Ounis Mohamed Amine

Master Thesis 2017: supervised by
Uni,-Prof.Dipl.-Ing.Dr.mont Gerhard Thonhauser
Dipl.-Ing Asad Elmgerbi
Dipl.-Ing Richard Kucs

Realistic Approach to Improve Pump Start up Procedures

dpe DEPARTMENT PETROLEUM ENGINEERING

MONTAN UNIVERSITÄT

To my mom and my late father.
To everyone who supported me during my studies.

Affidavit

I declare in lieu of oath that I wrote this thesis and performed the associated research myself using only literature cited in this volume.

Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich diese Arbeit selbständig verfasst, andere als die angegebenen Quellen und Hilfsmittel nicht benutzt und mich auch sonst keiner unerlaubten Hilfsmittel bedient habe.

Name, 26 November 2017

Abstract

The major objective of oil and gas operator companies is to increase the return on investment via increasing drilling efficiency and minimizing drilling cost. Due to the resent oil price drastic drop and the downward pressures on the oil price, saving as much as possible is important today more than any time else.

The cost of the well depends mainly on the time it takes to drill and complete it successfully. However, non-planned, unexpected events continue to plague the performance and the progress of drilling operations. These events are considered to create significant loss of time and productivity commonly referred to as non-productive time (NPT). One of the NPT contributors is wellbore stability.

Wellbore stability can be improved with the help of detailed real time simulation of pressure in the wellbore which provides a better control on the wellbore via transferring the downhole parameters to the surface in real time. Nevertheless, the problem is that the real time simulation is costly and cannot be afforded for all wells.

One of the issues related to wellbore stability is the mud pump start-up. The speed of how quickly the mud pumps are brought up during drilling operations has a big impact on the pressure regimes in the wellbore and wellbore stability.

Drilling mud is designed to form a gelled structure under static condition to keep the cuttings and mud additives in suspension. Once the gelled structure is formed, higher energy is required to break it. A fast increase in the pump strokes increases the downhole pressure and generates a pressure spike, which might lead to several problems like formation fracture, lost circulation, etc. In contrast a slow increase in the pump strokes may lead to increase in overall invisible lost time.

For decades, it was up to the driller how he thought it would be better to bring the pump up, however, today it is possible to simulate that and make it better. Hence, the conventional pump start-up procedure needs to be optimized taking into account several affecting parameters like wellbore and drill string geometry, mud characteristics and geologies, as well as other operating parameters. From this perspective the aim of this thesis is to define all the factors that might have impact on the pump start-up procedures and verify their impact by analysing historical data. Moreover, it will develop a new approach that will help to optimize the quality of the existing pump start-up producers. This approach integrates several downhole conditions to the known pump start up factors in order generate more reliable procedures. Finally, the steps of developing standard procedures in form of documentation and graphs based on the newly developed approach for various rigs operated by OMV worldwide are presented and discussed in details.

Zusammenfassung

Öl- und Gas unter nehmen haben ein großes Interesseihre Kapital rentabilität zuerhöhenindemsie die Effizienz beim Bohren und erhöhen und die Kostenzuminimieren. InsbesonderenachdemEinbruch der Rohstoffpreise in den letztenJahrenist dieses Interessegrößerals je zuvor.

Die Kosten der Bohrunghängen stark von der Dauer der Bohr- und Komplettierungsarbeiten ab, jedochhabenungeplante und unerwarteteVorkommnisseeinennegativenEinfluss auf den Fortschritt der Arbeiten. SolcheVorkommnissekönnenzusignifikantenZeit- und Produktivitätsverlustenführen, besserbekanntals „Non-Productive Time“ (NPT). EinwichtigerFaktorbei NPT ist die Bohrlochstabilität.

Die Stabilität der BohrungenkannmitHilfe von detailliertenEchtzeitsimulationen des Bohrlochdrucksverbessertwerden. Dies wirddurch die Übertragung der Parameter aus der Bohrungan die OberflächeinEchtzeitbewerkstelligt.Das Problem istjedoch, dassdieseEchtzeitsimulationensehrteuersind und sicherdahernichtfüralleBohrungenrechnen.

EinwichtigerPunktbeidiesem Problem ist das Anfahren der Spülungspumpen. Die Geschwindigkeitmit der die Pumpen auf die normaleHubzahlhochgefahrenwerden hat einengroßenEinfluss auf die DruckzuständeimBohrloch und somit auf dessenStabilität.

Die Bohrspülung ist der artz usammen gesetzt, dasssieunterstatischenBedingungeneinegelartigeStrukturentwickeln um das Bohrklein und Spülungsadditive in Suspension zuhalten. SobaldsichdieseGelstrukturgebildet hat, wirdbeimHochfahren der PumpenmehrEnergiebenötigt um eswiederzubrechen.Geschieht dies zuschnell, kommteszuDruckspitzenimBohrloch, welchemöglicherweiseausreichen die Formation aufzubrechen und zuSpülungsverlustenführenkönnen. EinzulangsamesAnfahrenführtdagegenzueinemAnstiegsogenannter „Invisible Lost Time“ (ILT) durchnichtoptimalesDurchführen des Vorganges.

ÜberJahrzehnte war esdemBohrmeisterüberlassen, wieer die Pumpenhochfährt; heutzutageistesjedochmöglichmittelsSimulationendiesenVorgangzuoptimieren. Dies geschieht, indemwesentliche Parameter, wieetwa die Bohrloch- und Bohrstranggeometrie, Geologie und Spülungscharakteristikamitbetrachtetwerden.

Das ZieldieserArbeitistesdaher, sämtlicheFaktoren, die einenEinfluss auf das Hochfahren der Pumpenhabenkönntenzudefinieren und diesendurch die Analyse von Datenzuverifizieren. Weiterswirdeinneuer Ansatz entwickelt, der helfensoll die existierendenVorgängezuoptimieren.Dieser Ansatz erweitert die

bekanntenEinflussfaktoren um mehrerebohrlochbedingteFaktoren um verlässlichereAblaufezuerstellen.ZumAbschlusswerden die notwendigenSchrittezurErstellung von Standardabläufenbasierend auf diesemneuen Ansatz, in Form von Dokumentation und GraphenfürmehrereBohranlagen, die weltweitfür OMV imEinsatzsind, präsentiert und im Detail diskutiert.

Acknowledgements

Firstly, I would like to express my gratitude to my advisorsUni,-Prof.Dipl.-Ing.Dr.mont Gerhard Thonhauser and Dipl.-Ing Asad Elmgerbi for their help and support throughout my thesis project. In addition to my mentor Mr. Rudolf-Nikolaus Knezevic for his time, guidance and valuable support and motivation.

I would also like to thank Mr. Neal Whatson, Head of well engineering department in OMV for his support, as well as my advisor in OMV; Mr. Richard Kucs for his time, support, and guidance.

Last but not least, a big thanks to family, my friends, and my colleagues who supported me and stood behind me during my studies as well as during my thesis project.

Table of Contents

Chapter 1 Introduction

1.1. Overview

Wellbore stability issues are among the major reasons for non-productive time thus increasing the overall cost of the well. For conventional overbalanced drilling, pump-start-up procedure is a major concern for wellbore stability issues.

While making the drill string connection, the mud pumps are turned off and the mud circulation is stopped. Under such static conditions, drilling mud is designed to form a gelled structure to keep the cuttings and mud additives in suspension. Once the gelled structure is formed, higher energy is required to break it.

Once the connection is made, the driller needs to start the mud pump to resume the drilling operations. While bringing the mud pump, a down hole pressure spike is generated. Such spikes can fracture the formation if it reaches the weakest fracture pressure which might generate some wellbore stability issues like formation damage.

The spike value is strongly dependent on some rheological parameters like gel strength and it is strongly related to the speed of how quickly the driller brings the mud pump. A fast increase of pump speed generates a higher pressure spike than a lower one. While a slower mud pump start-up may increase the overall invisible lost time and consequently the well construction cost will increase.

Previous work was done on automation of mud pump start-up in 2011 by Cayeux, E., Daireaux, B. and Dvergsnes, E. in which the best practices of starting the pump were illustrated and explained in details. Then a model was made presenting all the best practices into mathematical models to be applied for pump start-up. This work was mainly done to make an automatic pump start-up without driller intervention.

Another Work was done in 2011by Zoellner, P., Thonhauser, G., Lueftenegger, M. and Spoerker,Habout automated real-time drilling hydraulics monitoring where the authorsexplained how the stand pipe pressure surges variations can reflect the pressure variations exerted on the downhole formations but the pressure spike value remain unknown. The work was done to provide a pump start-up limitation based on stand pipe pressure value.

1.2. Motivationsand Objectives

The shortcomings which were mentioned in the foregoing were the main motivations for developing a new approach as alternative to the conventional pump start-up procedure. The presented concept is taking into consideration multiple factors that might have significant impact on the downhole pressure variation. In order for this thesis to be able to achieve the mentioned goal, the following objectives were set to be the main focus for the thesis:

- Analysing the factors effect on pressure spike when starting the pump. But since everything is related to the data quality, a data quality analysis is performed via checking the historical time based data used in Kongsberg which is real time data software and compare it with the raw data. The main focus will be the stand pipe pressure and mud pump flow rate variations while bringing the mud pumps after making connection. Briefly, the main focus of this part is to check the measurement quality and accuracy of the data to be used afterwards for the thesis and to analyse the pump start-up factors and check if there is any relationship between each other.
- Analysing the pump start up procedures via checking the variation of several important parameters as a function of depth and time such as: stand pipe pressure variation, stand pipe pressure response delay, flow rate variation in the time of start-up and over the depth of the drilled well, pressure required to break the gel strength in all the sections, time required to bring the mud pumps and rheology variation as a function of depth. For this section, 7 newly drilled wells in Pakistan were studied to show how the pressure required to break the gel strength varies from a well to well.
- Developing an alternative pump start-up procedure which takes into account several factors that have not been considered by the conventional pump start-ip procedure.
- Applying the developed approach to several rigs operated by OMV in order to deliver a paper providing the best practices and best performances to be used on rig site by the driller to start the mud pump to avoid the wellbore stability issues.

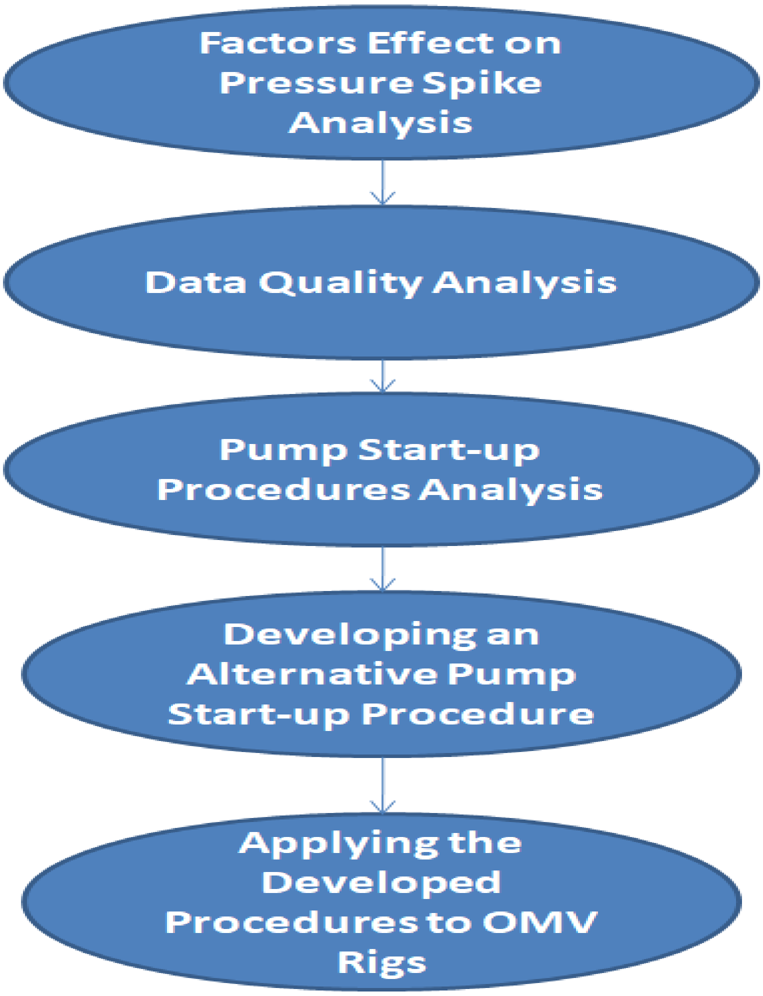


Figure 1. Thesis Workflow

Chapter 2 Factors Affecting Pump Start-up Procedures

As explained earlier, upon starting the pump, a downhole pressure spike is generated due to the gel breaking structure as illustrated in Figure 2.The magnitude of the pressure spike is controlled by several factors, some of them have direct impact other have indirect impact. In this section only the factors which have direct impact are highlighted and discussed.

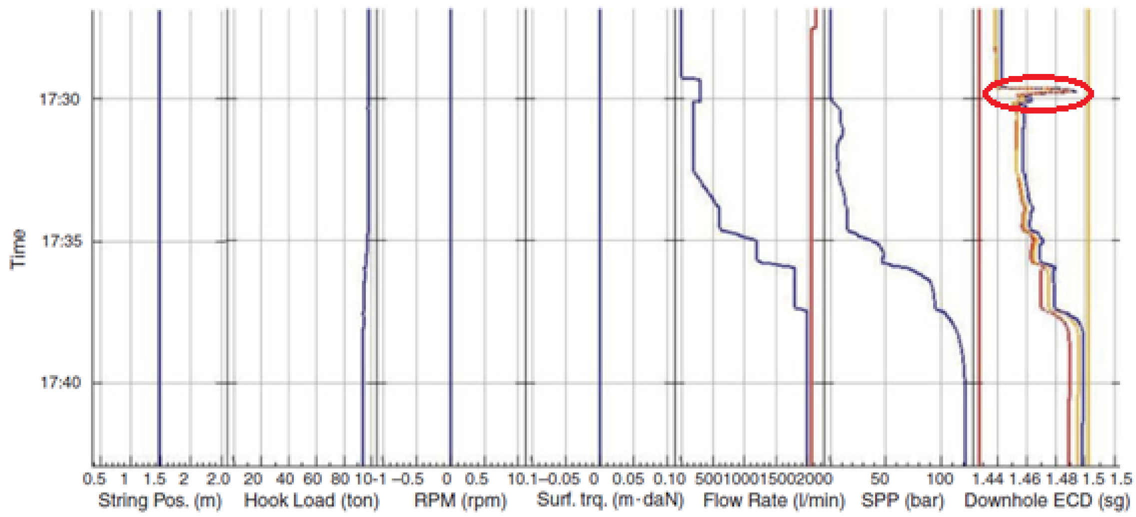


Figure 2. Pressure Spike (Cayeux, Daireaux and Dvergsnes, 2011)

2.1. Gel Strength

The gel strength indicates the ability of the fluid to hold cuttings in suspension. It occurs due to the presence of electrically charged molecules and clay particles which aggregate into a firm matrix when circulation is stopped.(Drilling Fluid Reference Manual, 2006). Gel strength value is strongly dependent on chemical treatment, solids concentration, time and temperature. It increases with time, temperature and solids concentration.

The gel strength of commonly used drilling fluids can be categorized in three main types as shown in Figure 3. Drilling fluids with flat gels have similar 10 seconds and 10 minutes gel strengths, remaining pumpable while static while progressive gel strength keeps increasing its gel strength with time. For drilling purpose, the low flat gel is the desirable type as it needs less pressure to resume the circulation compared to the progressive and high flat gel strength.

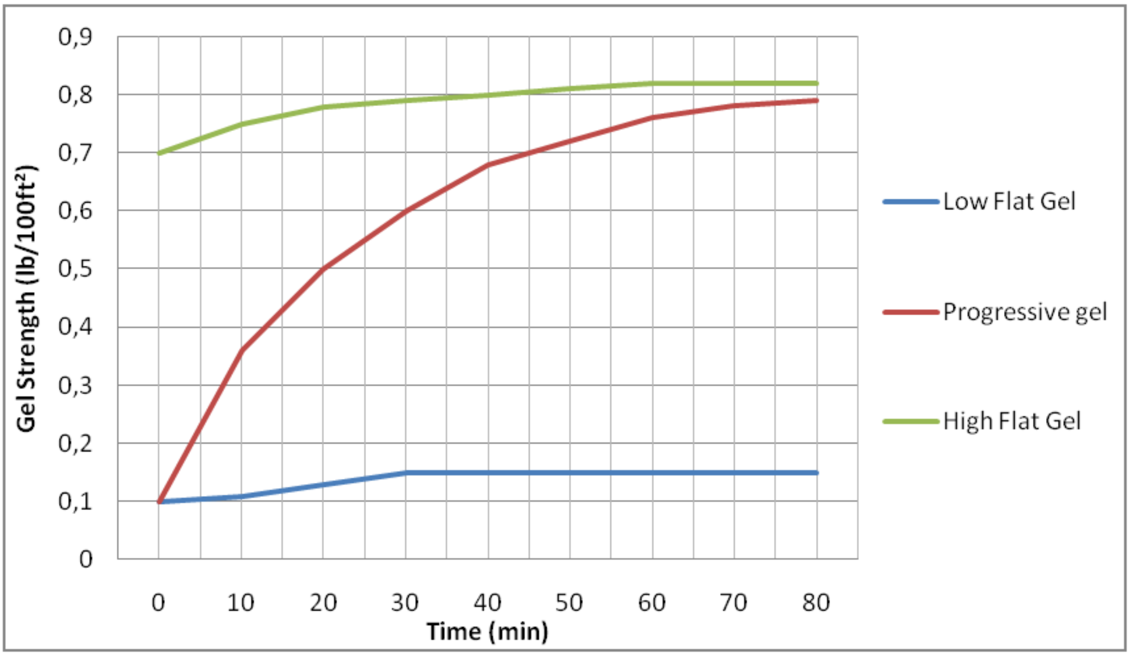


Figure 3. Gel Strength Types (Glossary.oilfield.slb.com, 2017)

Once the circulation is stopped, the gel strength starts to build a strong structure to suspend the solids. Depending on the type of gel strength as shown in Figure 3, the longer it takes to resume mud circulation when making connection, the higher the gel strength value will be, the higher the pressure required breaking the structure thus the higher the pressure spike when starting the mud pump.

