section with open hole section of 12 1/4" and 8 1/2" are the one of interest for this work. Like already done for wells drilled with the SDP, the data for each section is grouped together and a linear

regression analysis is obtained. Based on the equation resulting from the regression analysis, a prediction of the NPT (%) per day can be done and therefore the amount lost due to the poor hole cleaning can be estimated. The NPT for the analysis take only the time lost due the poor hole cleaning into considerations.

## **Well 4: WELL C**

### ***12 ¼ inches section:***

This section of the Well C was drilled with a Standard Drill pipe, from the depth of 200 meters to 2404 meters and with HDP from 2404 meters to 2810 meters. The same equation from the linear regression used for the analysis of the 12 ¼” without HDP will be use in the first part of this section, which is:

$$Cum.NPT = 0,078 * Cum.depth - 7,71 \quad (Eq.69)$$

And with 20% of safety factor the equation become:

$$Cum.NPT = 0,062 * Cum.depth - 6,17 \quad (Eq.70)$$

Where,

*Cum.NPT* is the Cumulative Non-Productive Time

*Cumdepth* is the cumulative depth of the section

The figure 45 shows the NPT versus time of the Well C, and we can clearly see that the NPT increased drastically. At the End of the section the NPT is about 55% which is more than the half day loss due to cuttings accumulation. This can be also remarks in the drilling report with a lot of back-reaming, wiper trip time during the drilling process. The blue dotted are used in the graph to show the real NPT per cumulative depth. The pink line represents the predicted cumulative NPT over the cumulative depth. And the yellow line represents the corrected cumulative NPT which takes into the consideration the loss none related to the poor hole cleaning.

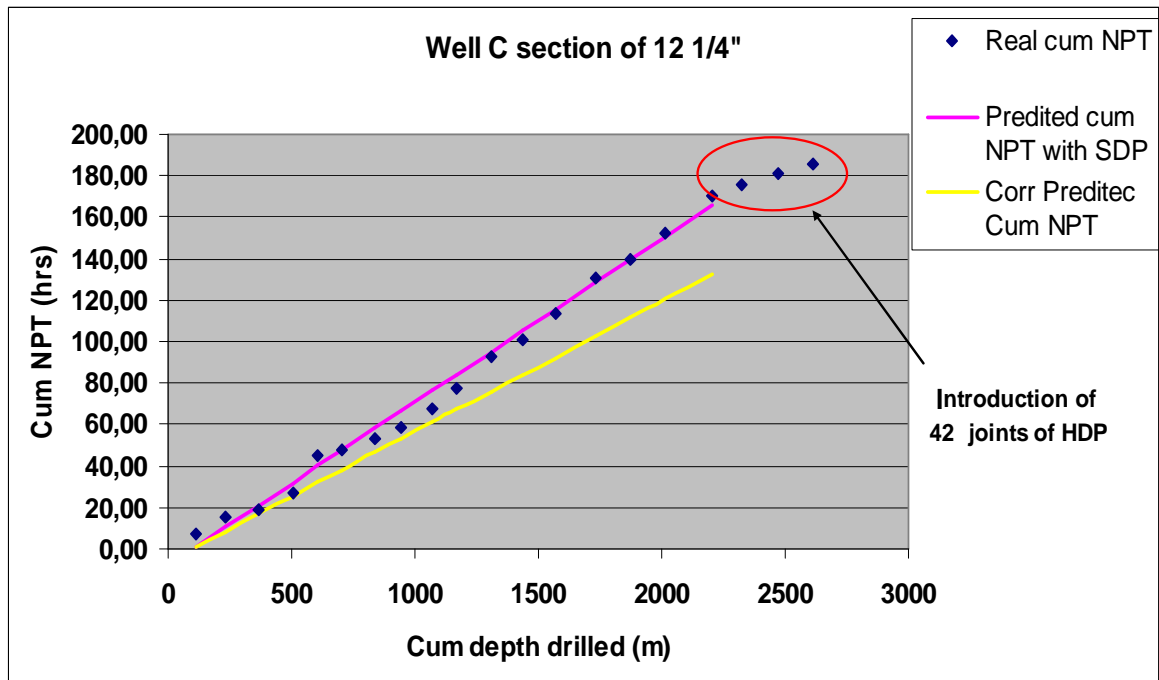


Figure 45: NPT versus Depth of the 12 1/4” section of the well C

The used of the HDP in the last part of the 12 1/4 “section, as you can see in the figure 46 has reduced the NPT considerably. The blue dotted points represent the NPT/meter in the section drilled. The high fluctuations of the NPT/meter show the change of the NPT each meter while the well is drilled. At the end of the section, the BHA is changed and the HDP is introduced into the drill string and the NPT/meter seems to be stabilized.

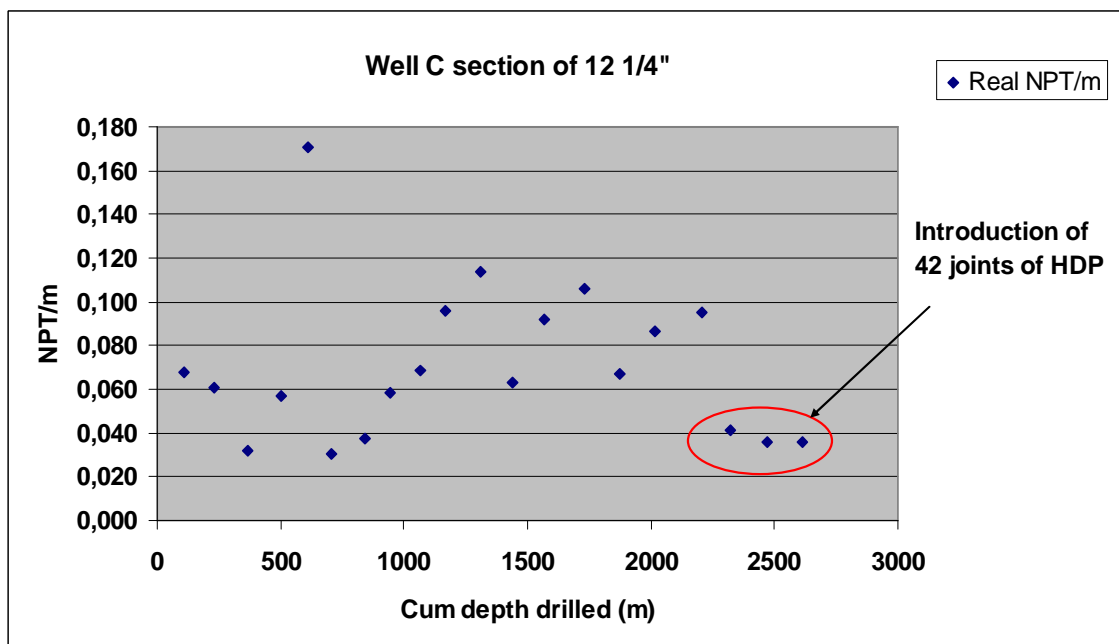


Figure 46: NPT per meter versus Depth of the 12 1/4” section of the well C

**Cost analysis:**

The first part of the well is drilled with Standard Drill Pipe to the depth of 2404 in 18 days. And the amount of money lost due the NPT which represents the wiper trips time, back reaming time, pumping out of the hole time and time lost due to the practices such as “washing and reaming” is summarized in the table 17 (below):

Rig rate per day: 40.000 \$/day

Daily production rate: 500 bbl/day

Days Drilled	NPT(hours)	NPT(days)	NPT Cost
18	162,4	6,77	270.800 \$

Table 17: Cost of the NPT at the end of the 12 ¼”section

To make the calculation more accurate, the amount lost due to the late production is also included into the total amount to give us a real idea of how much the company could have been lost while using the Standard Drill Pipe.