2.2. *Connection Time*

Connection time is defined as the time required by the drilling crew to connect a new joint (or stand) to the entire drill string. The connection process starts by stopping the drill string rotation, pick up the drill string off bottom to expose a threaded connection below the Kelly and turns the pump off. Then the crew connects the new joint to the drill string and the driller starts lowering the drill string while bringing the mud pumps and drill string rotation until the drill string reaches the bottom hole and drilling is resumed. (Glossary.oilfield.slb.com, 2017)

As mentioned previously, the mud circulation is stopped when making connection so the gel strength starts to build to suspend solids. This pump-off time provides an idea about the value of gel strength. The longer it takes to resume the circulation the higher the gel strength will be. Keep in mind that the gel strength variation between the pump-off and pump-on time is highly dependent on the type of the gel as it is illustrated in Figure 4.(A.Moore and A.Gillikin, 2010)

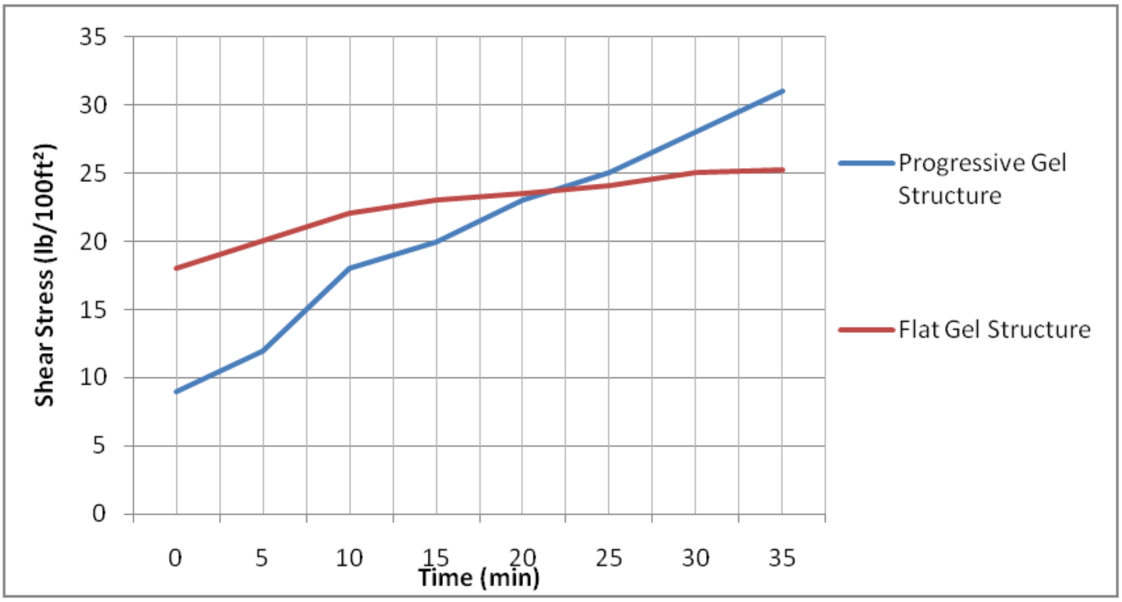


Figure 4. Gel Strength Development over Time, Flat Gel vs. Progressive Gel (A.Moore and A.Gillikin, 2010)

While flat gel structure does not increase rapidly as a function of time, progressive gel strength shows a positively sloped behaviour. This type is severely dependent on the pump-off time.

2.3. *Hole Geometry*

The hole geometry has a tremendous effect on the pressure required to break the gel strength thus the pressure spikes value expected when starting the mud pumps are higher in small hole size compared to the larger ones. This is due to the lower wellbore clearance between the hole size and the outside diameter of the drill string as demonstrated by equation (2).

The theoretical overall gel breaking pressure is simply the sum of the pressure needed to break the gel strength inside the drill string and in the annulus and it is modelled within these mathematical formulas (Geologie.vsb.cz, 2017):

$$P_{gsds} = \frac{Y * L}{300 * ID} \tag{1}$$

$$P_{gsa} = \frac{Y * L}{300 * (Dh - OD)} \tag{2}$$

$$P_{gst} = P_{gsds} + P_{gsa} \tag{3}$$

Figure 5 below illustrates the differences in pump pressures theoretically required to break the gel strength in different annulus size. Simply, if gel strength value is assumed to be 25 (lb/100ft²), and pipe outside diameter size is 5 inches, by using the equation (3) the gel strength value can be computed.

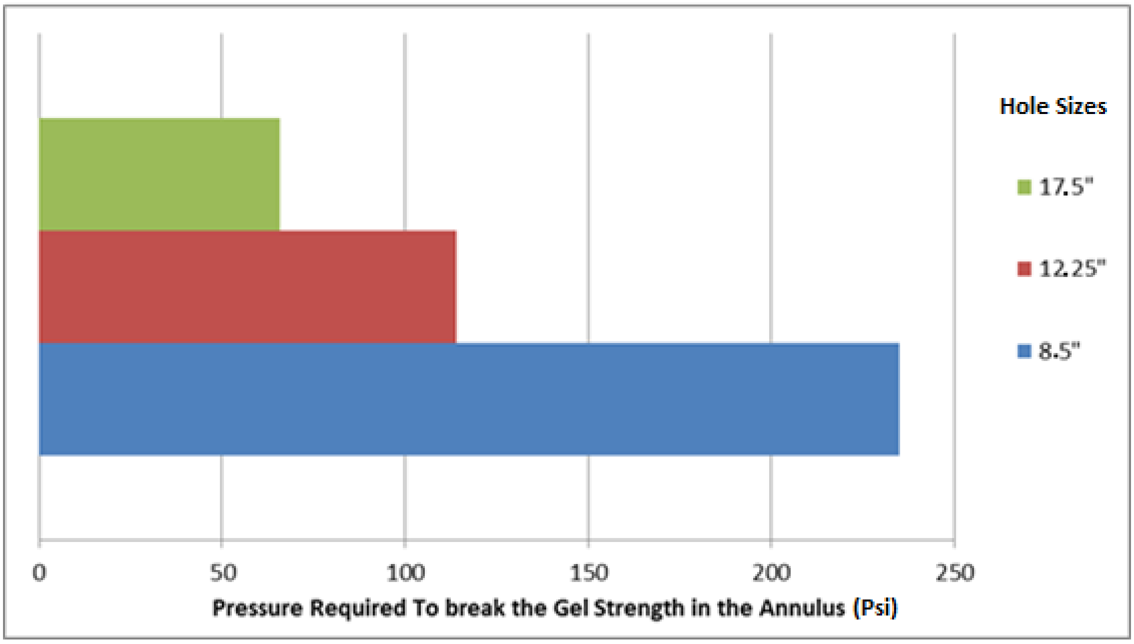


Figure 5. Pressure Required To Break Gel Strength in the Annulus in Different Hole Sizes

Due to the high clearance in big hole size, the theoretical pressure required to break the gel strength is less compared to the smaller hole size. Another factor is the depth within the same hole size, the deeper the wellbore the higher the theoretical pressure required to break the gel strength.

2.4. Rotation Effect

According to Walt Aldred et al (1998) and based on some performed experiments, the driller should break rotation first and then start circulation.(using downhole annular pressure measurements to improve drilling performance, 1998)

Figure 6shows how the annular pressure losses react as a function of drill string rotation and pump flow rate value. The results presented below are based on an experimental data conducted in 4.9 inch hole size with a pipe outer diameter of 3.5 inch and a Plastic Viscosity of 3.4 cp.

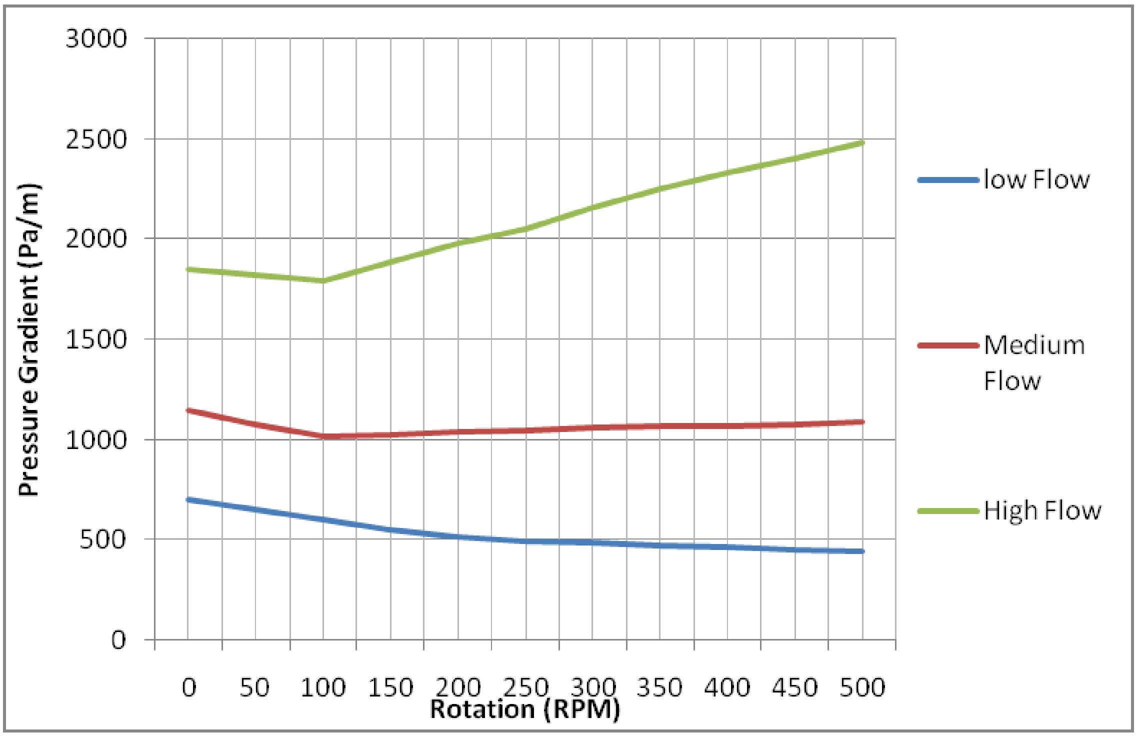


Figure 6. Annular Pressure Losses as a Function of Various Flow Rates and Drill String Rotation Speed (using downhole annular pressure measurements to improve drilling performance, 1998)

As shown above in Figure 6, the annular pressure losses decrease as long as the rotation value increases when using a low flow rate. For the medium and high flow rate the annular pressure losses tends to decreases till reaching the value of 70-80 RPM and then starts to increase again.

Figure 7 confirms this hypothesis and shows that at constant flow rate of 502 gpm, the stand pipe pressure decreased from 1413 psi to 1324 psi as soon as the rotation started and reached a value of 46 RPM.

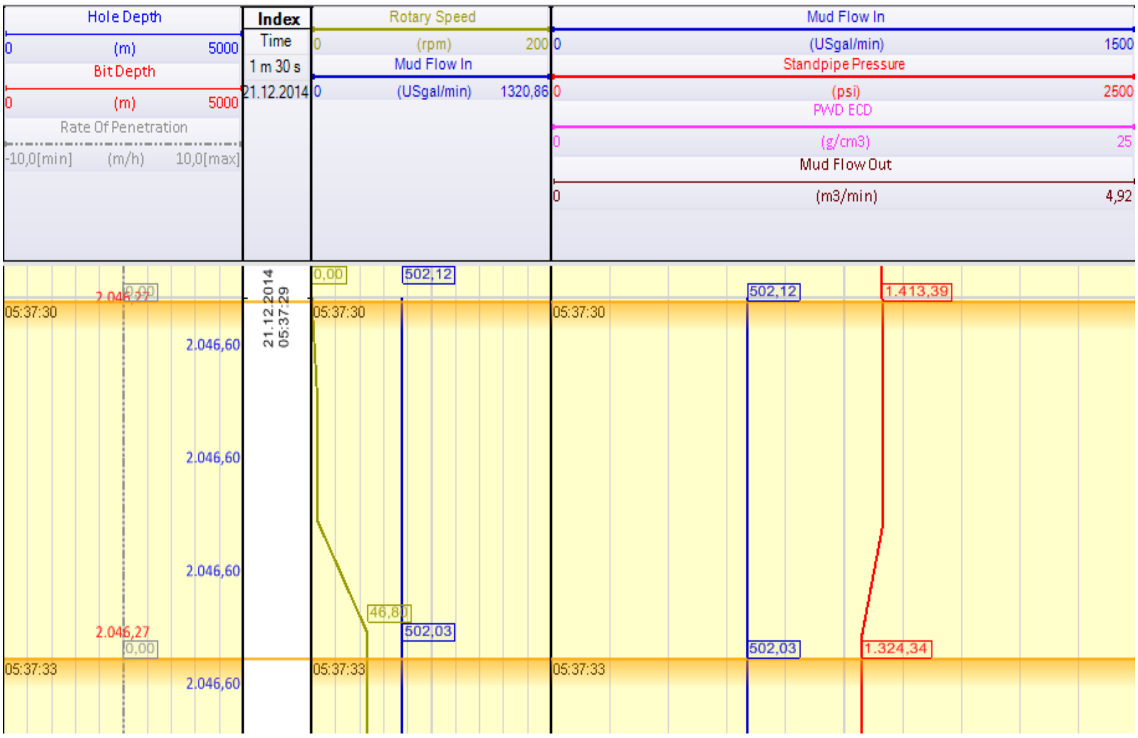


Figure 7. Rotation Effect on Stand Pipe Pressure

Based on the discussion mentioned above, breaking rotation before resuming circulation could help to reduce the stand pipe pressure value and as consequence pressure spike might decrease as well.

As an inconvenient for this procedure, breaking rotation first can be the reason behind drill string pack off. When the circulation stops the cuttings start to settle down and they normally accumulate near the connection between the drill pipe and bottom hole assembly.

Practically, the drill string pack-off is a bigger concern for the driller than the pressure spike when starting the mud pumps. That is why, as illustrated in later chapters and after analysing all the wells being drilled, the driller always brings circulation to full speed and then breaks rotation.

2.5. *Effect of Pump Start-up Procedures:*

Up to date, three different methods are mainly used to start the pumps after making a connection. Figure 8 illustrates the types of start-up used by the drillers on the rig site to start the mud pumps after making connection to resume drilling.

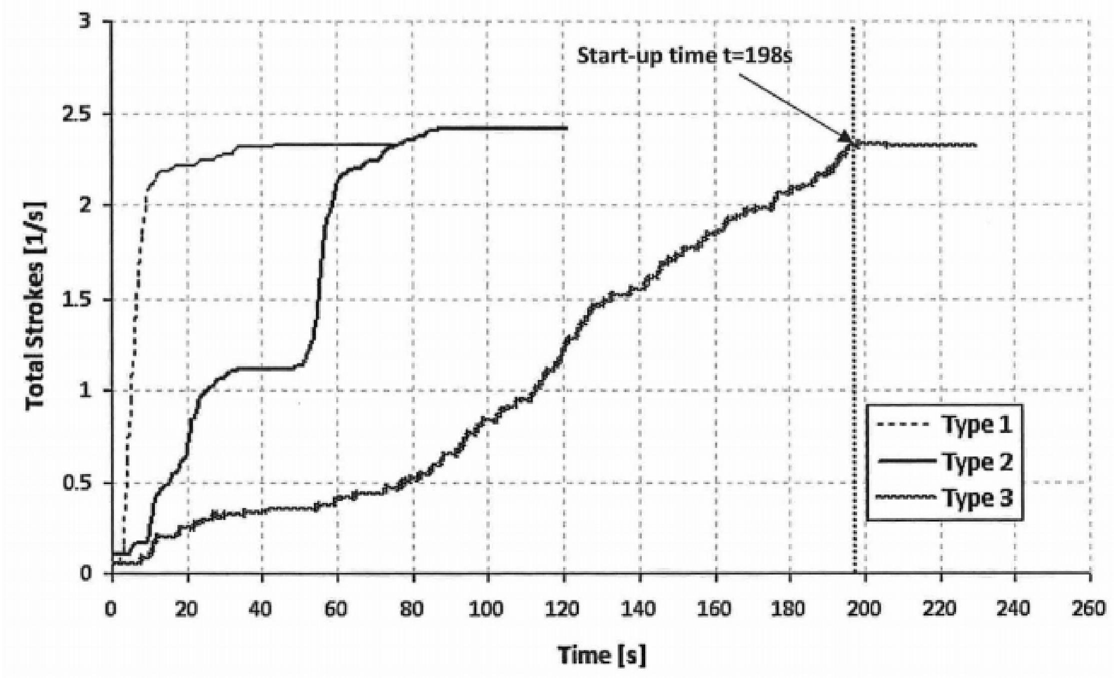


Figure 8. Pump Start-up Types (Thonhauser and Lüftenegger, 2017)

As it can be seen from Figure 8, the first type is implemented by bringing the pump to the desirable speed from the beginning within a few seconds, this method provides the highest pressure spikes and fastest pump start-up procedure compared to the other types. he second type is performed by bringing the pumps to an intermediate strokes level and keeps it constant for a short period of time so the pressure spike can stabilize and then increasing it to full strokes.