Actual price per Barrels	90,00 \$
Late production days	6,77
Production per day(barrel)	500
Amount lost due to the poor hole cleaning	304.650 \$
Late production interest (10%)	30.465 \$
Total amount Loss	301.265 \$

Table 18: Total amount loss for the 12 ¼”section

So the total amount lost as shown in the table 18 is about 301.265 \$. This huge amount shows that something must be done to reduce the losses due to the cuttings removal in the high inclined wellbore.

The second part of the section was drilled from 2404 meters to 2810 meters with the 42 joints of HDP add in the drill string within 3 days till the TD of the section. The cost will be not calculated in this section but the decrease of the curve shows give the impression to have less NPT with the introduction of HDP. But it will be very premature to give a conclusion based on this reduction. The economic comparison will be made for the next section of the hole.

### ***8 ½ inches section***

The 8 ½” section of this well was drilled with the HDP into the 9 5/8” casing from the starting depth of 2810 meters to the TD of 3522 meters. The well was drilled within 6 days and the cumulative NPT is predicted based on the equation obtained from the regression analysis. This equation is expressed as follows:

$$Cum.NPT = 0,014 * Cum.depth - 2,47 \quad (Eq.71)$$

And with 20% of safety factor the equation becomes:

$$Cum.NPT = 0,011 * Cum.depth - 1,97 \quad (Eq.72)$$

Where,

*Cum.NPT* is the Cumulative Non-Productive Time

*Cumdepth* is the cumulative depth of the section

As shown in figure 47 below, after the correction of 20 % safety margin, the cumulative NPT at the end of the section is about 11 hours. The blue dotted line is used in the graph to show the real NPT per cumulative depth. The pink line represents the predicted cumulative NPT over the cumulative depth. And the yellow line represents the corrected cumulative NPT which takes into consideration the loss not related to the poor hole cleaning. We can clearly see that the Hydroclean gives a low value of the daily NPT which decreases the total drilling cost and time of the well.

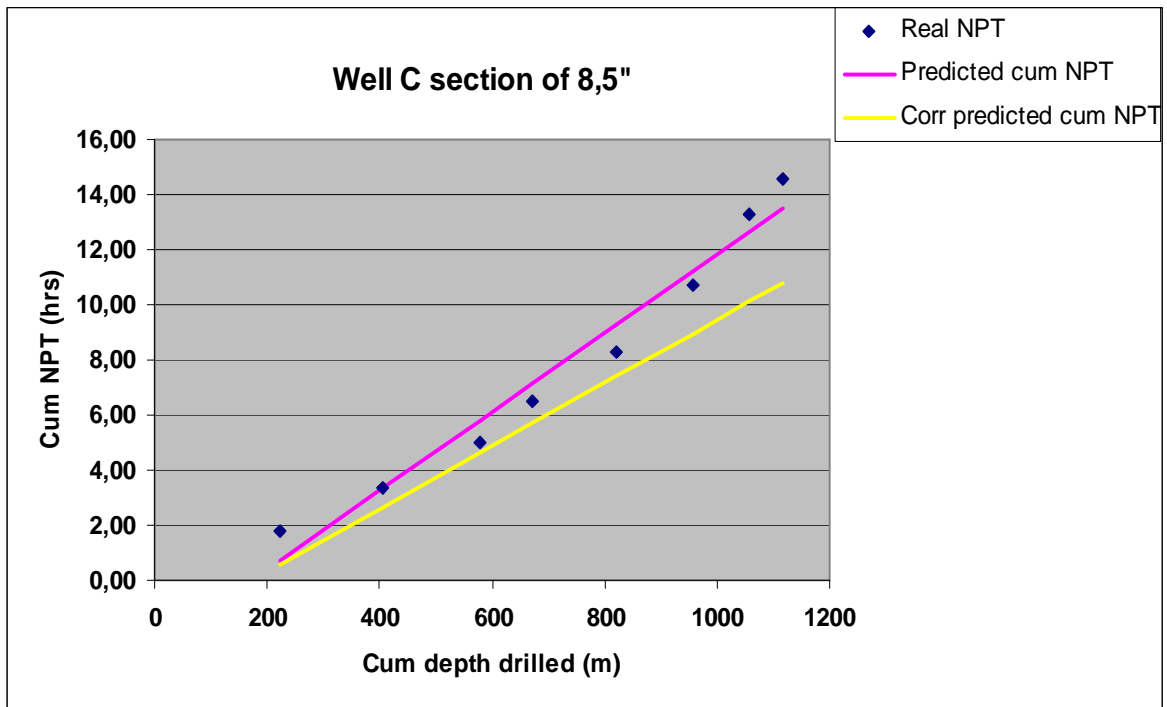


Figure 47: Cum NPT versus Cum Depth of the 8 ½” section of the well C with SDP and HDP

And the figure 48, the blue dotted points represent the cumulative metrage per meter over the cumulative depth. This graph gives us the possibility to identify whether or not is the NPT is proportionally increased with the depth. In the cumulative depth of almost 600 meters drilled, the NPT/meter high than the cumulative depth of 820 meters. As a conclusion while looking at the graph and at the figure 47, the NPT/meter increase even smoothly, with increasing depth. This section is a hold section which don't take the increase of the inclination into consideration because the inclination stays the same till the TD. In the build section as already mentioned before we have more fluctuations of the NPT/meter.

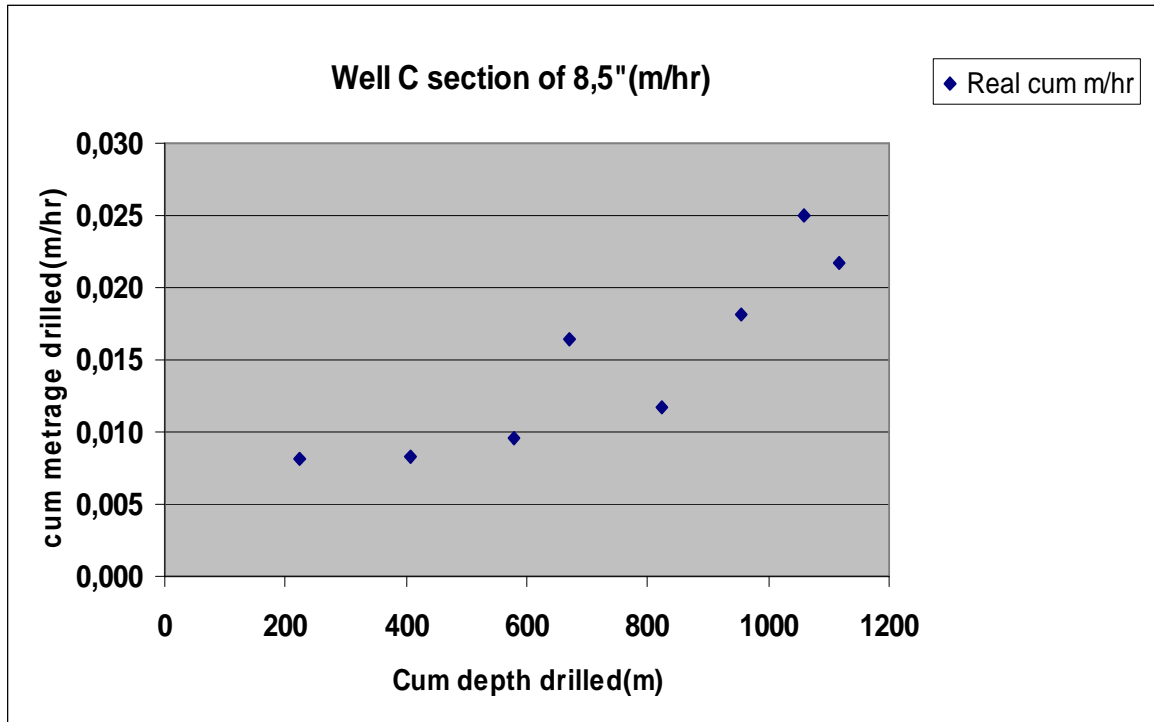


Figure 48: NPT per meter versus Cum Depth of the 8 ½” section of the well C with SDP and HDP

### Cost analysis:

The economic comparison between Hydroclean and Standard Drill Pipe done in this part of the work give us the amount saved. Based on my result the company will be able to make a good choice by using one of the two down hole equipments. The company can either rented or purchased the HDP depending on their internal policy. Both possibilities are taken into consideration in our calculation. The section was as already mentioned drilled from 2810 meters to the TD of 3522 meters in 6 days with HDP. The input data for the calculation are presented in table 19 below:

Days required to drill the section	6
Oil price per barrel	90 \$
Barrels oil production expected per day	500
Rig rate per day	40.000 \$
Number of HDP joint used for the section	45
Rental charges of HDP per joint per day	48 \$
Purchasing cost of HDP per joint per day	16 \$

Table 19: Input data for lost cost calculation

So if the company purchased the Hydroclean, the average life per joints is approximately 730 days and the purchasing cost per joint around 12000 \$, which lead to the 16 \$/day per joint.



With the others given prices, the savings cost when drilling with the HDP instead of the Standard Drill Pipe can be calculated and summarized in table 20 as follow:

Actual price per Barrels	90,00 \$
Late production days	0.46
Production per day(barrel)	500
Amount lost due to the poor hole cleaning	3.726 \$
Late production interest (10%)	- \$
Total amount Loss	40.000 \$

Table 20: Total saved with HDP

The total amount loss in this section after 6 drilled days is approximately half of a day. This total amount is estimated at 40.000 \$ which represent one day of rent the rig.

### **Conclusion:**

Comparing the wells drilled in the same area as Well C, G and H, following can be observed:

In the 8 ½ “section, well H and C give the equation:

$$Cum.NPT = 0,0376 * Cum.depth - 5,876 \quad , \text{ drilled with Standard Drill Pipe}$$

$$Cum.NPT = 0,011 * Cum.depth - 1,97 \quad , \text{ drilled with Hydroclean Drill Pipe}$$

By comparing the two equations we can come to the conclusion that in this case the HDP give us less NPT for this section.

In the 12 ¼” section, well C is partially drilled with HDP, and well G totally with SDP and the resulting equation from the linear equation are:

$$Cum.NPT = 0,068 * Cum.depth - 0,328 \quad , \text{ drilled with Standard Drill Pipe}$$

$$Cum.NPT = 0,062 * Cum.depth - 6,17 \quad , \text{ partially drilled with Hydroclean Drill Pipe}$$

Even in this case we can see the effect of the HDP in the 12 ¼” section.

But this conclusion can not be valid for all the wells, because as we can see in the well P the 8 ½” and 12 ¼” section, the comparison can not be made. This well P was drilled in another country with different formations.

## 6.3 Cuttings Bed Impellers

### 6.3.1 Definition of the Cuttings Bed Impellers (CBI)

The build up of the cuttings in high angle wells can cause drill pipe wear, hole instability, excessive torque and drag. These problems lead to the development of the CBI. Cuttings Bed Impeller is a down hole drill string tool intended for use in deviated wells where excessive build up of cuttings causes drilling problems.

The CBI is an integral drill string component consisting of a short mandrel with no moving parts, shaped in such a way as to stimulate any cuttings which have a tendency to settle out of the mud in the high angled sections of the well bore. The high angled sections could be inside the casing or in open hole: the tool is adaptable to suit several environments. The illustration of the CBI is shown in the figure below:

- The Chevron shaped blades to ensure effective cuttings agitations in both directions
- The Incut zone designed as we can see in the figure to encourage loosening of cuttings beds and allow for flexibility in the mandrel
- End the mandrel strength matches maximum strength of drill pipe tool joint.

#### Features

The features of the CBI (see figure 49) are as follow:

- One piece mandrel with mechanical properties which exceed the drill pipe in which it is placed
- Dimensions which allow the use of up to two tools within a standard drilling stand in most drilling derricks
- Hydraulic and mechanical dual acting mechanisms to remove cuttings beds
- Tool can be dressed with different coatings according to the severity of the down hole conditions.

The CBI are available in the size of 3 ½” , still 6-5/8” outer diameter and their mechanical data are given in the table 21 (below) and even one comparison between a new 5” S135 string and a new 5” CBI.