The third type is done by bringing the pumps in a steady manner with small increments until it reaches the final strokes. This method provides the lowest pressure spikes and the highest time consuming compared to the other types.

Depending on the situation, the mud pump is brought up to speed using one of the aforementioned procedures, however, the second type is the most common used procedure since it provides a medium pressure spikes and medium timing. (Thonhauser and Lüftenegger, 2017)

2.6. Human impact

The driller experience and practice have a huge impact on the pump start-up procedures. Depending on the way he starts the mud pump, the driller affects the pressure spike generated when starting the mud pump. Once the flow rate is reduced to a minimum value, the gel breaking phase starts, the pressure starts to build up until it reaches a certain value so that the gel is fully broken and mud flow circulation is resumed. (Cayeux, Daireaux and Dvergsnes, 2011)

Once the gel is broken and for a safe gel breaking process, the driller has to wait for the stand pipe pressure spike to stabilize and make sure that this transition period is over and the steady state behaviour is reached. Then the circulation is resumed and the mud pumps are brought to the final desired flow rate. While bringing the mud pumps to the final flow rate, there are several things which need to be kept in driller mind. A high acceleration can generate a pressure spike which might exceed the geo-pressure margin thus a lost circulation situation is expected. A low acceleration will increase the invisible lost time. (Cayeux, Daireaux and Dvergsnes, 2011)

2.7. Acceleration Effect:

In practice, the driller uses several intermediate stages to check whether pump pressure variation is acting normally or not. When the driller accelerates the mud pump a pressure spike is generated and stabilized as soon as the steady state flow is reached. The pressure build-up is heavily dependent on the acceleration value. Mainly, a high acceleration provides a high pressure spike. (Cayeux, Daireaux and Dvergsnes, 2011). It is agreed that the mud pump acceleration highly depends on the current flow rate and the downhole situation. In practice, the driller uses a high acceleration in the beginning and decreases it as soon as the equivalent circulating density is getting closer to the fracture gradient as it is illustrated in Figure 2.

When bringing the pumps to full strokes, the whole open hole section needs to be taken into account and not only the bottom part or casing shoe. For example, as illustrated in Figure 9, starting the pump at the depth of 3000m looks safe but it is not since the pressure spike wave will reach the 2500m where there is a low difference between the ECD and the fracture pressure so a fracture can occur that is why, taking into consideration the whole open hole area is important.

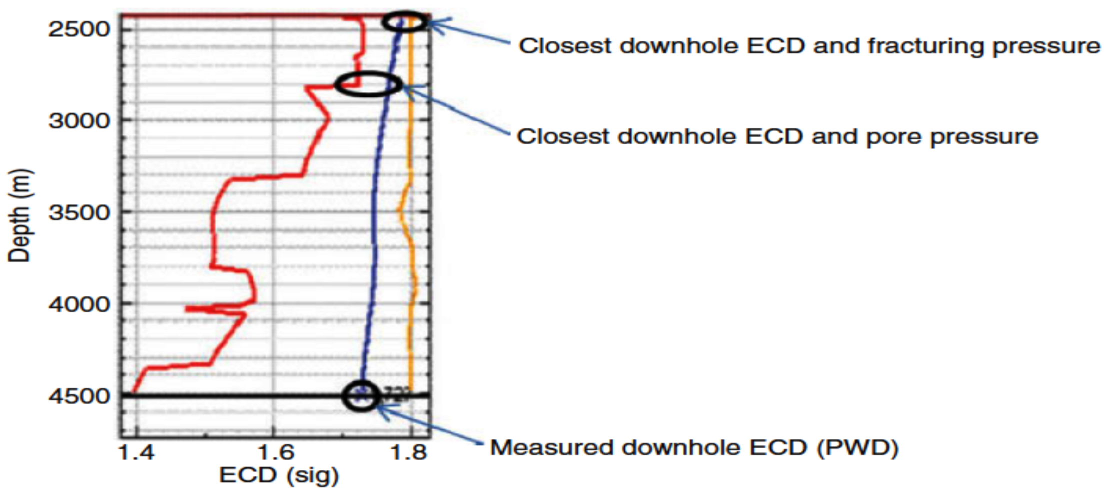


Figure 9. Open Hole Area Importance (Cayeux, Daireaux and Dvergsnes, 2011)

Chapter 3 Analysis and Verifying the Impact of Several Factors on Stand Pipe Pressure Spikes

As it was clearly mentioned in previous chapter, several factors have been proven to have significant impact on the value of pressure spike when starting the mud pump. Therefore, the aim of this chapter is to evaluate the impact of these factors on the magnitude of the pressure spike by analysing real historical data. Since the integrity and reliability of any data analysis is always related the quality of the used data, thus, data quality analysis is performed as first step via checking the historical time based data used in Kongsberg which is real time data software and compare it with the raw data. The main focus of this study will be the stand pipe pressure and mud pump flow rate variations while bringing the mud pumps after making connection. The gained results of this part will be used in later chapters to analyse the pump start-up factors and check if there is any relationship between each other and to develop a new approach that will help to improve the conventional pump start-up procedure.

3.1. Data Quality:

Necessary analyses for this study performed using historical data belonging to wells drilled in different countries and have different measurement frequency. Table 1 illustrates the data used for data quality analysis. The examples are extracted from five different depths and sections, five different rigs and five different countries. Only two cases will be explained here, one is considered to be a bad data quality, whereas the second one is considered as a good data quality.

Case Number	Country	Well Name	Rig Name
1	Austria	Bockfließ 205	RAG_E200
2	Pakistan	Miano 20	SLB RIG_215
3	Yemen	Habban 037	Nabors Rig 221
4	New Zealand	MR7AP5ST1	Ensco 107
5	Tunisia	Sana_1	RIG CTF 06

Table 1. Data Quality Analysis Cases Information

3.1.1. *Case 1 (Bad Data Quality)*

Figure 10 presents the pump start up process at the measured depth of 1196m. The blue curve presents the mud pump flow rate while the red curve shows the stand pipe pressure. The data can be classified into 4 zones, A, B , C and D. Each zone has unique description.

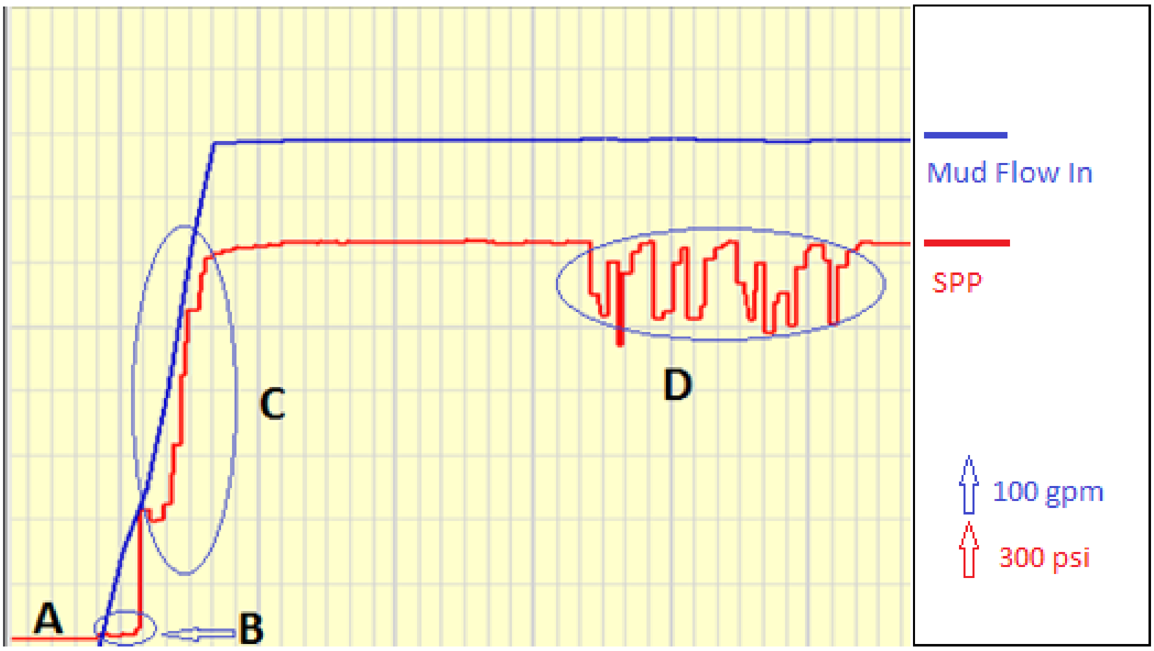


Figure 10. Case#1-Time Based Log for Pump Start-up

As it is presented by zone C, there are a huge difference between the stand pipe pressure variation and the mud pump flow rate. The blue line shows almost a direct and constant increase until it reaches the final flowrate of 790 gpm. The red curve has unsteady behaviour till it reaches the final and stable stand pipe pressure value of 1900 psi.

Zone A shows a stand pipe pressure value different than 0 psi. By further investigation, it was recognized that at this particular time the mud pump was off and there was no drill string rotation. In the presence of the whole mentioned conditions, logically the stand pipe pressure must be 0 psi. However this pressure value was generated due to the presence of mud column into the surface equipment acting on the stand pipe pressure sensor.

Zone D shows the stand pipe pressure responses while activating the directional drilling tool. Zone B shows a time delay of 9 seconds between the stand pipe pressure and the mud flow rate and this is due to the fluid compressibility and distance difference between the stand pipe pressure sensor and the mud flow rate sensor.

For a better analysis of the data quality, the raw data were extracted from Kongsberg and plotted accordingly in excel. Figure 11 presents the raw data distribution in which the red curve presents the stand pipe pressure variation in psi and the blue curve illustrates the mud pump flow rate in gpm. The raw data clearly demonstrate a different reading frequency between the SPP and the mud flow rate.

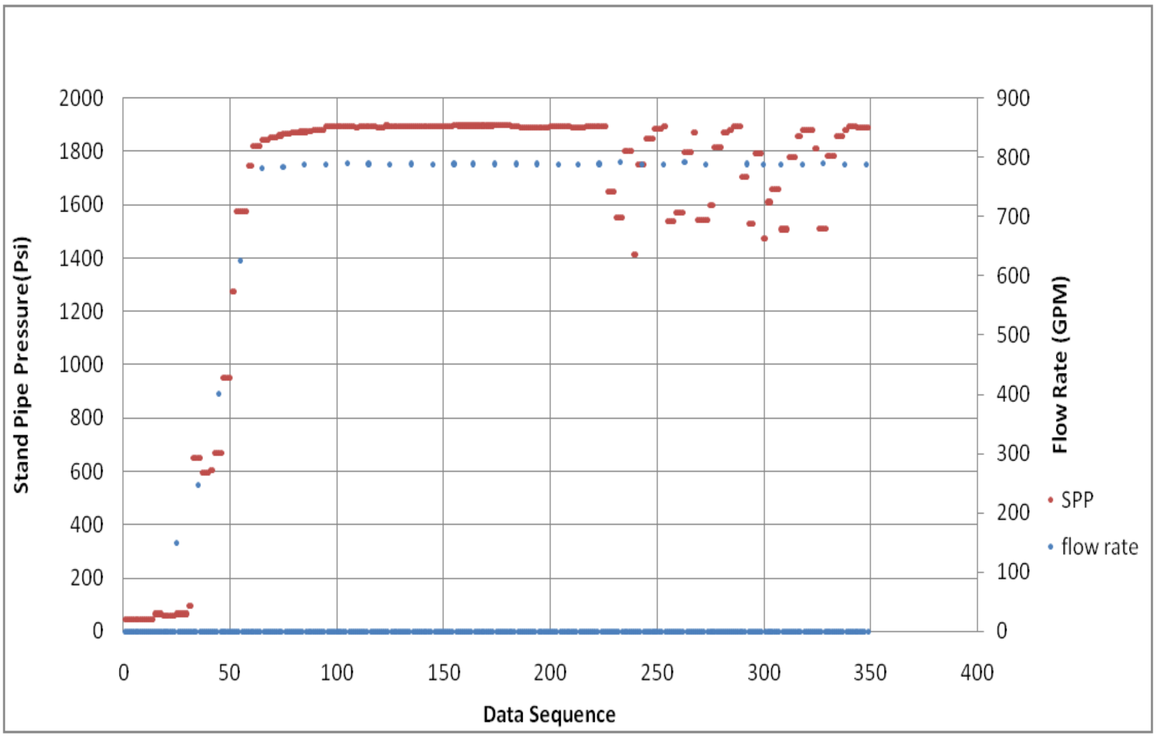


Figure 11. Case #1 - Pump Start-Up (Raw Data Points)

In order to verify that the data quality is not reliable, a cross plots between the stand pipe pressure and mud flow rate readings is established. Figure 13 shows the cross plots between the stand pipe pressure readings in psi and the mud flow rate in gpm. In the ideal case and when there is no drill string rotation, the cross plot shows a linear relation and constant increase behavior. However, in this case the plot shows a different behavior than expected and a lot of data loss present on the SPP pressure axis due to the reading frequency difference as explained previously.

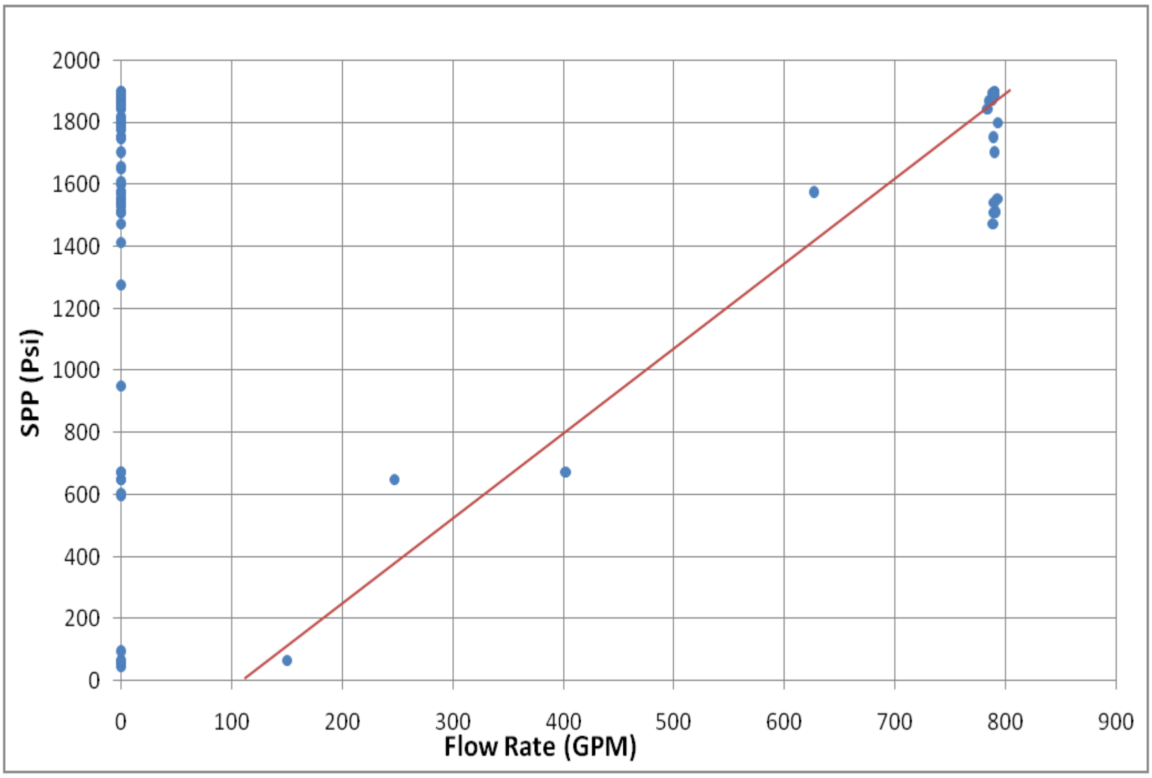


Figure 12. Case#1-Data1- Cross plot (SPP vs Flow Rate)

3.1.2. Case 2 (Good Data Quality)

Table 2 illustrates the data used for the second Case. As mentioned in the table, the stand pipe pressure and mud pump flow rate reading frequency in this case has the same reading frequency, which is 5 second.

MR7AP5ST1/ New Zealand	**Ensco 107**
Data 1	981m MD
Data2	1689m MD
Data3	3136m MD
SPP	5 seconds
Flow Rate	5 seconds

Table 2. Data Quality Analysis-Case#2

Figure 14 presents the pump start up procedure at the measured depth of 981m. The blue curve presents the mud pump flow rate while the red curve shows the stand pipe pressure.