Figure 49: Representation of the Cuttings Bed Impellers

Descriptin		3-1/2"	4"	5"	5-1/2"	6-5/8"
Standard connection		2-7/8"IF	3-1/2"IF	4-1/2"IF	5-1/2"IF	6-5/8"FH
Min. Make Up Torque	Ft-lbs	13,5	15	28	43,5	54
Overall Length(sh-sh)	in	42.5	45.375	40.50	40.50	40.50
<b>Body</b>						
Tool Joint O.D.	in	5.25	6	6,5	7.375	8.20
Tool Joint I.D.	in	2.13	2.13	3.25	3.25	4.25
Maximum Body O.D	in	5.5	6.25	7.40	7.75	8.50
Length of Fish Neck	in	11	11	10,5o	10.50	10.50
Tensile Yield	Lbs	802,814	954,317	1,336,600	1,656,900	1,592,100
Torsional Yield	Ft-lbs	47,975	56,325	115,9	145,3	173,5

Table 21: Cuttings Bed Impellers specification

Description		New 5" S135	New 5" CBI
Standard connection		4-1/2"IF	4-1/2"IF
Min. Tool Joint O.D.	in	6,68	6,5
Min. Tool Joint I.D.	in	2,75	3,25
Minimum Make Up Torque	Ft-lbs	32,21	28
Tensile Yield	Lbs	1,551,706	1,268,900
Torsional Yield	Ft-lbs	62,387	51,4
<b>Body</b>			
Minimum Body O.D	in	5	5,25
Minimum Body I.D	in	4,275	3,25
Overall Length(sh-sh)	in	30.00	40.25
Tensile Yield	Lbs	710	1,336,600
Torsional Yield	Ft-lbs	77,4	115,9

Table 22: 5" Cuttings Bed Impellers and 5" Standard Drill Pipe comparison

### 6.3.2 Applications of the CBI

Basically the Cuttings Bed Impeller (CBI) is a down hole drill string intended to agitate any cuttings accumulation which have the tendency to settle out of the mud in deviated wells above 30° inclinations where excessive build up of cuttings causes drilling problems. The CBI can be use inside the casing section as also in the open hole section. The CBI tool is designed so that the coating over the top of the blades is suitable for both applications inside casing and in open hole. When running the tools primarily inside casing the coating has a low friction property to reduce casing wear. And running in the open hole the same hard, abrasive resistant coating allows for extended run lengths in arduous wellbore condition. The figure 50 (below) showed the typical case where cuttings have fallen out of the mud and have come to rest just below the build section and the action of the CBI to agitate cuttings into the flow mud. The most effective spacing of the CBI down hole tools is normally between 91 meters and 152 meters<sup>20</sup> through the tangent section of the well trajectory, which can ensure the re-agitation and the re-introduction into the mud flow of the cuttings build at the low side. The flow pattern of the returning mud around the tool annulus has been optimized to ensure maximum lifting of the debris from the low side of the hole.



Figure 50: mechanical agitation of cuttings bed with the CBI

### **6.3.3 Advantages and Limitations of the CBI**

Some benefits of the CBI are to:

- Reduces torque and drag on the string while in drilling mode which is not always easy to achieve in deviated wellbore
- Reduces wear on the drill pipe and rotating equipment
- Ensures cleaner and more stable hole conditions
- Reduces the drilling costs
- Only a small number of tools are required for effective hole cleaning
- Acts as a vibration damper in the string
- Overcomes difficulties in sliding and increase the rate of penetration
- Reduces frequency of twists-off and stuck pipe

And one of the major limitations of the tools is that we have a lot of connections due to the short length of the CBI. This will increase first the connection time and increase the possibility of losses into the hole.

## 6.4 Helical Drill Pipe

### 6.4.1 Definition and features

The Helical Drill Pipe (HE-DP) is a future alternative approach to overcome cuttings accumulation problems in high angle and horizontal wells. Compared to conventional drill pipe this helical pipe requires an additional manufacturing step, during which the major portion of the pipe body is transformed into an internally and externally helical tube, shaped similar to the rotor of a multi lobe mud motor. Drill pipe segments required for slips and elevators, the upset areas at both ends and the tool joints remain circular in shape. The minimum internal diameter of this helical section is at least as large as the internal diameter of the tool joint. The maximum outer diameter of the helical section is close to or identical to the outer diameter of the tool joints as you can see in the figure 51 illustrating the design of the Helical Drill Pipe.

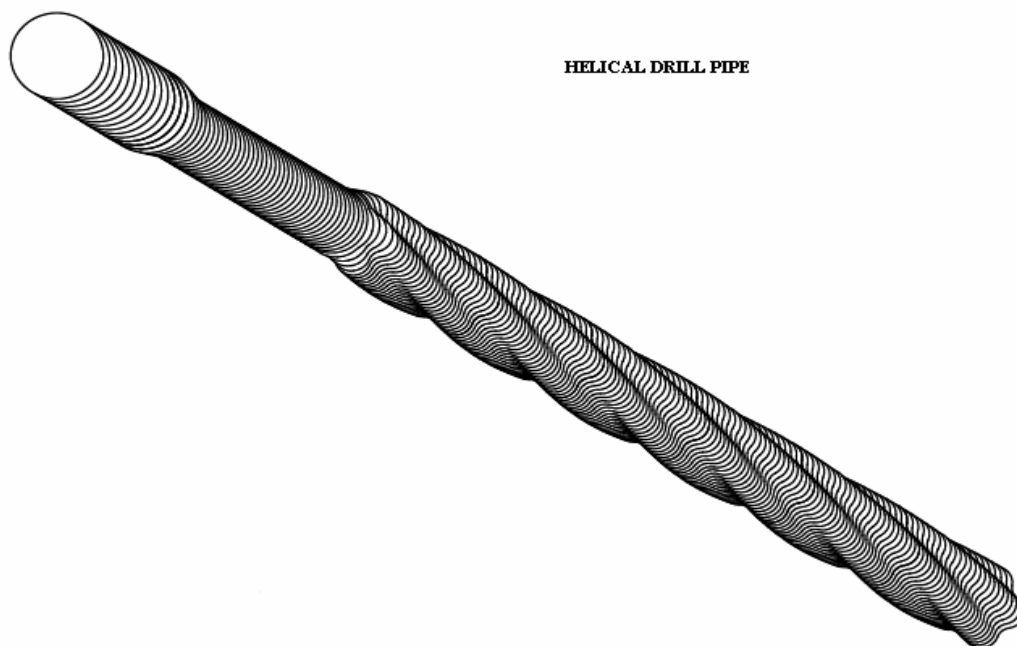


Figure 51: Design of Helical Drill Pipe

Helically shaped “multi-lobe” drill pipe improves the transport of cuttings in highly inclined and horizontal sections of the well both in the rotating and sliding mode of steerable systems.

In highly inclined or horizontal sections drilled with conventional drill pipe the annulus between drill string and borehole wall is considerably reduced by cuttings deposited in the form of cuttings beds. Helical pipe considerably reduces the amount of solids deposited at

the low side of the hole. The Figure 52 illustrates the HE-DP in case of differential sticking. Because of the unconventional shape of the helical pipe the contact between pipe and borehole wall is only a fraction of the contact between round and conventional bore hole elements with spirally milled grooves.

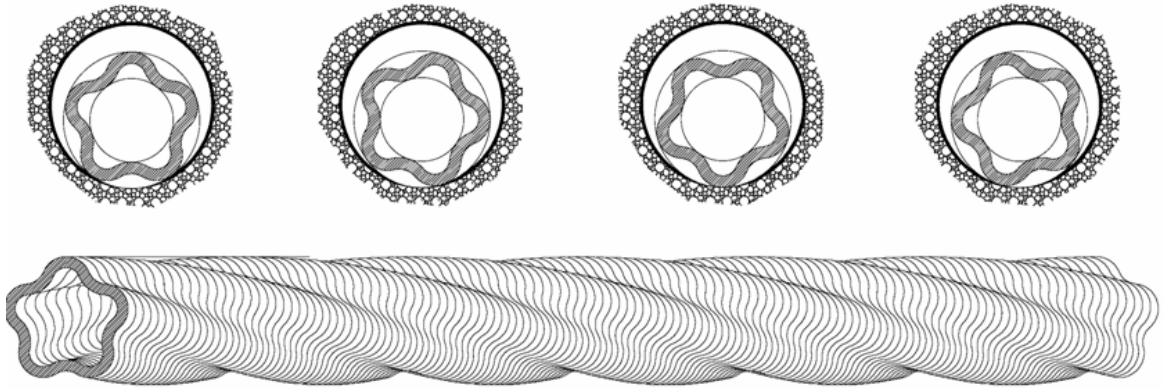


Figure 52: Cross section of Helical Drill Pipe in the borehole

#### **6.4.2 Advantages of Helical Drill Pipe**

The advantages of this pipe will be comparing with standard Drill pipe like:

The net annular flow area around helically enhanced drill pipe vs. conventional pipe is increased because of the lack of an obstruction by settled solids, thus reducing the pressure drop in the annulus.

- Torque and Drag are minimized hand in hand with the reduction or elimination of cuttings beds. Less wear and tear on surface and down hole equipment, lower energy consumption and an increased potential to reach more distant targets with existing equipment are the consequence.
- Because of the unique construction the average time between the generation of cuttings at the bit and the appearance at the shale shaker is considerably reduced because of the elimination of sedimentation at the low side of the hole. Mud rheology and density can be controlled easier and more cost effective when re-drilling of cuttings between drill string and borehole wall is reduced.
- Poor cementing jobs resulting from annular sections partially filled with deposited cuttings can be avoided.
- The need for wiper trips, back reaming, pumping out of the hole and practices already mentioned in this work can be minimized.

- The price of a joint of Helical Drill Pipe is less than one joint of HDP

### **6.4.3 Limitations of the Helical Drill Pipe**

One of the major question while using Helical Drill Pipe is the fishing of the tools in case of lost in the hole. But this situation can be solved as follows:

#### ***External Engagement with Overshots***

Helical pipe can be engaged by conventional overshots with a bull nose attached to the top sub that enters the pipe to prevent it against radial deformation when engaging the helix with the grapple

#### ***Internal Engagement with Spears:***

Spears can be set inside the helical sections and for maximum pulling loads in the circular section of a joint of pipe (tool joints, upset area or slip and elevator area)

The availability of the Helical Drill pipe can be also an issue to solve when deciding the run it for a section.



## 7 Conclusion and Recommendations

### 7.1 Conclusion

At the rig site while drilling deviated wells, poor hole cleaning can most of the time be identify by the following events:

- High torque on the drill string which result from the resistance to the rotation of the drill string
- Excessive drag on the drill string while tripping which result from the resistance to reciprocation
- And the type and quality of the cuttings at the shale shaker

The major drilling operating parameters influencing the hole cleaning are the flow rate, flow regime, the drilling mud properties and drill pipe rotation. These drilling parameters are controllable and can be optimized to increase the cuttings transport in deviated wells.

So, determining the optimum flow rate for good cuttings transport must be done in the well planning phase and must be adjusted as the real time during the drilling phase of the wellbore. If the optimum flow rate is below the minimum annular velocity, increase it until all annulus sections have a velocity greater than, or equal to, the minimum allowed.

Back-reaming and wiper trip for hole cleaning issues must be reduced, even avoided as possible on the rig site. The drilling operators have taken them as a normal drilling practice.

The use of HDP in deviated wells must be follow by the “best” drilling practice in order to give the expected good cleaning result. But the availability of the HDP must be carefully checked before deciding to run them for a section.

Based on the analysis did in this work, when comparing well G, H and well C, the linear regression shows less NPT for the well C drilled with HDP. The well P compare with the well C shows less NPT. This led to the conclusion that the NPT can not be reduced only with HDP, and is also depending on the formation drilled. There are many factors like formations, drilling practices that must be taken into consideration.

## 7.2 Recommendations

Based on the results from oldest studies used for this thesis and from various field experiences the following general guidelines can be recommended to partially solve the cuttings accumulation problem in high deviated wells:

- Design if possible the well path of the section as smooth as possible so that we can avoid critical angles and high dogleg.
- Maximize fluid velocity in the annulus, while avoiding hole erosion, by increasing pumping power and/or using large diameter pipes and collars.
- In large diameter horizontal wellbores, where turbulent flow is not practical, use mud with high suspension properties and mud with high meter dial readings at shear rates
- Pump Hi-viscosity and Low-viscosity pills at the right time, and adjust the plastic viscosity and yield point as per recommendation in the section.

More analysis must be done in future research in order to come out with a definitive conclusion, of whether the HDP can be more effective by reducing the NPT in all high deviated wells rather than SDP.

## 8 Nomenclatures

- $A_{bed}$  : Cross-section flow area of the cutting bed in sqft  
 $A_w$  : Cross-section flow area of the wellbore in sqft  
 $A_{ann-new}$  : New annular area after cuttings deposition  
 $C_c$  : Feed cuttings concentration  
 $C_{conc}$  : Concentration correction factor  
 $C_{ang}$  : Angle correction factor  
 $C_{size}$  : Cuttings size correction factor  
 $C_{RPM}$  : RPM correction factor  
 $C_i$  : Angle correction factor for the new cutting lifting equation  
 $C_{MW}$  : Density or mud weight correction factor  
 $C_{bed}$  : Cuttings bed  
 $C_{cutt}$  : Corrected cuttings bed concentration  
 $\overline{C_{cutt}}$  : Cuttings bed concentration  
 $C_{corr-cutt}$  : correction factor of cuttings bed  
 $D_{hole}$  : Hole diameter in inches  
 $D_{pipe}$  : Pipe diameter in inches  
 $K$  : Consistency index, dimensionless  
 $\alpha$  : Angle in degree versus vertical  
 $N_{Re}$  : Reynolds number  
 $N_{Fr}$  : Froude number  
 $Q_{min}$  : Minimum flow rate to keep the hole clean  
 $Q_{pump}$  : Pump flow rate  
 $Rt$  : Cuttings transport ratio  
 $V_{slip}$  : Slip velocity  
 $V_{cut}$  : Cuttings velocity

- $V_{cut-new}$  : New cuttings velocity
- $V_{min}$  : Minimum velocity
- $V_{open}$  : Velocity of the open area above the cuttings bed
- $V_{ann}$  : Annular velocity
- $\mu$  : Mud viscosity at shear rate in flow stream in centipoise
- $v$  : Annular velocity, ft/min
- $\rho_{mud}$  : mud weight, ppg
- $\rho_p$  : particle density, ppg
- $n$  : Flow index, dimensionless
- $\theta_{300}$  : 300 viscometer dial reading
- $\theta_{600}$  : 600 viscometer dial reading
- $\tau_y$  : Shear stress in pounds per square inches
- $\rho_s$  : Solid density in pounds per gallon
- $\rho_f$  : Fluid density in pounds per gallon
- $\mu_a$  : Apparent fluid viscosity in centipoise
- $V_{ann}$  : Annular velocity in feet per minute
- $d_s$  : Solid diameter in inches
- $\tau_y$  : Shear stress