As highlighted in the red oval shape, the data are showing a short delay of 8 seconds between the stand pipe pressure and the mud flow rate reading. As explained in the previous cases the delay is due to distance difference between the stand pipe pressure and the mud flow rate sensors and to the compressibility of the mud. The data are showing a very good correlation. As highlighted on the plot with the blue oval shape, the stand pipe pressure variation is showing an excellent alignment with the flow rate curve with a constant time delay of 8 seconds.

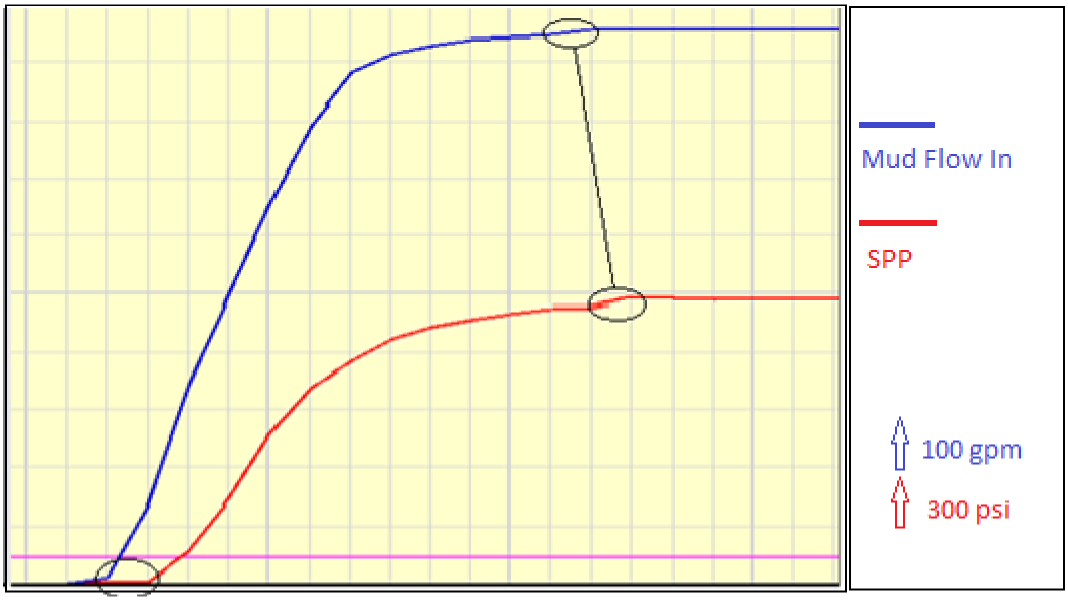


Figure 13. Case #2 -Time Based Log for Pump Start-up

Similar to the first case, the raw data were extracted from Kongsberg and plotted accordingly in excel.

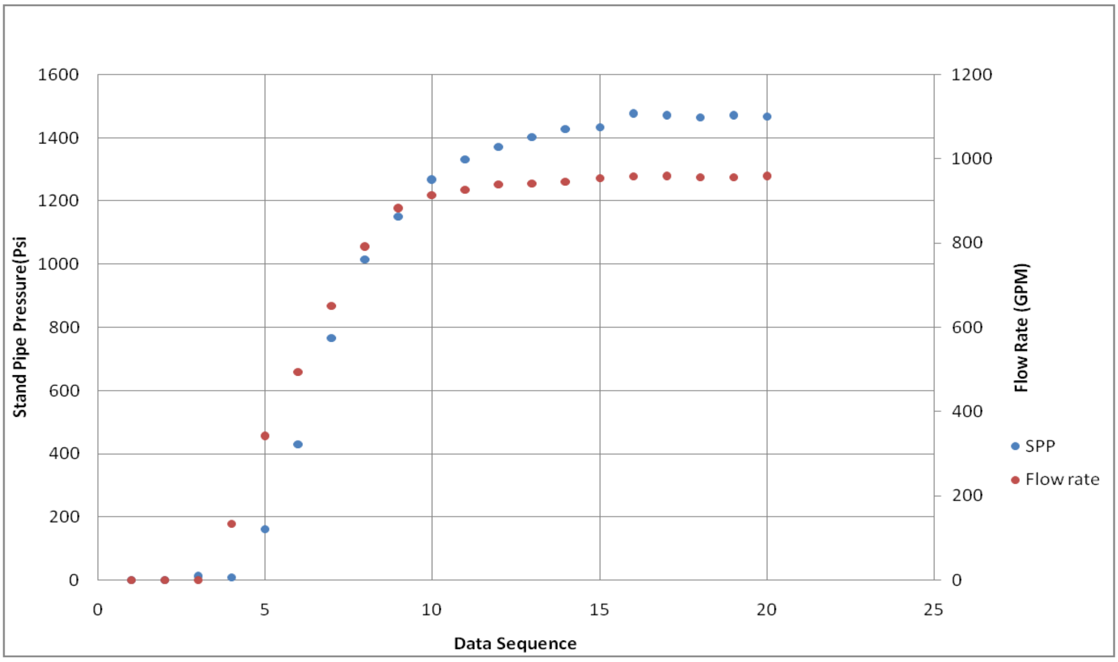


Figure 14. Case #2 - Pump Start-Up (Raw Data Points)

In comparison with the first case, cross plots between the stand pipe pressure and mud flow rate readings in the second case shows perfect curve behavior, a constant and linear increase, as it clearly depicted in Figure 15.

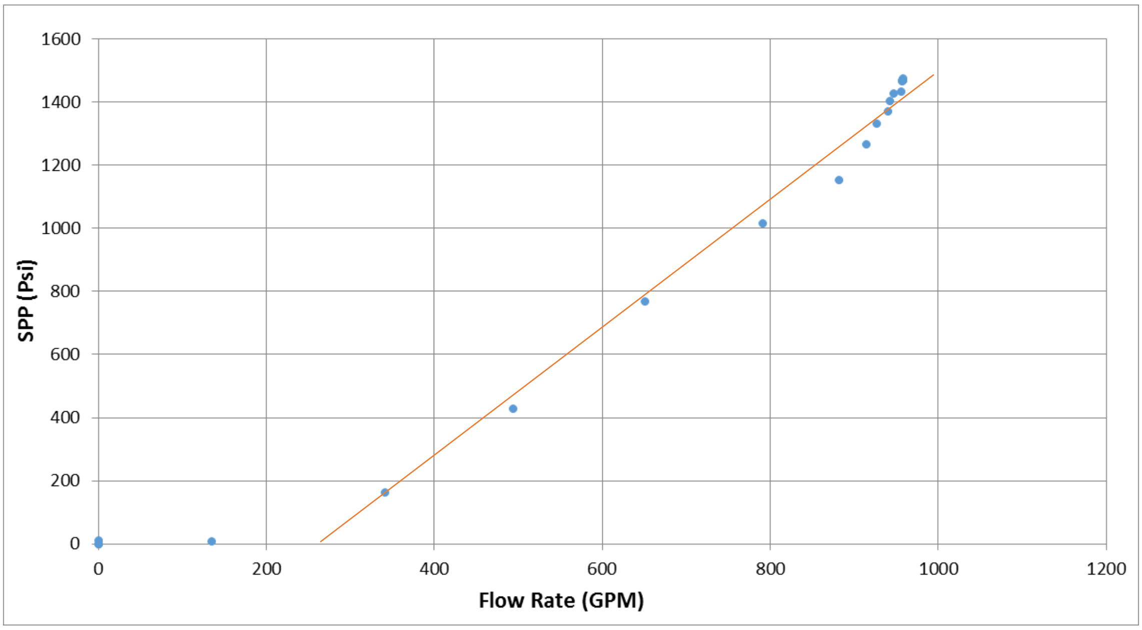


Figure 15. Case#2-Data1- Cross plot (SPP Vs Flow Rate)

3.2. *Pump Start-up Factors effect on Stand Pipe Pressure Spike*

In chapter 2, several factors which have direct influences on the pressure spikes are presented such as gel strength, connection time, etc. In this section a predetermined pump start-up factors will be analysed in details to verify their impact on the pressure spike by using real data. The factors that will be studied are:

- Gel Strength
- Rotation Effect
- Pump Start-Up Types

For the sake of this study, the criterion used to select the best well was based on data quality and data availability. The best candidate was Bockfließ 208 well drilled by RAG E200 in Austria. The data was extracted from two deferent sources, the historical time based data are extracted from Kongsberg and the other data like mud weight, gel strength and hole size which are extracted from OMV data base.

3.2.1. *Well Overview*

Table 3 illustrates the data used for the cross plots.

Well	Bockfließ 208
Country	Austria
Rig Name	RAG E200
Stand Pipe Pressure Measurement Frequency	1 second
Mud Flow Rate Measurement Frequency	10 seconds
True Vertical Depth	1650 m
Measured Depth	2600 m
Well Geometry	Horizontal
KOP	620 m

Table 3. Well Data Overview

3.2.2. Pump Start-Up Factors Analysis and Interpretations

3.2.2.1. Gel Strength

The first factor that considered having highest impact on the pressure spike is the gel strength of the drilling fluid, thus it was studied first. Ten data points were used to present the relation between the value of gel strength and the pressure spike. The data points were plotted as it can be seen in Figure 16. The graph clearly shows a strong correlation between the gel strength value and the pressure spike when starting the mud pump. Depending on the gel strength, the stand pipe pressure have shown a different value of spike ranging from 0 psi for 7 $lb/100ft^2$ up to 190 psi for 25 $lb/100ft^2$.As a conclusion, the higher the gel strength value, the higher the pressure spike will be.

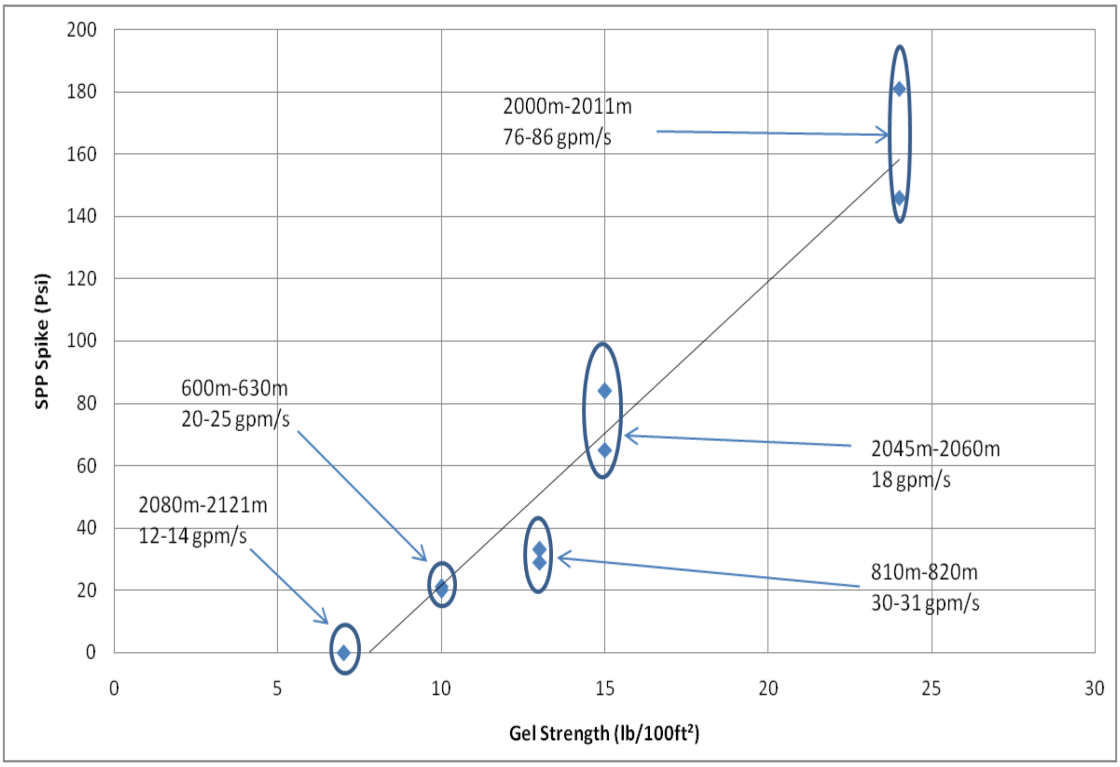


Figure 16. Gel Strength Effect on Pressure Spike

3.2.2.2. *Rotation Effect*

As mentioned earlier, the pipe rotation might have significant effect on the SPP, as it is common practise once the SPP has stabilized; the driller starts to rotate the drill string. This rotation will cause the SPP to decrease. In order to prove this phenomenon, the SPP prior to commencing pipe rotation and after commencing pipe rotation for multiple data points was plotted versus RPM (Figure 17). As it was expected when the rotation starts, the SPP immediately decreases. But in some cases the stand pipe pressure increases. After analysing the provided data, it was recognised that the pressure increase or decrease is related to the hole size. When the drill string starts to rotate, the fluid movement changes from linear to helical movement. So, if the hole size is relatively big, the contact with the wellbore wall is reduced thus there is a lower pressure losses so the stand pipe pressure decreases. For the other way around, when there is a relatively small hole size, the contact with the wellbore wall is increased thus there is a higher pressure losses so the stand pipe pressure increases.

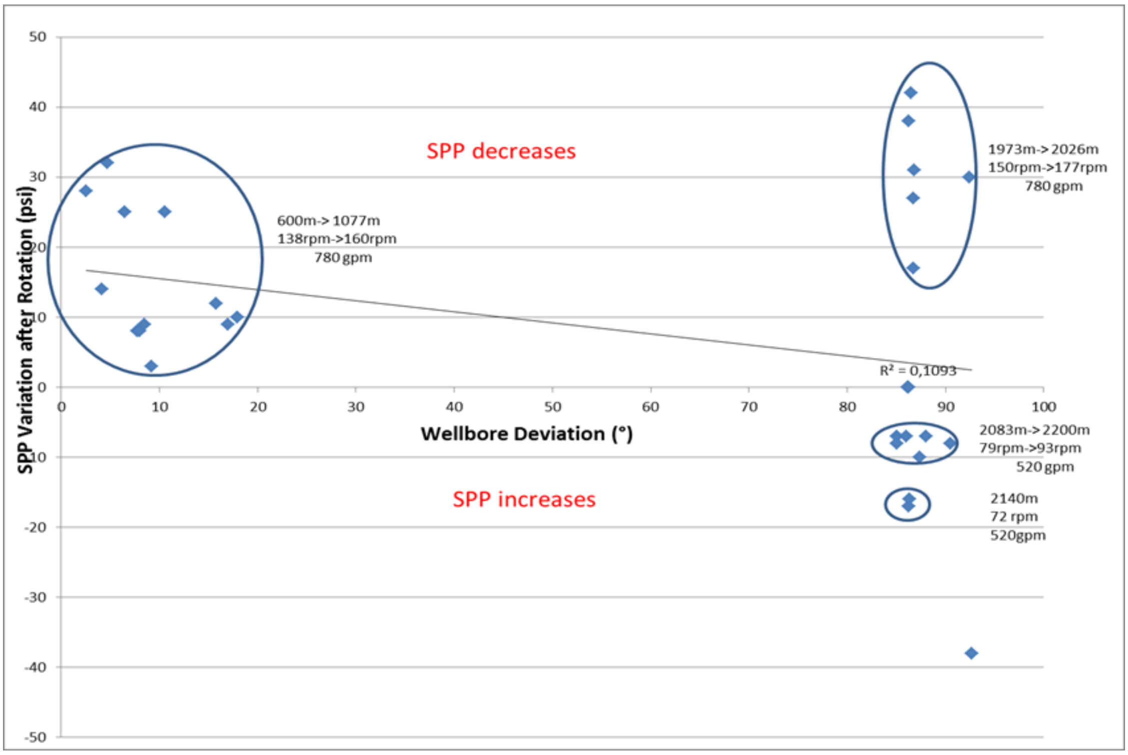


Figure 17. SPP Variation after Rotation (Psi) vs Wellbore Inclination (°)

3.2.2.3. *Pump Start-up Types Effect*

Depending on the driller and the situation, three types of pump start-ups can be distinguished:

Type 1: The mud pump is brought to final desired flow rate in one stage without using any intermediate stage.

Type 2: The mud pump is increased fast till it reaches an intermediate stage and then the flow is kept constant so that the pressure inside the wellbore is stable and then the mud pumps are brought to the final desired flow rate with a lower acceleration compared to the first one.

Type 3: is considered the slowest type and it is used to bring the pump up to the desired flow rate in a dangerous area like reservoir section, low geo-pressure margins and lost circulation zones. It is based on bringing the pump to two intermediate stages before reaching the final desired flow rate. The first, second and third stop is related to the time used to stabilize the pressure regimes in the wellbore before resuming the mud pump acceleration to the next stage and it is calculated as the period of time in which the flow rate was stable. Figure 18shows the three types explained above.

.