### ABBREVIATIONS:

- Abs : Absolute value of
- ANN : Artificial Neural Network
- BHA : Bottom Hole Assembly
- CBI : Cuttings Bed Impellers
- Cum Depth: Cumulative Depth in meters
- Cum NPT: Cumulative Non Productive Time in hours
- ESV : Equivalent Slip Velocity
- ID : Internal Diameter
- gpm : Gallon per minute

HBZ : Hydrodynamical Bearing Zone  
HCZ : Hydromechanical Cleaning Zone  
HDP : Hydroclean Drill Pipe  
HE-DP: Helical Drill Pipe  
KOP : Kick Of Point  
LSRV: Low Shear Rate Viscosity  
LSYP: Low Shear Yield Point  
MD : Measured Depth  
NPT : Nom Productive Time  
OD : Outer Diameter  
PT : Productive Time  
ppg : Pounds per gallon  
RSS : Rotary Steerable System  
ROP : Rate Of Penetration  
RPM : Rotation Per Minute  
SG : Specific Gravity of the mud  
SDP : Standard Drill Pipe  
TD : Total Depth

## 9 References

1. Drilling Engineering by Jamal, J. Azar, G. Robello Samuel
2. J. Azar et al. "Important Issues in Cuttings Transport for Drilling Directional Wells" paper SPE 39020.
3. W.B Bradley et al. "Task Force Approach to Reducing Stuck Pipe Cost" paper SPE 21999 presented in March 1991
4. Rudi Rubiani et al. "Equation for Estimating Mud Minimum Rate for Cuttings Transport in an Inclined-until-Horizontal Well", paper SPE/IADC 57541 presented at November 1999
5. S.A. Mirhaj et al. "Cuttings Removal Simulation for Deviated and Horizontal Wellbores" paper SPE 105442 presented Middle East Oil & Gas Show and Conference, 11-14 March 2007
6. Larsen et al. "Development of a new cuttings transport Model for High-Angle Wellbores Including Horizontal Wells" paper SPE presented in June 1997
7. A.A. Pilehvari et al. "State of the Art Cuttings Transport in Horizontal Wellbores" paper SPE, presented in September 1999
8. David Power, Deepwater Technical Advisor "Hole Cleaning: Challenges and Solutions"
9. Exxon Company, USA "Drilling Fluid Technology"
10. Baker Hughes INTEQ "Drilling Engineering Workbook"
11. M.I Swaco "Drilling Fluid Engineering Workbook"

12. Hyon cho et al. " A Three Segment Hydraulic Model for Cuttings Transport in Horizontal and Deviated wells" paper SPE presented in November 2000
13. R.K. Clark et al. " A mechanistic Model for cuttings Transport" paper SPE 28306 presented in September 1994
14. Tomren, P.H., Iyoho, A.W.,and Azar, J.J.: "Experimental Study of Cuttings Transport in Directional Wells," paper SPE presented in August 1986
15. Zeidler U. and Rice U. "An Experimental Analysis of the Drilled Transport of Drilled Particles" paper SPE 3064 presented in Houston in February 1986
16. Ozbayoglu et al. " Analysis of Bed Height in Horizontal and Highly Inclined Wellbores by Using Artificial Neural Networks" paper SPE 78939 presented in Alberta in November 2002
17. Gavignet and Sobey " Models Aids Cuttings Transport Predictions" paper SPE 15417 presented in September 1989
18. Pilehvari, A.A., Azar, J.J. and Shirazi, S.A. "State-of-the-Art Cuttings Transport in Horizontal Wellbores", paper SPE presented in September 1999
19. Kamp, A.M. and Rivero, M. "Layer Modeling for Cuttings Transport in Highly Inclined Wellbores", paper SPE 53942 presented in September 1999
20. Pilot drilling Control Ltd handout
21. Desmond Nguyen and S.S. Rahman, "A Three Layer Hydraulic Program for Effective Cuttings Transport and Hole Cleaning in Highly Deviated and Horizontal Wells" , paper SPE 51186 presented in March 1998

22. Okrajni and J.J. Azar, “ The Effects of Mud Rheology on Annular Hole Cleaning in Directional Wells” paper SPE 14178 presented in 1986
23. Sifferman and T.R. Becker, “Hole Cleaning in Full-Scale Inclined Wellbores” paper SPE 20422 presented in March 1992
24. Martins and C. Santana “Evaluation of Cuttings Transport in Horizontal and Near-Horizontal –A Dimensionless Approach” paper SPE 23643 presented in March 1992
25. Belavadi and G.A. Chukwu, “ Experimental Study od the Parameters Affecting Cutting Transportation in a Vertical Wellbore Annulus” paper SPE 27880 presented in March 1994
26. Kenny and al. “Hole Cleaning Modelling: What’s ‘n’ Got To Do With It?” paper SPE 35099 presented in March 1996
27. Sanchez, J.J. Azar, A.A Bassal, A.L. Martins “Effect of Drill Pipe Rotation on Hole Cleaning during Directional Well Drilling” paper SPE 56406 presented in June 1999



# 10 Appendix

## 10.1 Appendix A

### 10.1.1 Minimum flow rate determination

#### INPUT DATA

Title

6 5

Mud weight	<input type="text" value="9.80"/>	ppg
Plastic viscosity	<input type="text" value="12"/>	cps
Yield Point	<input type="text" value="24"/>	lb/100ft <sup>2</sup>
Hole Diameter	<input type="text" value="8.5"/>	inches
Drill pipe OD	<input type="text" value="5"/>	inches
Inclination angle	<input type="text" value="65"/>	degree
Diameter of Particle	<input type="text" value="0.175"/>	inches
Density of Particle	<input type="text" value="12"/>	ppg
Rate of penetration	<input type="text" value="50"/>	ft/hr
Assume viscosity	<input type="text" value="7"/>	ppg
Circulation rate	<input type="text" value="110"/>	gpm
RPM	<input type="text" value="60"/>	tr/min

Calculate

Reset

**OUTPUT  
VARIABLES**

Cutting concentration	2,397
-----------------------	-------

Velocities	(ft/min.)
◆ cuttings	1,424473125
◆ ESV	3,257867993
◆ minimum	9,701267753
◆ Qmin(gpm)	584,1024938

### **10.1.2 Visual Basic Application (VBA)**

Dim X As Double

Static Function Log10(X)

Log10 = Log(X) / Log(10#)

End Function

Private Sub CommandButton1\_Click()

Const c = 12

Dim arr(1 To c) As Double

Dim Cconc As Double

Dim Vcut As Double

Dim Vmin As Double

Dim ESV As Double

Dim Qmin As Double

Dim i As Double

Dim n As Double

Dim k As Double

Dim mu As Double

Dim NRE As Double

Dim f As Double

```

Range("B5").Select
arr(1) = TextBox1.Value ' Mud weight
arr(2) = TextBox2.Value 'Plastic viscosity
arr(3) = TextBox3.Value 'Yield point
arr(4) = TextBox4.Value 'Hole diameter
arr(5) = TextBox5.Value 'pipe diameter
arr(6) = TextBox6.Value 'inclination angle
arr(7) = TextBox7.Value 'diameter of particle
arr(8) = TextBox8.Value 'density of particle
arr(9) = TextBox9.Value 'rate of penetration
arr(10) = TextBox10.Value 'ESVassume
arr(11) = TextBox11.Value 'circulation rate
arr(12) = TextBox12.Value ' RMP

Dim assume As Double
assume = arr(10)

'Calculation of Vs
Dim Cutting_Slip As Double
Dim annv As Double
Dim teta300 As Double
Dim teta600 As Double
Dim mu1 As Double
Dim mu2 As Double

teta300 = arr(2) + arr(3)
teta600 = teta300 + arr(2)
n = 3.32 * Log10(teta600 / teta300)
k = teta300 / (511 ^ n)

annv = (24.5 * arr(11)) / ((arr(4) ^ 2) - (arr(5) ^ 2))
mu1 = (((2.4 * annv) / (arr(4) - arr(5))) * ((2 * n + 1) / (3 * n))) ^ n
mu2 = (200 * k * (arr(4) - arr(5))) / annv
mu = mu1 * mu2

Cutting_Slip = (175 * arr(7) * (arr(8) - arr(1)) ^ 0.667) / (arr(1) ^ 0.333 * mu ^ 0.333)

```

'Calcul of Cconc

$$Cconc = 0.01902 * arr(9) + 0.495$$

'Calcul of cuttings velocities

Dim temp As Double

$$temp = (36 * (1 - ((arr(5) / arr(4)) ^ 2))) * Cconc$$

$$Vcut = arr(9) / temp$$

Dim ESVsave As Double

' Assume a value

Beginn:

$$Vmin = Vcut + assume$$

$$mu = arr(2) + (5 * (arr(3) * (arr(4) - arr(5)))) / Vmin$$

If (mu < 55) Then

$$ESV = 0.0052 * mu + 3.1$$

Else

$$ESV = 0.025 * mu + 3.26$$

End If

If (Abs(ESV - assume) >= 0.001) Then

$$assume = ESV$$

GoTo Beginn

End If

Dim temp2 As Double

Dim temp3 As Double

$$temp2 = 1 + (arr(6) * (600 - arr(12)) * (3 + arr(1))) / 202500$$

$$temp3 = 1 + (600 - arr(12)) * (3 + arr(1)) / 4500$$

If (arr(6) < 45) Then

$$Vmin = Vcut + temp2 * ESV$$

Else

$$Vmin = Vcut + temp3 * ESV$$

End If

'Caculation of Qmin

$$Q_{min} = V_{min} * 60 * 7.48 * ((3.14 * (arr(4) ^ 2 - arr(5) ^ 2)) / 4) * 0.006944444$$

```
Dim string1 As String
```

```
string1 = "*Valid value in range 6.0 to 50.0"
```

```
Range("B5").Select
```

```
i = arr(1)
```

```
Select Case i
```

```
Case 6# To 50#
```

```
ActiveCell.Value2 = ""
```

```
Case Else
```

```
Cconc = 0
```

```
Vcut = 0
```

```
ESV = 0
```

```
Vmin = 0
```

```
Qmin = 0
```

```
ActiveCell.Value2 = string1
```

```
End Select
```

```
Dim string2 As String
```

```
string2 = "*Valid value in range 1.0 to 120.0"
```

```
Range("B6").Select
```

```
i = arr(2)
```

```
Select Case i
```

```
Case 1# To 120#
```

```
ActiveCell.Value2 = ""
```

```
Case Else
```

```
Cconc = 0
```

```
Vcut = 0
```

```
ESV = 0
```

```
Vmin = 0
```

```
Qmin = 0
```

```
ActiveCell.Value2 = string2
```

```
End Select
```

```
Dim string3 As String
```

```
string3 = "*Valid value in range 0.0 to 120.0"
```

```
Range("B7").Select
```

```
i = arr(3)
```

```
Select Case i
```

```
Case 0# To 120#  
ActiveCell.Value2 = ""  
Case Else  
Cconc = 0  
Vcut = 0  
ESV = 0  
Vmin = 0  
Qmin = 0  
ActiveCell.Value2 = string3  
End Select
```

```
Dim string4 As String  
string4 = "**Valid value in range 2.0 to 36.0"  
Range("B8").Select  
i = arr(4)  
Select Case i  
Case 2# To 36#  
ActiveCell.Value2 = ""  
Case Else  
Cconc = 0  
Vcut = 0  
ESV = 0  
Vmin = 0  
Qmin = 0  
ActiveCell.Value2 = string4  
End Select
```

```
Dim string5 As String  
string5 = "**Valid value in range 1.0 to 30.0"  
Range("B9").Select  
i = arr(5)  
Select Case i  
Case 1# To 30#  
ActiveCell.Value2 = ""  
Case Else  
Cconc = 0  
Vcut = 0  
ESV = 0  
Vmin = 0
```

```
Qmin = 0
ActiveCell.Value2 = string5
End Select
```

```
Dim string6 As String
string6 = "**Valid value in range 0.0 to 90.0"
Range("B10").Select
i = arr(6)
Select Case i
Case 0# To 90#
ActiveCell.Value2 = ""
Case Else
Cconc = 0
Vcut = 0
ESV = 0
Vmin = 0
Qmin = 0
ActiveCell.Value2 = string6
End Select
```

```
Dim string7 As String
string7 = "**Valid value in range 0.05 to 1.0"
Range("B11").Select
i = arr(7)
Select Case i
Case 0.05 To 1
ActiveCell.Value2 = ""
Case Else
Cconc = 0
Vcut = 0
ESV = 0
Vmin = 0
Qmin = 0
ActiveCell.Value2 = string7
End Select
```

```
Dim string8 As String
string8 = "**Valid value in range 1.0 to 50.0"
Range("B12").Select
```

```

i = arr(8)
Select Case i
Case 1# To 50#
ActiveCell.Value2 = ""
Case Else
Cconc = 0
Vcut = 0
ESV = 0
Vmin = 0
Qmin = 0
ActiveCell.Value2 = string8
End Select

```

```

Dim string11 As String
string11 = "*Valid value in range 10.0 to 3000.0"
Range("B15").Select
i = arr(11)
Select Case i
Case 10# To 3000#
ActiveCell.Value2 = ""
Case Else
Cconc = 0
Vcut = 0
ESV = 0
Vmin = 0
Qmin = 0
ActiveCell.Value2 = string11
'MsgBox ActiveCell.Value2
'ActiveCell.Value = " * Please enter a value between 0.05 and 1"
'MsgBox "Valid value for the diameter of particle in range 0.05 to 1 ", vbExclamation
End Select