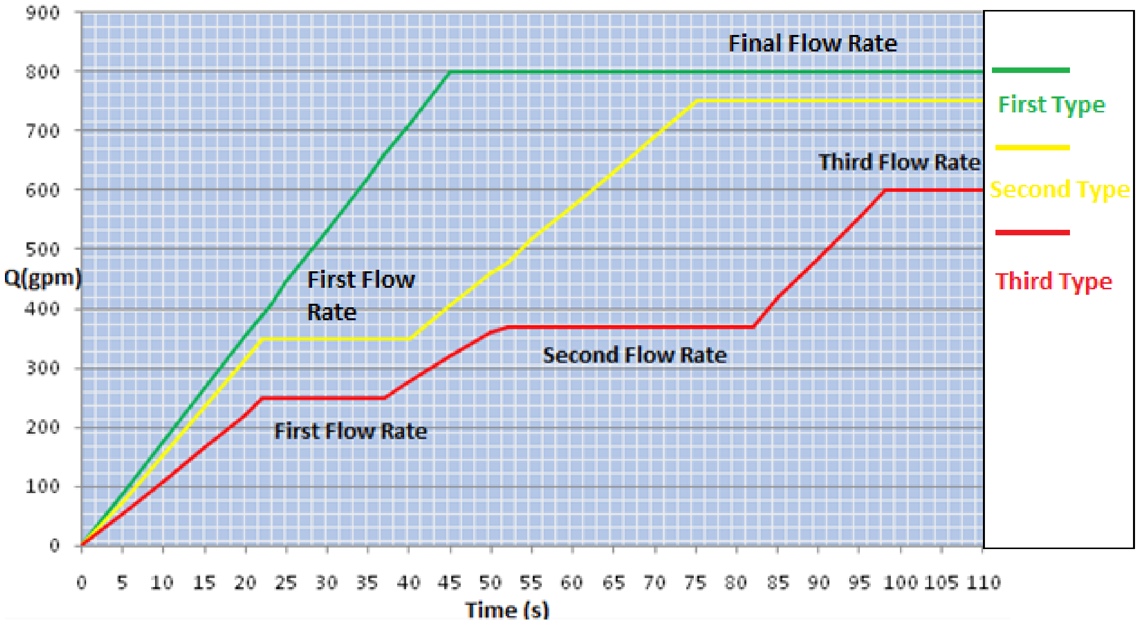


Figure 18. Pump Start-up Type Comparison

In order to determine the relation between the SPP spike and the pump start up type, the SPP peaks with commonly used pump start up methods were plotted. As it is illustrated in Figure 19, the pump start-up does not bring any indication about the stand pipe pressure spike, in other words no clear relation between the two parameters. However, there is an important observation which can be extracted from the relation; this observation is that the SPP spike is depending on the acceleration.

The pump acceleration is defined as the pump speed increase in a certain time. It is considered to have the highest impact on the pressure spike. The higher the acceleration the higher the pressure spikes.

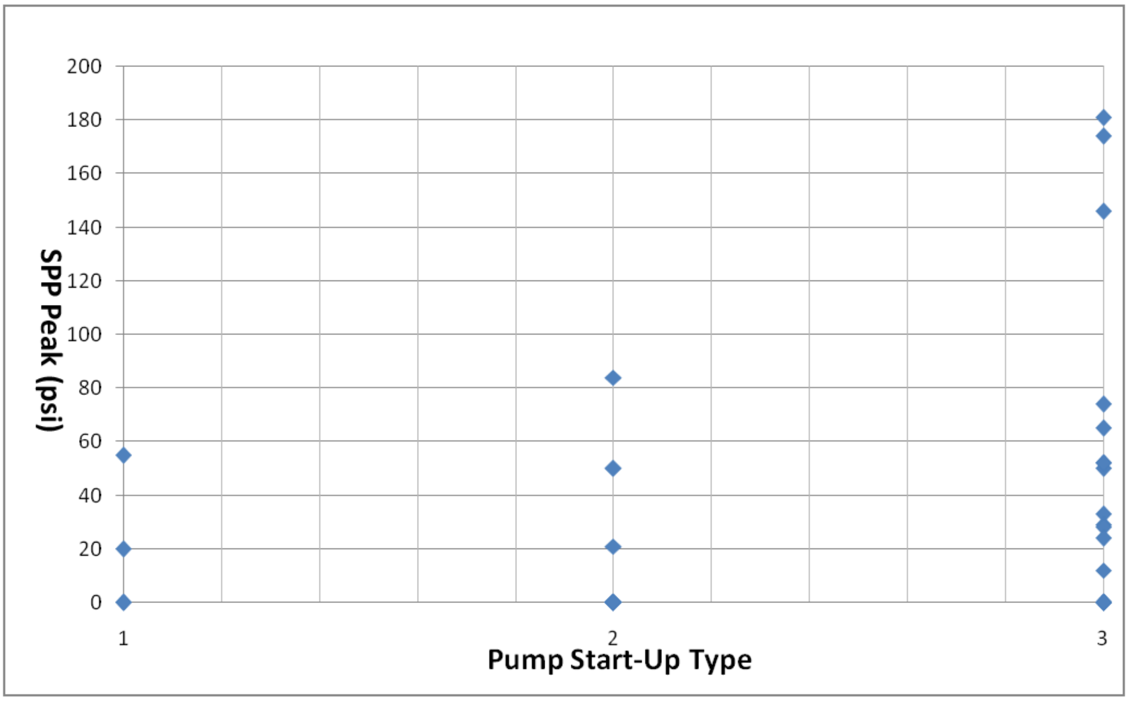


Figure 19. Start-Up Type vs SPP Peak (Psi)

Chapter 4 Pump Start-up Procedures Analysis

In chapter two the top factors that proved to have significant impact on the SPP spike have been study individually. However, the questions that remain open and require definite answers now are: what is the relation between those factors and what is the best pump start up procedures method to be used and what are the criterions which have to be used to determine the best method. In order to answer these questions an extra study has been performed here. The main objective of this study is to analyse the pump start up procedures via checking the variation of several important parameters as a function of depth and time such as: stand pipe pressure variation, stand pipe pressure response delay, flow rate variation in the time of start-up and over the depth of the drilled well, pressure required to break the gel strength in all the sections, time required to bring the mud pumps and rheology variation as a function of depth. The data used for this study belongs to Miano20. Due to the learning factor, it was decided to study Miano 20 which is the newest well drilled for a more detailed analysis.

Kongsberg was used to analyse pump start-up real time data. Due to the lack of data and technical issues, it was not possible to track the data which were from 1092m until 2780m.

4.1. Gel Strength Value and Pressure Required to Break the Gel

As it was explained earlier the gel strength value is time-dependent and since the pressure required breaking the gel is mainly controlled by the instant value of gel strength, then it can be said that the pressure required to break the gel is time-dependent as well. The gel starts to build once the circulation has stopped. So, the longer it takes to resume circulation the higher the gel strength will be; the higher pressure required breaking the gel strength which leads to a higher pressure spike. From this fact it can be concluded the following: if the instant value of gel strength can be measured or predicted, the exact pressure to break down the gel can be estimated. However, so far there are no tools that can measure the gel strength downhole, the measurement can be done only at the surface and it is not continuous measurement. Thus, only the 10 minutes gel strength value is available and all the further predictions have to rely on this value.

For better understanding about time dependent effect, 10 minute gel strength value and connection time are plotted versus depth. The connection time means here is not the weight to weight connection time; it is the last time since the circulation has stopped and resumed to start drilling. Weight to weight connection usually includes hole conditioning like reaming, wash up-ward, wash down-ward…etc. and then the pump might be started and turned off for more than one time within this period.

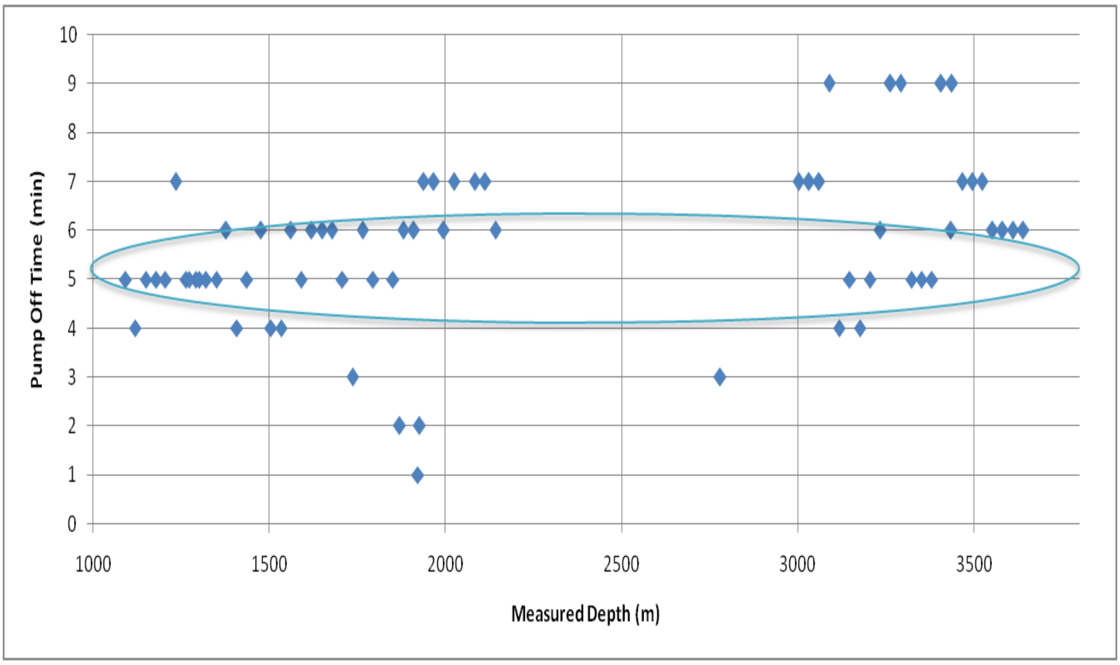


Figure 20. Pump-off Time vs Measured Depth

As illustrated previously in Figure 20, most of the pump off time are around 5 to 6 minutes, thus the 10 min gel strength can be used and regarded as worst case scenario.

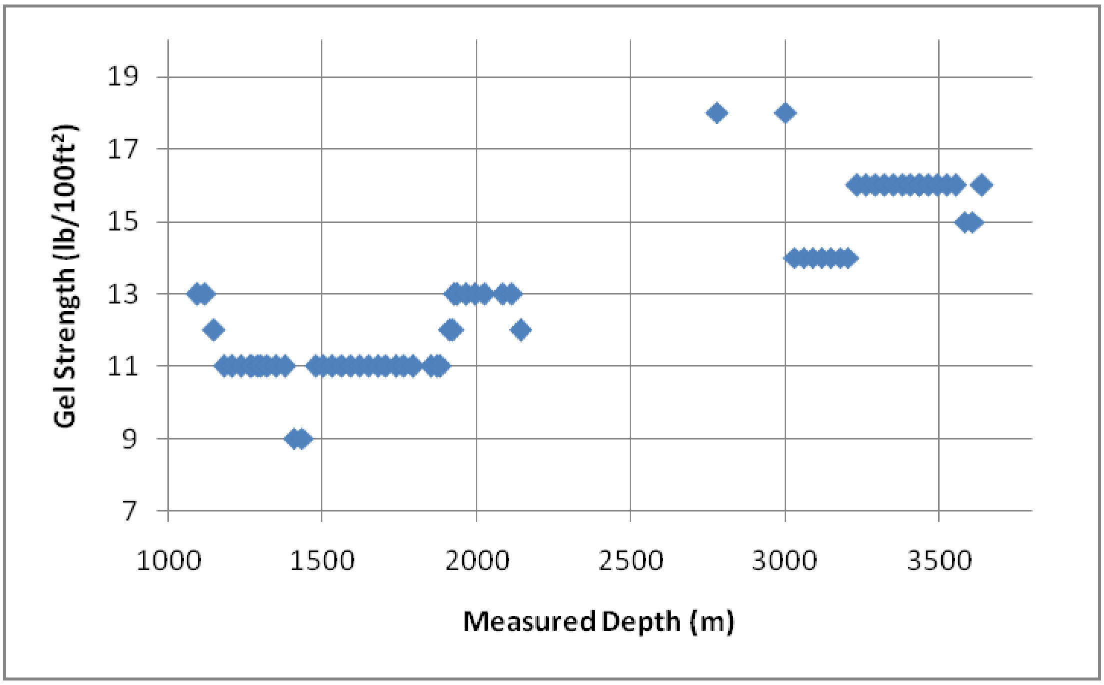


Figure 21: Gel Strength Vs Measured Depth

The 10 min gel strength value is nearly constant in the non-reservoir area (11 to 13 lb/100ft^2) and it increases in the reservoir area to reach (16 lb/100ft^2).

Using the equations (2), (1) and (3) the theoretical pressure required to break the gel strength has been calculated as a function of measured depth.

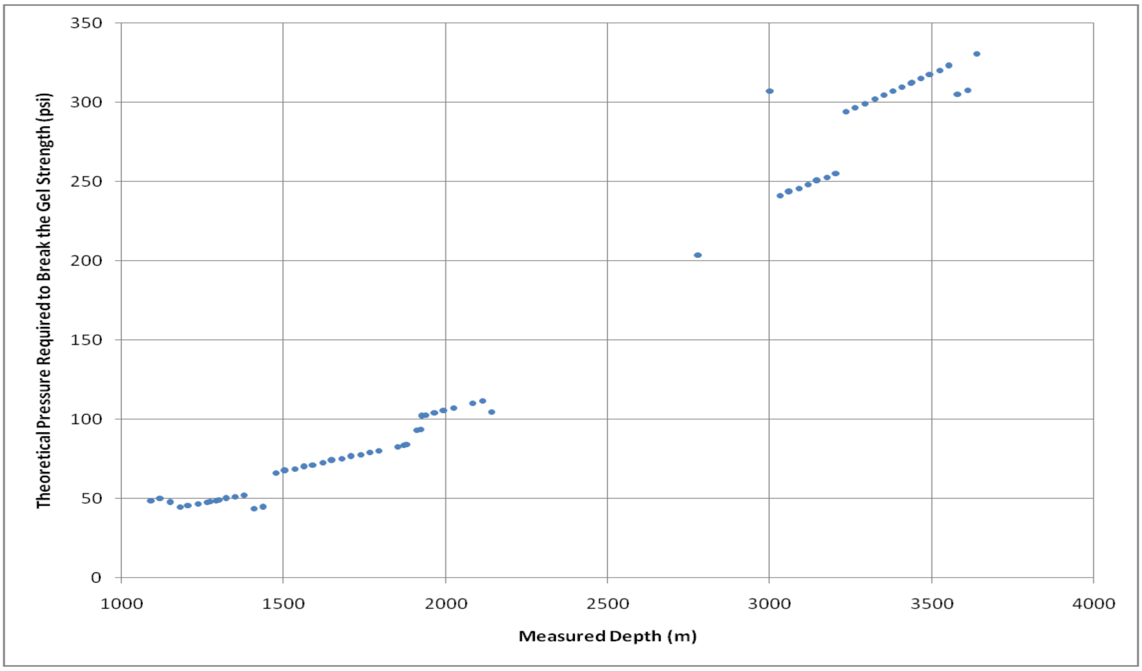


Figure 22. Theoretical Pressure required To Break the Gel Strength Vs Measured Depth

Figure 22 illustrates the calculated total theoretical pressure required to break the gel strength as a function of measured depth. The theoretical pressure required to break the gel strength tends to increase with almost a linear manner and this is due to the linear increase of the measured depth and the variation of the gel strength value as a function of depth.

4.2. Pump Start-Up Procedures Type and ECD

The study manifests that the three typical pump start-up procedures was used by the driller during the construction of this well. In this section the effect of each type on the ECD for preselected cases will be analysed and discussed. The pressure pump start-up procedures considered through this analysis belong to drilling phase only. In other words the pump start after tripping is not considered.

4.2.1. Type I

The first one, which is illustrated in Figure 23, consists of increasing constantly the pump rate to reach the final flow rate in one go with a constant acceleration of 17 gpm/s up to 25 gpm/s. The results have shown that this pump start-up type was the fastest; the driller was able to reach the desired final flow rate within 45 seconds in the best case. As the driller starts to accelerate the pump, the ECD starts to increase as well but due to the high geo-pressure margin between the ECD and the fracture pressure, the driller does not stop and use an intermediate stage to stabilize the pressure spike.

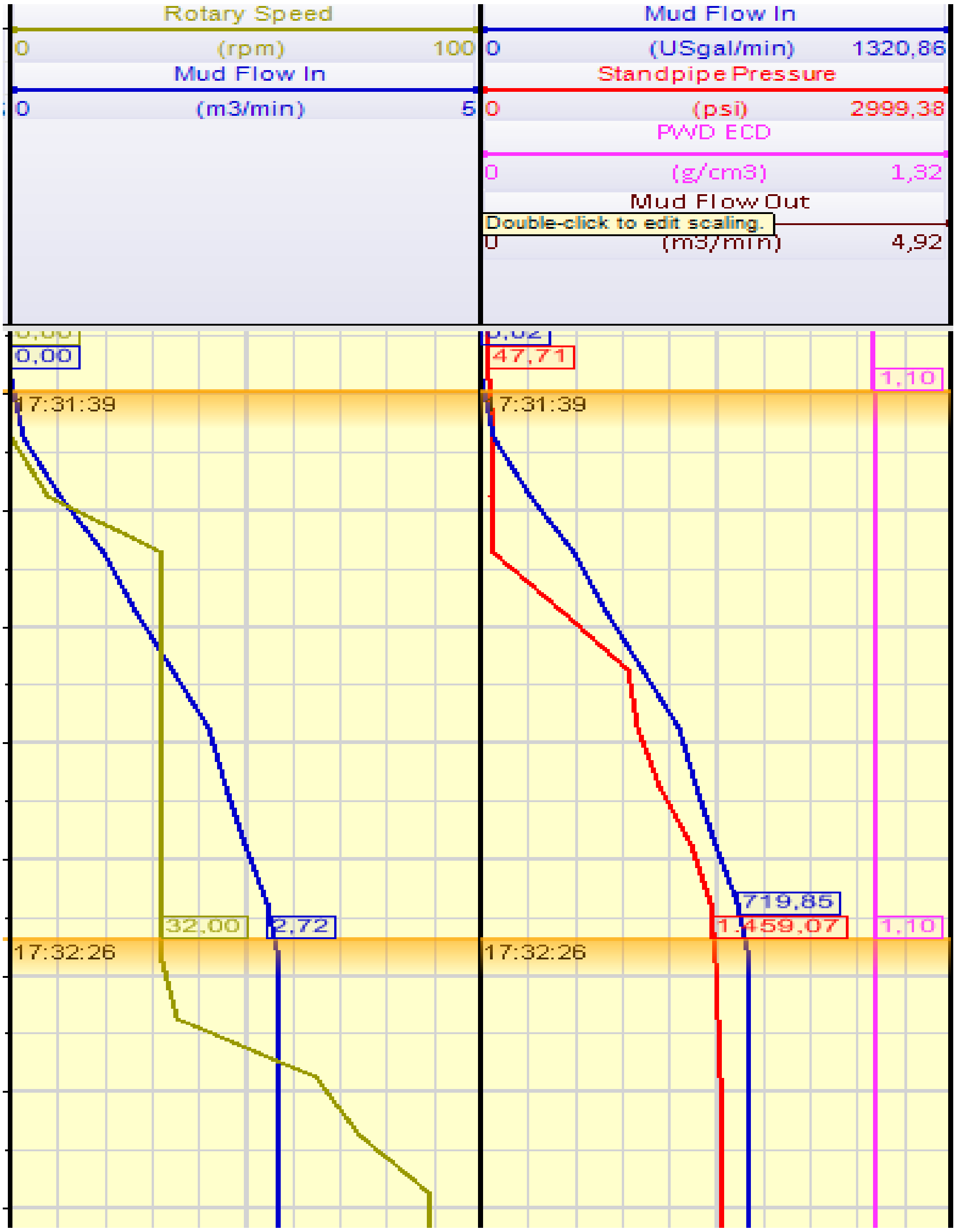


Figure 23. Pump Start-up Type 1

4.2.2. *Type II*

The second one, as it is shown in Figure 24, consists of increasing the flow rate to a certain level then wait until the stand pipe pressure stabilizes then increasing the pump rate again to the final desired flow rate. This type was the most common one. With a constant acceleration of 12 gpm/s up to 16 gpm/s, the final desired flow rate was reached within 75 seconds in the best case. As the driller starts to accelerate the pump, the ECD starts to increase as well but due to the medium range between the geo-pressure margin between the ECD and the fracture pressure, the driller reduces the acceleration because the ECD tends to get closer and closer to the fracture pressure.

Figure 24. Pump Start-up Type 2

4.2.3. *Type III*

The third type, as it is illustrated in Figure 25, was the most careful one and it was usually applied within expected lost circulation or reservoir areas. This pump start-up type consists of increasing the pump rate to final desired flow rate with several intermediate stops. Normally, 2 intermediate stops were applied but in some cases 3 or 4 or even more was applied. With a constant acceleration of 6 gpm/s up to 12 gpm/s, the final desired flow rate was reached within 98 seconds in the best case.

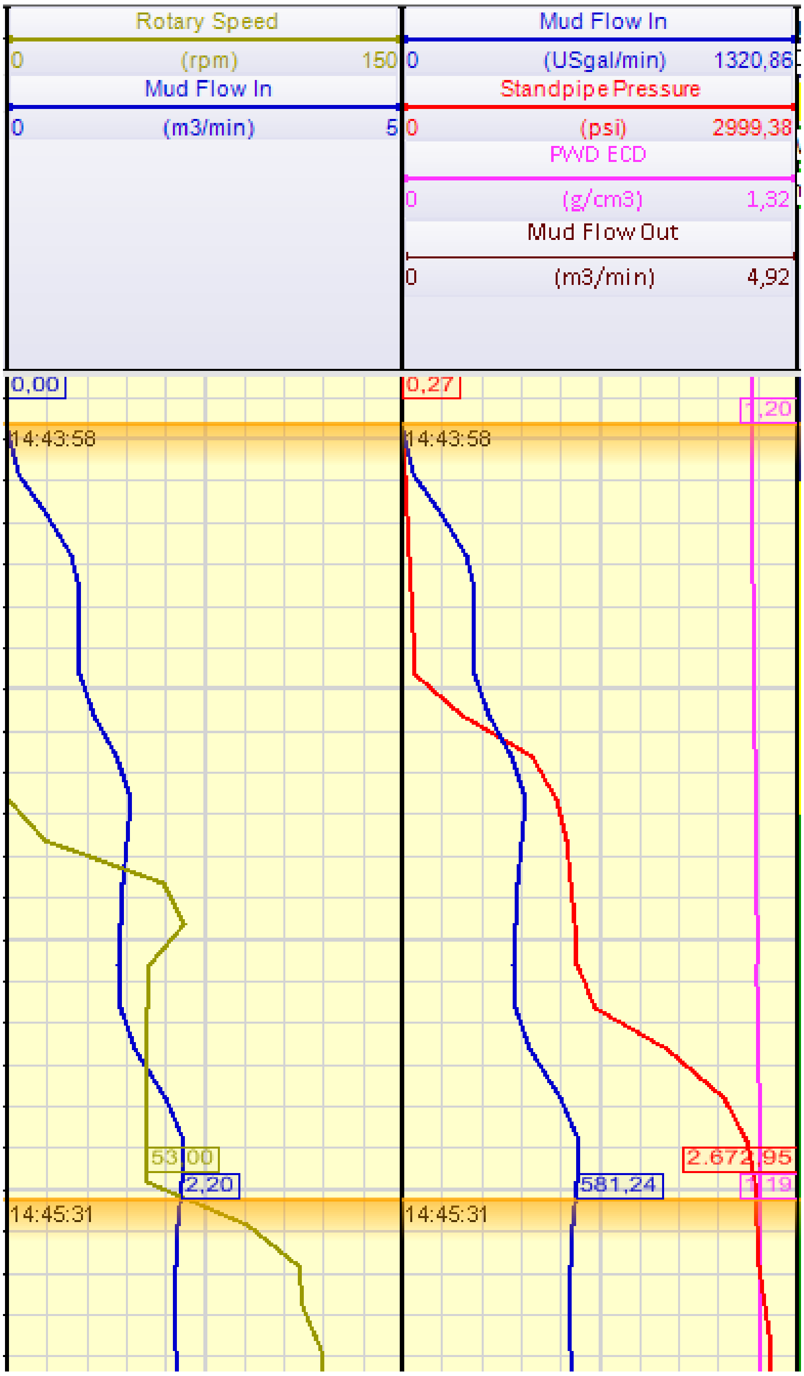


Figure 25. Pump Start-up Type 3

4.3. Stand Pipe Pressure Response Delay

Another important issue which is worth mentioning here is pressure sensor response delay. As it can be clearly seen in Figure 26 the delay time variation as a function of measured depth. With 10 second as a lower limit and 40 second as an upper limit, it was concluded that the delay time got almost a constant increase as a function of depth.

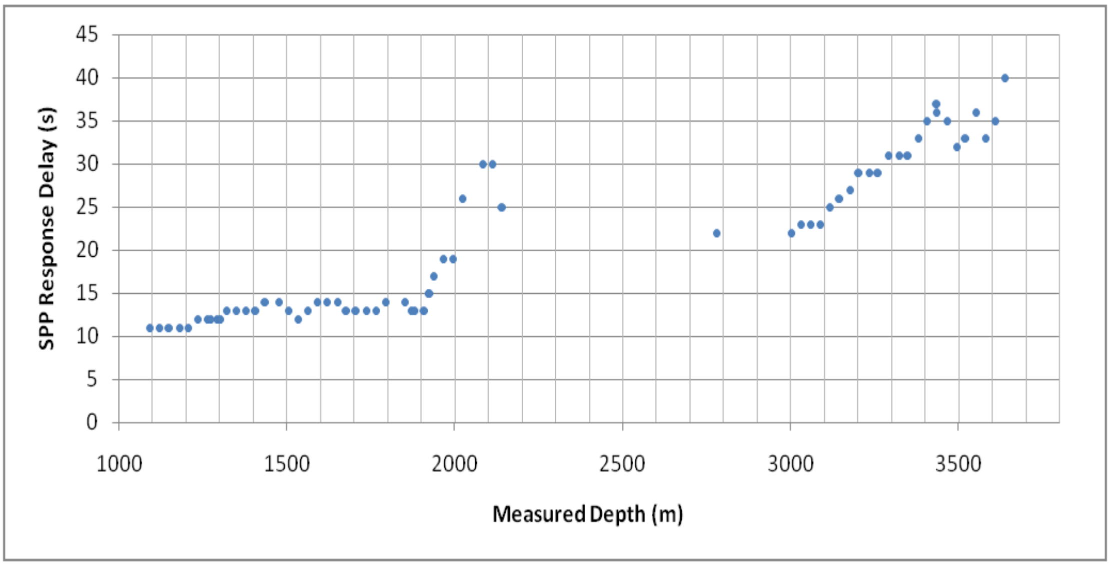


Figure 26. Depth vs Time Delay for Stand Pipe Pressure Response

If the stand pipe pressure delay is not taken into account, especially with the 2nd and 3rd type of start-up, a huge time loss can be resulted since the driller needs to wait for the stand pipe pressure to stabilize.

4.4. Human Effect

In order to study the human behaviour effect on the pump start-up, statistical study was performed. Main objectives behind this study were to

- Which pump start-up procedure type was mostly used
- Is there are specific rule for selection the method
- In type 2 and 3, what is the waiting time between stages
- Is there basic rule for determining the increase in flow rate between the stages

4.4.1. Pump Start-Up Time Distribution

Figure 27shows how the time range is split within the first, second and third start-up as a function of measured depth.

The bleu column illustrates the percentage of time needed for the first start-up until the next intermediate stage out of the whole time needed to fully start the pump.

The red column illustrates the percentage of time needed for the second start-up until the next intermediate stage out of the whole time needed to fully start the pump.

The green column illustrates the percentage of time needed for the third start-up until the desired final flow rate out of the whole time needed to fully start the pump.

If the column contains one single colour (blue) it means that the driller has used the first start-up type. If the column contains two colours (blue and red) it means that the driller has used the second type of start-up. Otherwise, the driller have used the third type of start-up.

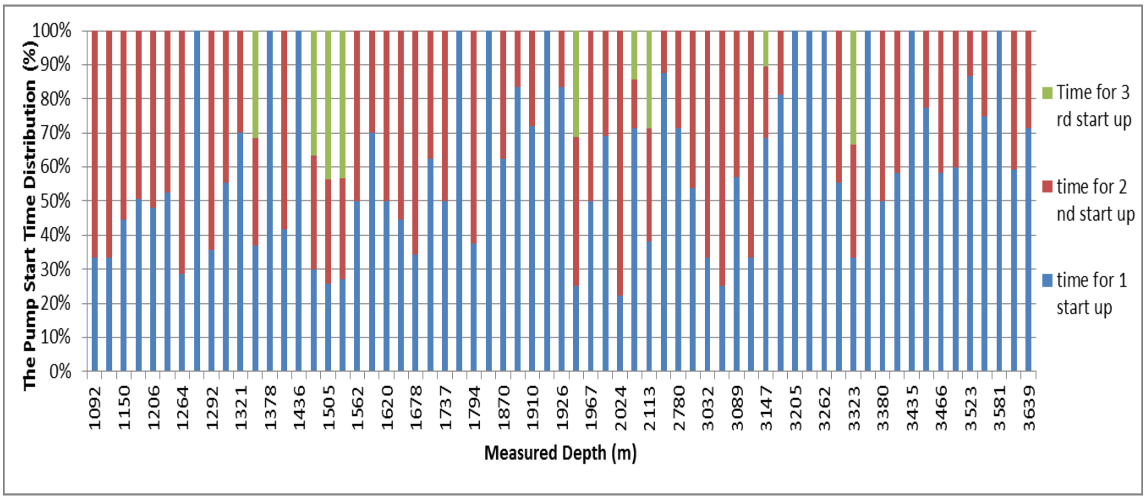


Figure 27. Pump Start-up Time Distribution as a Function of Types

4.4.2. Flow Rate Distribution

Figure 28 shows how the flow rate range is split within the first, second and third start-up as a function of measured depth.

The bleu column illustrates the percentage of flow rate used for the first start-up until the next intermediate stage out of the final desired flow rate.

The red column illustrates the percentage of flow rate used for the second start-up until the next intermediate stage out of the final desired flow rate.

The green column illustrates the percentage of flow rate used for the third start-up until the next intermediate stage out of the final desired flow rate.

If the column contains one single colour (blue) it means that the driller has used the first start-up type. If the column contains two colours (blue and red) it means that the driller has used the second type of start-up. Otherwise, the driller has used the third type of start-up.

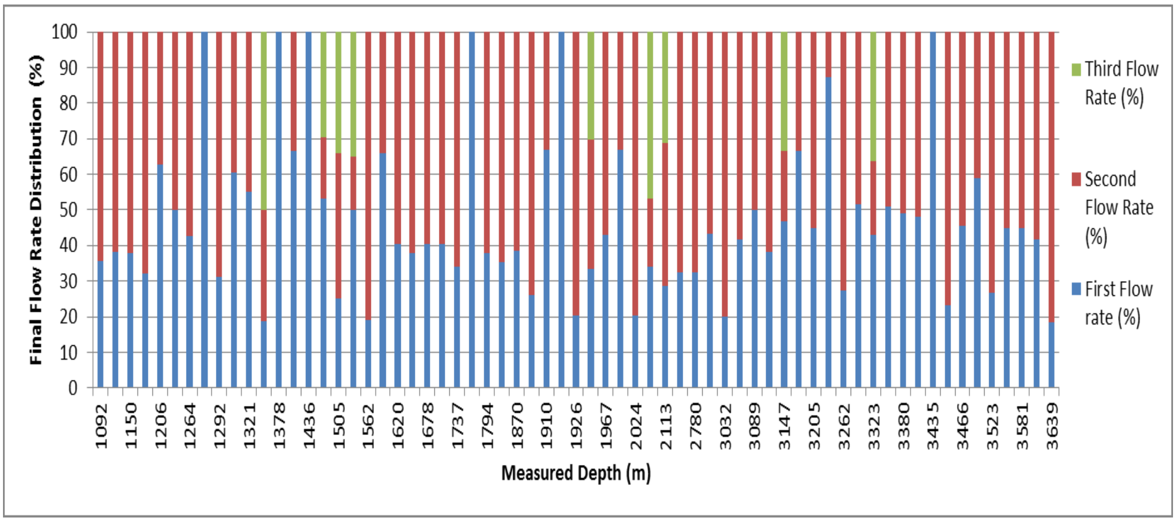


Figure 28. Pump Start-up Flow Rate Distribution as a Function of Types

4.5. Conclusion

Based on the findings of this analysis the following conclusion can be drawn:

- The surface section has the lowest pressure required to break the gel strength and the deeper the depth, the smaller the hole size, the higher the pressure required to break the gel strength.
- Three main acceleration types are used by the driller:
  - Direct increase of flow rate until reaching the final desired flow rate.
  - One intermediate stage before reaching the final desired flow rate.
  - Two intermediate stages before reaching the final desired flow rate.
- In most cases, the driller needs around one to one minute and half to start the pump.
- There is no rule of thumb of the flow rate distribution in the different types of pump start-up, it is only depending on the driller how he thinks how he thinks to start the pumps.
- Using 10 minutes gel strength for the analysis is more conservative. As it was proved through this study, in all cases, except the tripping procedure, the pump off time did not exceed10 minutes with a maximum of 9 minutes. In average, the pump off time is between 4 and 7 minutes.
- Stand pipe pressure shows a linear increase as a function of depth with a minimum of 10 seconds and a maximum of 40 seconds in worst case scenario.
- There is a room for improvement in the pump start-up procedures via benchmarking the best performance and applying it through the whole well, some economic benefits can be extracted.

Chapter 5 Alternative Pump Start-Up Procedures

5.1. Overview

Several factors have been proven to have significant influence on the pump start up procedures; these factors can be classified into two main categories, controllable and uncontrollable, these factors have different impact severity, some of them have high impact others have less. The controllable factors include:

- Type of pump start up
- Starting flow rate
- Acceleration between two stages
- Waiting time between two stages
- Connection time

Whereas uncontrollable factors can be defined as the factors which cannot be controlled by the driller, they comprise:

- Gel strength value
- Geo-pressure margin
- Lost circulation zones
- Rock properties of the reservoir
- Borehole size and shape

If we come back to conventional pump start up procedures and see if they cover all the mentioned factors, we can see that these procedures have remarkable disadvantages, their main shortcomings are:

- they do not take into account the uncontrollable factors
- there is no a specific guideline that help to select the best type

Therefore, it was necessary to come up with a new approach which will help to improve the conventional pump start up procedures by overcoming the disadvantages mentioned above. In this chapter the development of the new approach will be explained.