```

```

Range("B26").Select
ActiveCell.Value = Cconc
Range("B30").Select
ActiveCell.Value = Vcut
Range("B31").Select
ActiveCell.Value = ESV

```



```

Range("B32").Select
ActiveCell.Value = Vmin
Range("B33").Select
ActiveCell.Value = Qmin

End Sub

Private Sub CommandButton2_Click()

Range("B5").Select
TextBox1.Value = ""
TextBox2.Value = ""
TextBox3.Value = ""
TextBox4.Value = ""
TextBox5.Value = ""
TextBox6.Value = ""
TextBox7.Value = ""
TextBox8.Value = ""
TextBox9.Value = ""
TextBox10.Value = ""
TextBox11.Value = ""
TextBox12.Value = ""
'ActiveCell.Offset(1, 0).Select

End Sub

```

## 10.2 Appendix B

### 10.2.1 *Minimum transport velocity (MTV) calculation<sup>6</sup>*

The calculation of the Minimum transport velocity and the minimum flow rate to keep the well clean, very complex calculations must be done. Using the Larsen method developed in this work and with the given drilling parameters, the critical flow rate and cuttings bed concentration can be highlighted.

DRILLING PARAMETERS FOR CALCULATIONS		
Drilling fluid	polymer mud	
Yield point	lbf/sqft	7
Plastic viscosity	cp	7
Pump operating flow rate	gal/min	600
Angle of inclination	degree	47
Cuttings size	inches	0,175
Mud weight	lbm/gal	11,1
Rate of penetration	ft/hr	52
Hole diameter	inches	12,25
Pipe diameter	inches	5,5
Bed porosity	%	36

To calculate in this example is the minimum flow velocity, flow rate to transport all the cuttings to the surface, and the cuttings concentration at the operating flow rate of 600 gal/min.

**Minimum Flow rate prediction:**

Cuttings concentration at the minimum flow rate can be calculated with the equation 26.

$$C_{conc} = 0,01902 \times 52 + 0,495 = 1,48\%$$

Average cuttings transport at the minimum flow rate:

$$V_{cut} = \frac{52}{36 \left[ 1 - \left( \frac{5,5}{12,25} \right)^2 \right] \times 1,48} = 1,22 \text{ ft/sec}$$

**Equivalent slip velocity calculation (ESV):** to find the ESV, the apparent viscosity  $\mu_a$  has to be calculated. The apparent viscosity will be calculated by estimating the minimum transport velocity to clean up the hole  $V_{min}$  and iterating until an acceptable value has been obtained. First the ESV has to be estimated, as for example 3,3 ft/sec. This will lead to:

$$V_{min-estimated} = 1,22 \text{ ft/sec} + 3,3 \text{ ft/sec} = 4,52 \text{ ft/sec}$$

Then the **apparent viscosity** can be calculated using the equation 31:

$$\mu_a = 7 + \frac{5 \times 7 \times (12,25 - 5,5)}{4,52} = 59,3 \text{ cp}$$

As  $\mu_a > 55 \text{ cp}$ , ESV will be calculated with the equation 30:

$$ESV = 0,025 \times 59,3 + 3,26 = 4,74 \text{ ft/sec}$$

For a better accuracy, the calculated ESV will be used for a calculation of new  $V_{\min}$  and a new  $\mu_a$  which lead to:

$$V_{\min\text{-calc}} = 1,22 \text{ ft/sec} + 4,74 \text{ ft/sec} = 5,96 \text{ ft/sec}$$

Based on this  $V_{\min\text{-calc}}$  the new apparent viscosity is calculated,  $\mu_{a\text{new}}$  by the same equation 31 as:

$$\mu_{a\text{-new}} = 7 + \frac{5 \times 7 \times (12,25 - 5,5)}{5,96} = 46,64 \text{ cp}$$

And the  $ESV_{\text{new}}$  have to be calculated by the equation 30 as:

$$ESV_{\text{new}} = 0,0052 \times 46,64 + 3,10 = 3,34 \text{ ft/sec}$$

This iteration has to be done till:

$$abs|ESV_{\text{new}} - ESV| \leq 0,01$$

For the simplicity of the example let us assume that  $ESV_{\text{new2}} = 3,34 \text{ ft/sec}$ . The correction of the angle, cuttings size and mud weight must be taking into consideration.

**Angle of inclination correction factor:** Using the equation 32,

$$C_{\text{ang}} = 0,0365 \times 47 - 0,0002 \times 47^2 - 0,20 = 1,08$$

**Cuttings size correction factor:** Using the equation 33:

$$C_{\text{size}} = -1,02 \times 0,175 + 1,27 = 1,09$$

**Mud weight correction factor:** Using the equation 35:

$$C_{\text{MW}} = 1$$

The **cuttings slip velocity** can be now found with the equation 36 by:

$$V_{\text{slip}} = 3,34 \times 1,08 \times 1,09 \times 1 = 3,93 \text{ ft/sec}$$

The minimum transport velocity can be calculated by the equation 37.

$$V_{\min} = 1,22 \text{ ft/sec} + 3,93 \text{ ft/sec} = 5,15 \text{ ft/sec}$$

And the corresponding apparent viscosity is about  $\mu_{a-end} = 43,8cp$

The minimum transport velocity must be converted into flow rate in order to compare with the operating flow rate 600 gal/min.

$$Q_{\min} = \left(5,15 \frac{ft}{sec}\right) \left(\frac{60 sec}{1 min}\right) \left(\frac{7,48 gal}{1 ft^3}\right) \times A_{ann}$$

The cross sectional area of the annulus can be calculated by:

$$\begin{aligned} A_{ann} &= \frac{\pi(D_{hole}^2 - D_{pipe}^2)}{4} \\ &= \frac{3,14 \times (12,25^2 - 5,5^2)}{4} = 98,2 in^2 = 0,68 ft^2 \end{aligned}$$

$Q_{\min} = 1576 gal / min$ . As minimum flow rate is higher than the operating flow rate the cuttings will accumulate in the borehole. The cuttings accumulation can be calculated by:

$$\begin{aligned} \bar{C}_{cutt} &= \left(1 - \frac{Q_{pump}}{Q_{\min}}\right) (1 - \Phi) \\ &= \left(1 - \frac{600}{1576}\right) (1 - 0,36) = 0,39 = 39\% \end{aligned}$$

**Correction for cuttings accumulation:**

$$C_{CF-cutt} = 0,97 - 0,00231 \times 43,8 = 0,87$$

The **corrected cuttings accumulation** is calculated by:

$$\begin{aligned} C_{cutt} &= \bar{C}_{cutt} \times C_{CF-cutt} \\ &= 0,39 \times 0,87 = 0,38 = 34\% \end{aligned}$$