The underlying steps followed to develop this approach can be summarized in the following points:

- Gather all the important factors related to the pump start-up procedures
- Evaluate the impact of each factor on the start-up process

- Compute Pump Start-up Index [PSUI] and generate a heat map
- Builda hydraulic model and compute theoretical pressure required to break gel strength
- Determine the pump flow rate required to provide theoretical pressure required to break gel strength
- Compare the pump flow rate required to provide theoretical pressure required to break gel strength with desired flow rate
- Propose the ideal number of accelerations and the increase of flow rate for each acceleration

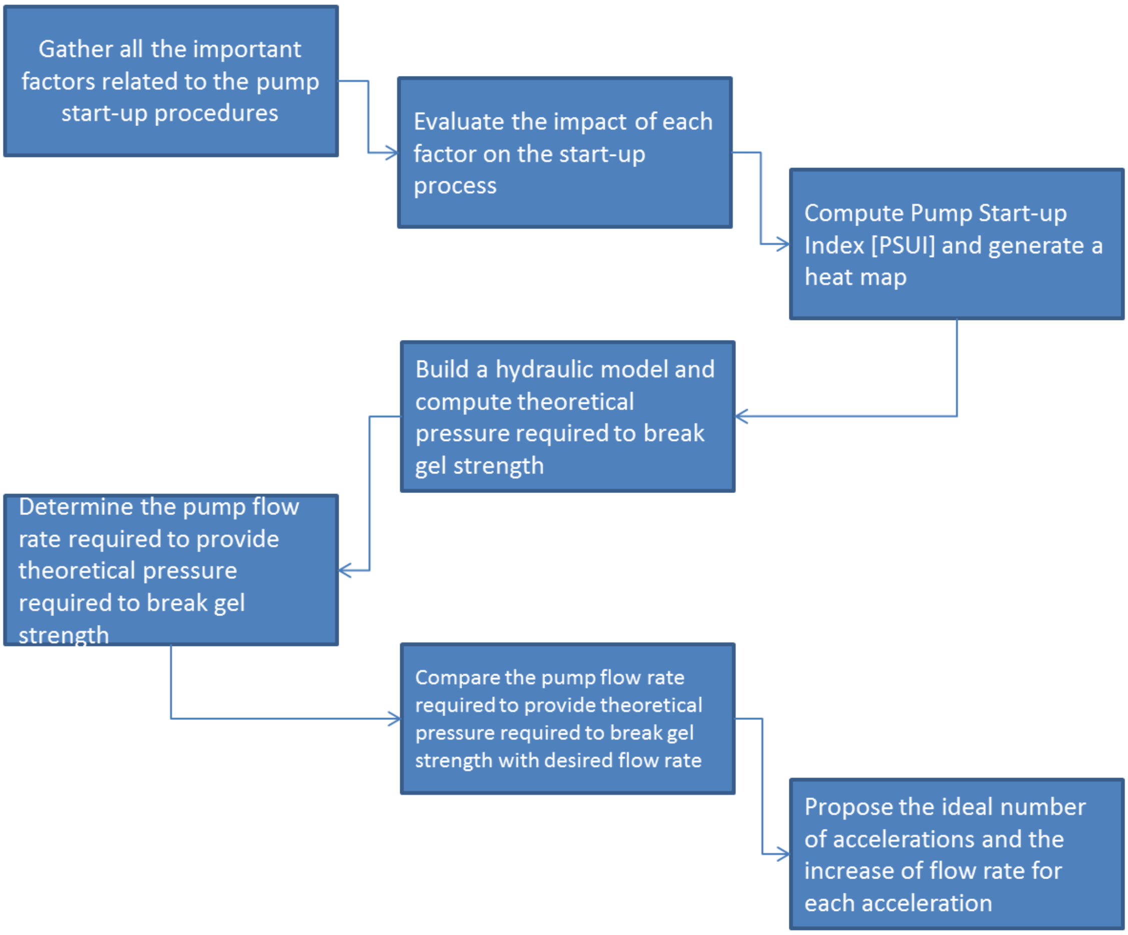


Figure 29. Alternative Pump Start-Up Procedures Workflow

5.2. Methodology

5.2.1. Factors Affecting Pump Start-up

The process starts by collecting the factors related to the pump start-up procedures which were extracted from the previous studies performed in chapter 2 and 3. As it is shown in Figure 30, the pump start-up depends on several factors like geological situation, rheological parameters and others.

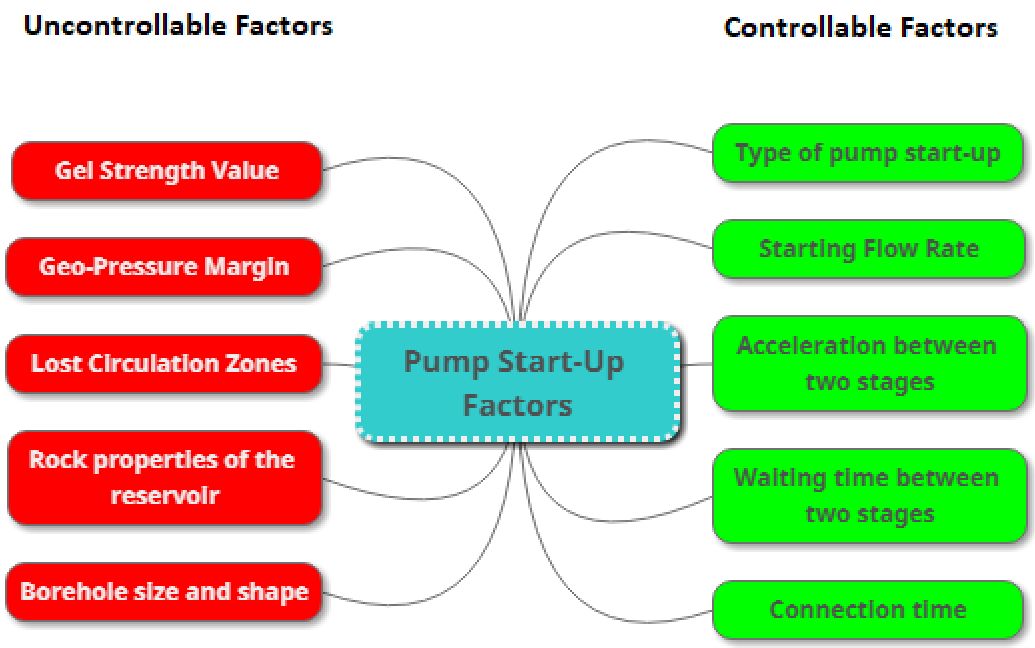


Figure 30. Pump Start-Up Related Factors

5.2.1.1 Geology

– *Geo-Pressure Margin*

The geo-pressure margin is defined as the difference between the ECD and the fracture initiation pressure of the formation. When there is a low geo-pressure margin, the pump start-up is limited compared to a wider geo-pressure margin, since there is a higher chance that the pressure spike when starting the pump can reach the fracture initiation pressure causing induce fracture which can lead to fluid loss and formation damages.

– *Reservoir Area*

Having a lost circulation or fracturing the formation in the reservoir zone leads to severe impact which can devastate the whole wellbore like decreasing the reservoir productivity due to fluid invasion, so starting the pump as slowly as possible to decrease the probability of reaching the fracture pressure is the most suitable practice in this dangerous and highly risky zone.

5.2.1.2. Rheology

– *Mud Density*

For conventional overbalanced drilling, the mud density should be within the pore pressure and the fracture pressure to prevent wellbore influxes and fracturing the formation. Having an excessive mud weight leads to decrease the geo-pressure margin thus it will increase the chances to reach the fracture pressure when starting the mud pump.

– *Gel Strength*

As discussed previously, using a high gel strength value will increase the value of the pressure spike which increases the probability to reach the fracture pressure.

5.2.1.3. Flow Rate

As the flow rate increases the equivalent circulating density tends to increase as well due to the increase in the frictional pressure losses so using a higher flow rate will decrease the geo-pressure margin when using the same mud density and same drill string configuration.

5.2.1.4. Depth

As illustrated previously in equation (3), the deeper the well, the higher the theoretical pressure required for breaking the gel strength the higher the pressure spike when starting the pump. So as the wellbore gets deeper, the tendency to fracture the formation gets higher.

5.2.1.5. Wellbore Shape

Having a different wellbore trajectory affects directly the hydraulics of the wellbore. For example, in the case of an horizontal wellbore, the cuttings will settle on the lower side of the wellbore, which result in reducing the clearance between the outside diameter of the drill string and the hole size, thus increasing the pressure spike.

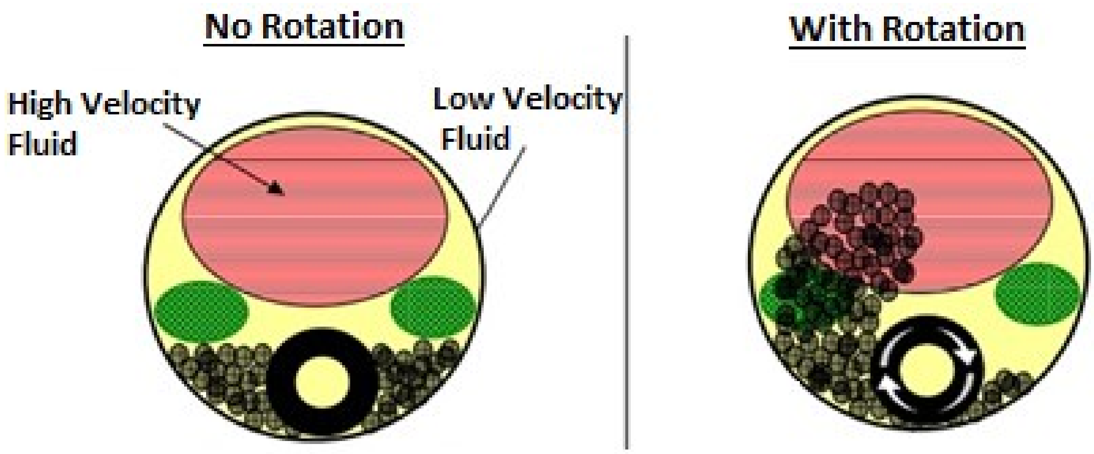


Figure 31: Rotation Effect on Wellbore Cleaning

Figure 32 shows the severity impact of aforementioned factors.

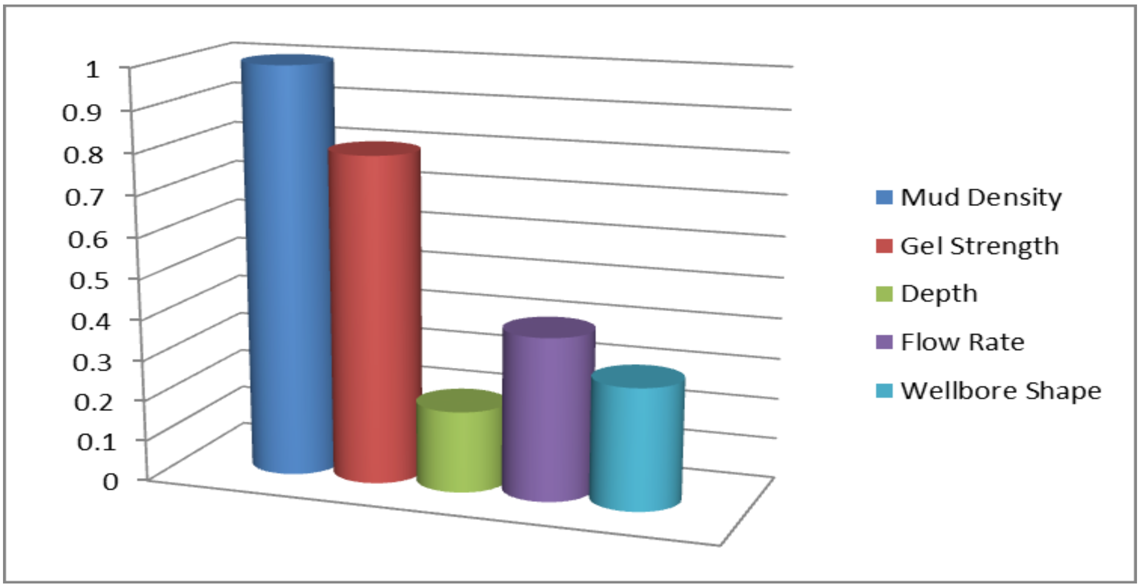


Figure 32. Severity Impact of the Factors on Pump Start-Up

5.2.2. *Pump Start-up Index [PSUI]*

Pump start up index [PSUI] is an index which can be used as an early warning indictor; it is designed in way that allows the user to differentiate between the danger and safe zones. The factors integrated into this index were carefully selected based on the multiple data analysis studies performed in the earlier chapters. These factors are:

[1] Geology [ε_G]

[2] Rheology [ε_R]

[3] Geo-pressure margin[ε_{GP}]

Geology Factor

This factor is used to distinguish between reservoir and non-reservoir areas. Two integer numbers are used here, 1 indicates non reservoir whereas -1 indicates reservoir area.

Geo-pressure Margin Factor

As mentioned earlier, this geo-pressure margin is the difference between the Equivalent Circulating Density[ECD] and the fracture initiation pressure [P_f] for a given formation; however Geo-pressure Margin Factor for PSUI is calculated as following

$$\varepsilon_{GP} = \frac{P_f - ECD}{100} \tag{4}$$

Rheology Factor

This factor reflects the gel strength effectiveness on system. It can be computed as following:

$$\varepsilon_R = \frac{1}{Value\ of\ 10\ minute\ Gel\ Strength} \quad (5)$$

Once the three factors have been obtained the pump start up index [PSUI] can be determined by using the following equation:

$$\text{PSUI} = \varepsilon_G * \varepsilon_R * \varepsilon_{GP} \quad (6)$$

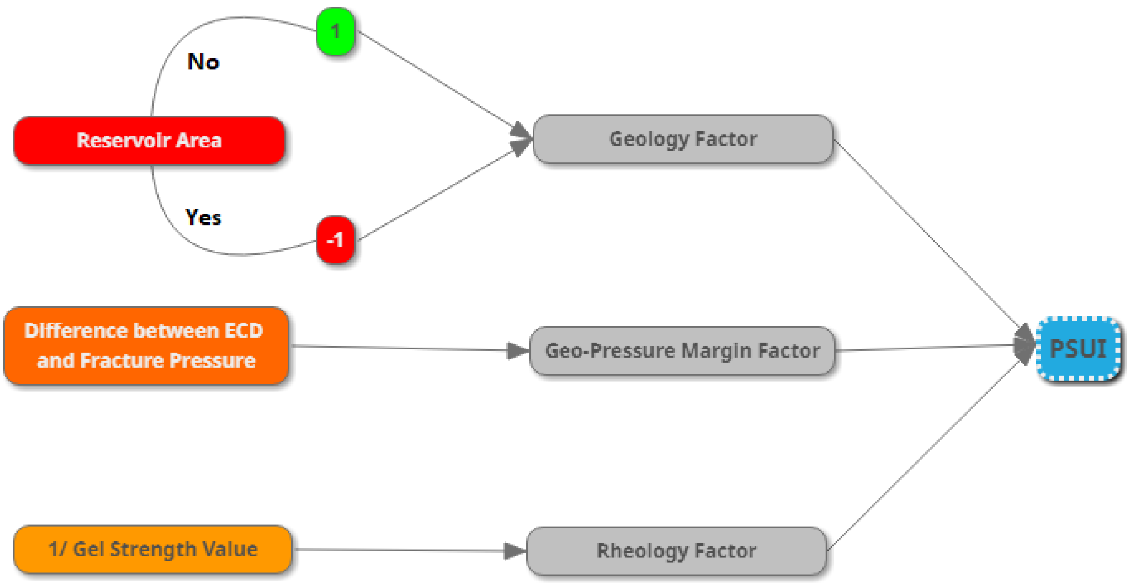


Figure 33. PSUI Factor Decision Tree

The resultant Pump start up index can be used to define the danger level. The table below summarizes the possible cases.

PSIU Value	Meaning	Danger Level
PSIU <-1	Reservoir Area	Medium
-1<PSIU<0	Reservoir Area	Dangerous
PSIU >1	Non- Reservoir Area	Safe
0.5<PSIU<0.1	Non- Reservoir Area	Medium
0<PSIU<0.5	Non- Reservoir Area	Dangerous

Table 4. PSUI Value, Meaning and Danger Level

For a more practical outcome, a heat map was developed based on the PSUI, for every danger level, a colour is assigned as listed in Table 5.

Colour	Danger Level
	Dangerous
	Medium
	Safe

Table 5. Danger Level - Colour Code

The PSUI must be computed for every single depth point along well-bore in question. By doing so it is become easy to indicate the danger zones and the transition zones.

5.2.3. *Hydraulic Modelling and Gel breakdown Pressure*

Once the danger level is obtained based PSUI, the question now how it can be used to optimize the pump start up procedures. In order to answer this question, we have to follow few steps.

[1] As it is well known prior running any BHA the hydraulic must be calculated in order to estimate the friction pressure and the optimum flow rate. Similar steps must be followed here, by knowing all pertinent data required to perform the hydraulic calculation, the optimum pump flow rate can be determined ($Q_{optimum}$).

[2] As second step, the theoretical pressure required to break the gel strength must be computed, it can be done by using equations 1, 2 and 3. The 10 minutes gel strength value has to be used since it is the worst case.

[3] Pressure obtained in step 2 is used by the model built in step 1 to determine the corresponding flow rate. This flow rate is called here theoretical flow rate required to break the gel strength (Q_{gst}).

[4] Finally, the optimal flow rate and theoretical flow rate are compared. This comparison will help to determine the most effective and efficient pump start up procedures.

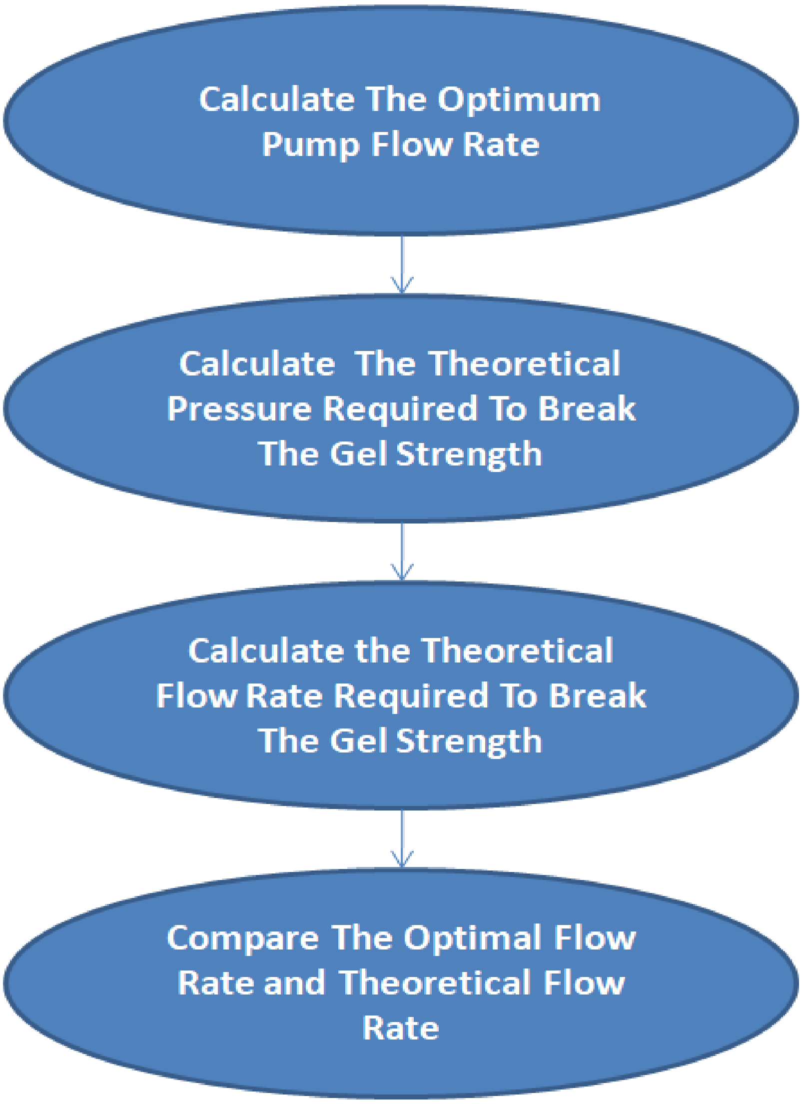


Figure 34. Hydraulic Modelling Workflow

5.2.4. Final Product

The decision of selecting the best pump start up procedures in term of number of stages and acceleration value can be made based on the ratio between optimal flow and theoretical flow rate and PSUI value. Several cases are expected to be encountered; the following matrix explains the expected cases and optimum pump start up procedures for each case.

<table>
<tr><th>Danger Level</th><th>$R = Q_{gst}/Q_{optimum}$</th><th>Recommended Procedures</th></tr>
<tr><td>Dangerous</td><td>R< 25%</td><td>– Increase Pump flow rate to Q_{gst}value
– Wait for few seconds
– Increase Pump flow rate to 50/% of $Q_{optimum}$
– Wait few seconds
– Bring the pump up to$Q_{optimum}$</td></tr>
<tr><td>Dangerous</td><td>25%<R<50%</td><td>– Increase Pump flow rate to 25/% of $Q_{optimum}$ Value
– Wait for few seconds
– Increase Pump flow rate to Q_{gst}value
– Wait for few seconds
– Increase Pump flow rate to 75/% of $Q_{optimum}$
– Wait few seconds
– Bring the pump up to Q_{optimum}</td></tr>
<tr><td>Medium</td><td>R< 25%</td><td>– Increase Pump flow rate to Q_{gst}value
– Wait for few seconds
– Bring the pump up to $Q_{optimum}$</td></tr>
<tr><td>Medium</td><td>25%<R<50%</td><td>– Increase Pump flow rate to Q_{gst}value
– Wait for few second
– Increase Pump flow rate to 75/% of $Q_{optimum}$
– Wait few second
– Bring the pump up to $Q_{optimum}$</td></tr>
<tr><td>Safe</td><td>R< 25%</td><td rowspan="2">– Increase Pump flow rate to Q_{gst}value
– Wait for few seconds
– Bring the pump up to $Q_{optimum}$</td></tr>
<tr><td>Safe</td><td>25%<R< 50%</td></tr>
</table>

Table 6. Optimal Pump Start up Procedures Matrix

5.3. Case Study

For this case study, the alternative pump start-up procedure is applied to Sana 1 which is a well in Anaguid Field. This wellbore was chosen since the data related to the wellbore was accessible in the online OMV Data base and the historical time based data are accessible as well in Kongsberg. Another big reason behind choosing this wellbore is that, this wellbore is one of the latest wells drilled in that field so the previous learning and experience was applied into designing and drilling this wellbore.

So the process started by calculating the pump start-up index in the whole wellbore, then based on the results, the wellbore was plotted as a heat map which shows the danger zones and the safe areas to the start the mud pump.

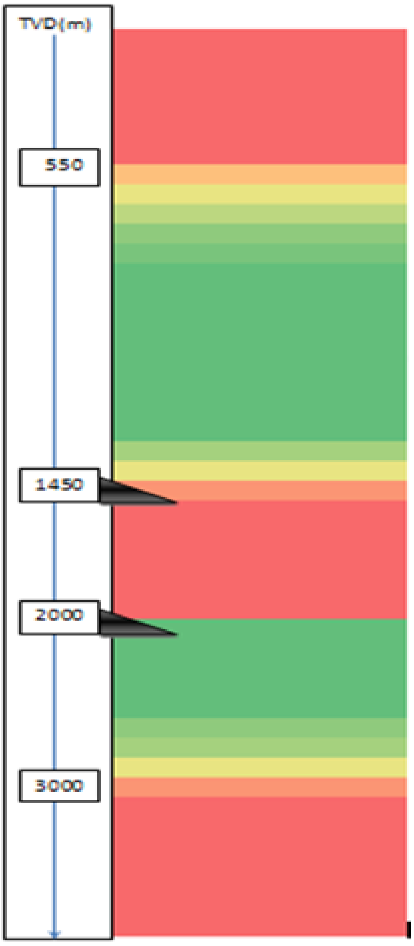


Figure 35: PSUI Heat Map-Sana 1

Then, after applying the mentioned procedure, the hydraulics part was calculated and presented in the table which shows the acceleration and the required flow rate for each stage for different danger zones.

Danger Zone		Safe Zone	
28gpm/s	400gpm	35gpm/s	420gpm
22gpm/s	570gpm	26gpm/s	550gpm
12gpm/s	670gpm	15gpm/s	700gpm

Reservoir Area	
22gpm/s	220gpm
20gpm/s	450gpm
10gpm/s	600gpm

Figure 36. Hydraulics outcome- Sana 1

After gathering all the data, Figure 37 is provided to the driller so that he can start the pump based on this alternative procedure.

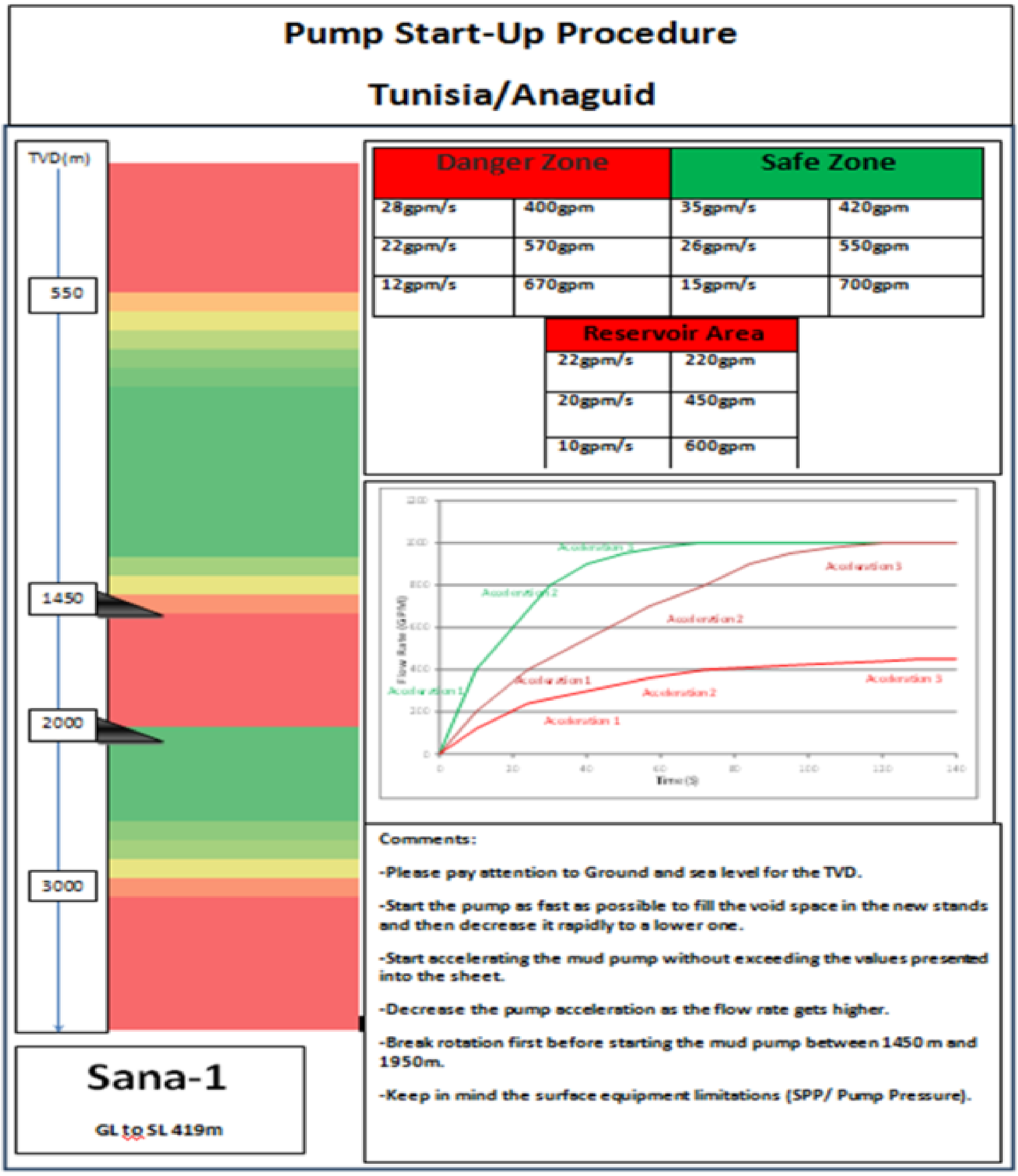


Figure 37. Alternative Pump Start-up Procedure Final Outcome- Sana 1

5.4. *The Advantages and Limitations of the Presented Approach*

5.4.1. *Advantages*

The main advantages of the newly developed approach are:

- It helps to guide the driller through the pump start-up procedures as there is no common rule or guide for the driller to start the pump.
- It considers hydraulics and downhole conditions as ones of the prime factors of pump start up procedures and integrates them with other factors to improve the conventional procedures.
- It is clear and does not require any extra effort to be done by the driller.
- It provides a safe pump start-up procedure so there should be no worries about the reservoir or dangerous zones when bringing the pumps up.

5.4.2. *Limitations*

Since the approach is new, it has several limitations, these limitations are:

- The uncertainty of the data required to compute the hydraulics will influence the results gained from the approach.
- The uncertainty of the geological data like geo-pressure margin can affect the whole procedure.
- The value of gel strength, which might change will affect the result as well.
- The new approach is not direct, so it needs to be calculated separately for each wellbore so an extra work is required by the engineers.

Chapter 6 Conclusions and Recommendations

6.1. Conclusions

The main conclusion of the thesis can be summarized in the following points:

- The pressure spike generated when starting the mud pump is due to the gel strength which forms when the circulation is stopped to make connection.
- The pump start up procedure is a major concern in certain situations where the difference between the equivalent circulating density and the fracture pressure.
- The data which were extracted from OMV data base cannot fulfil the thesis requirements since the highest reading is second and therefore the pressure spike was not observed in most of the times. So a better attention needs to be payed to the data quality in order to study such small and highly detailed phenomena.
- The cross plots have shown a different things than shown in the literature about the drill string rotation effect; braking the rotation first is not always the best way to reduce the pressure spike, the study have shown that the pressure spike could increase sometimes when the hole size is getting smaller plus the concern of the bottom hole assembly sticking issues when the rotation starts before the mud flow, consequently, breaking rotation first is not a good option unless the situation is super critical.
- Pump Start-up procedure is not only related to surface equipments: downhole parameters need to be taken into account.
- The analysis has shown that the pump start-up is mainly dependent on the pump acceleration and not on the type of start-up (one or two or three steps) so a higher acceleration normally provides a higher pressure spike.
- There is no clear guideline for the drillers to start the mud pump, therefore, the developed approach can be used especially in conditions when pressure margin is very small or gel strength is very high.

6.2. Recommendations

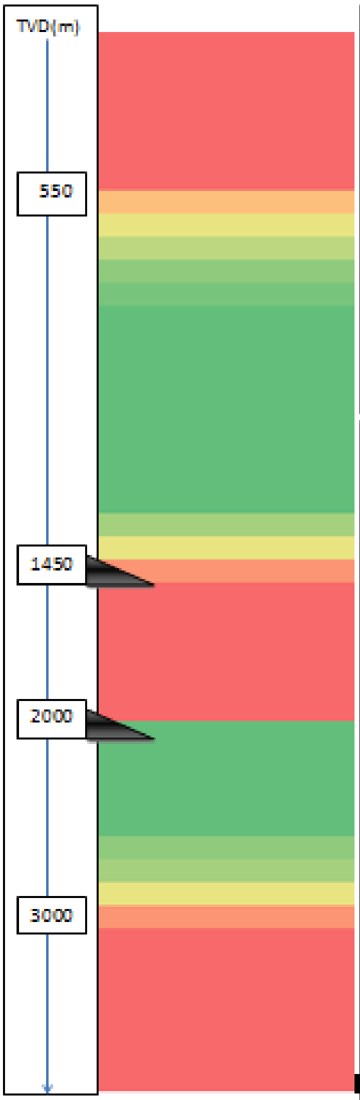
Several recommendations can be drawn that can help to overcome most of the shortcomings of the developed approach. These recommendations are summarized in the following points:

- **The uncertainty associated with hydraulics:** In order to resolve this problem, the hydraulic model needs to be verified (Herschel-Bulckley, Power Law, Bingham,...).
- **The uncertainty associated with geological data:** Measurement while drilling needs to be used to measure the ECD and Mechanical Earth Modelling can be applied to improve the mud window.
- **Time implication on gel strength:** The gel strength must be measured beyond the API standard (at time more than 10 minutes) and measured more frequently.
- **Process Time:** In order to reduce the time required to execute the required steps of the developed approach, it is recommended to integrate this approach with commercial hydraulics software.

Chapter 7 : Appendix

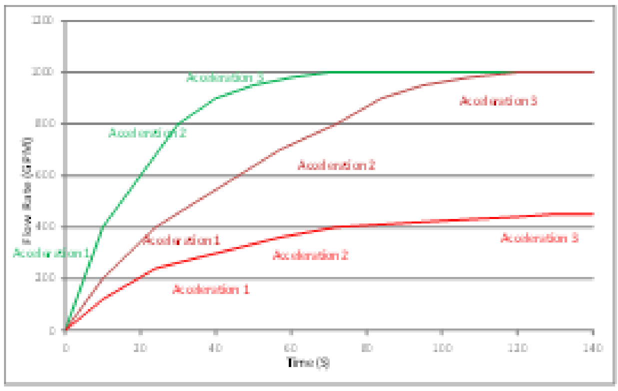
Pump Start-Up Procedure

Tunisia/Anaguid



Danger Zone		Safe Zone	
28gpm/s	400gpm	35gpm/s	420gpm
22gpm/s	570gpm	26gpm/s	550gpm
12gpm/s	670gpm	15gpm/s	700gpm

Reservoir Area	
22gpm/s	220gpm
20gpm/s	450gpm
10gpm/s	600gpm



Sana-1

GL to SL 419m

Comments:

-Please pay attention to Ground and sea level for the TVD.

-Start the pump as fast as possible to fill the void space in the new stands and then decrease it rapidly to a lower one.

-Start accelerating the mud pump without exceeding the values presented into the sheet.

-Decrease the pump acceleration as the flow rate gets higher.

-Break rotation first before starting the mud pump between 1450 m and 1950m.

-Keep in mind the surface equipment limitations (SPP/ Pump Pressure).

Figure 38. Tunsia/Anaguid Final Outcome

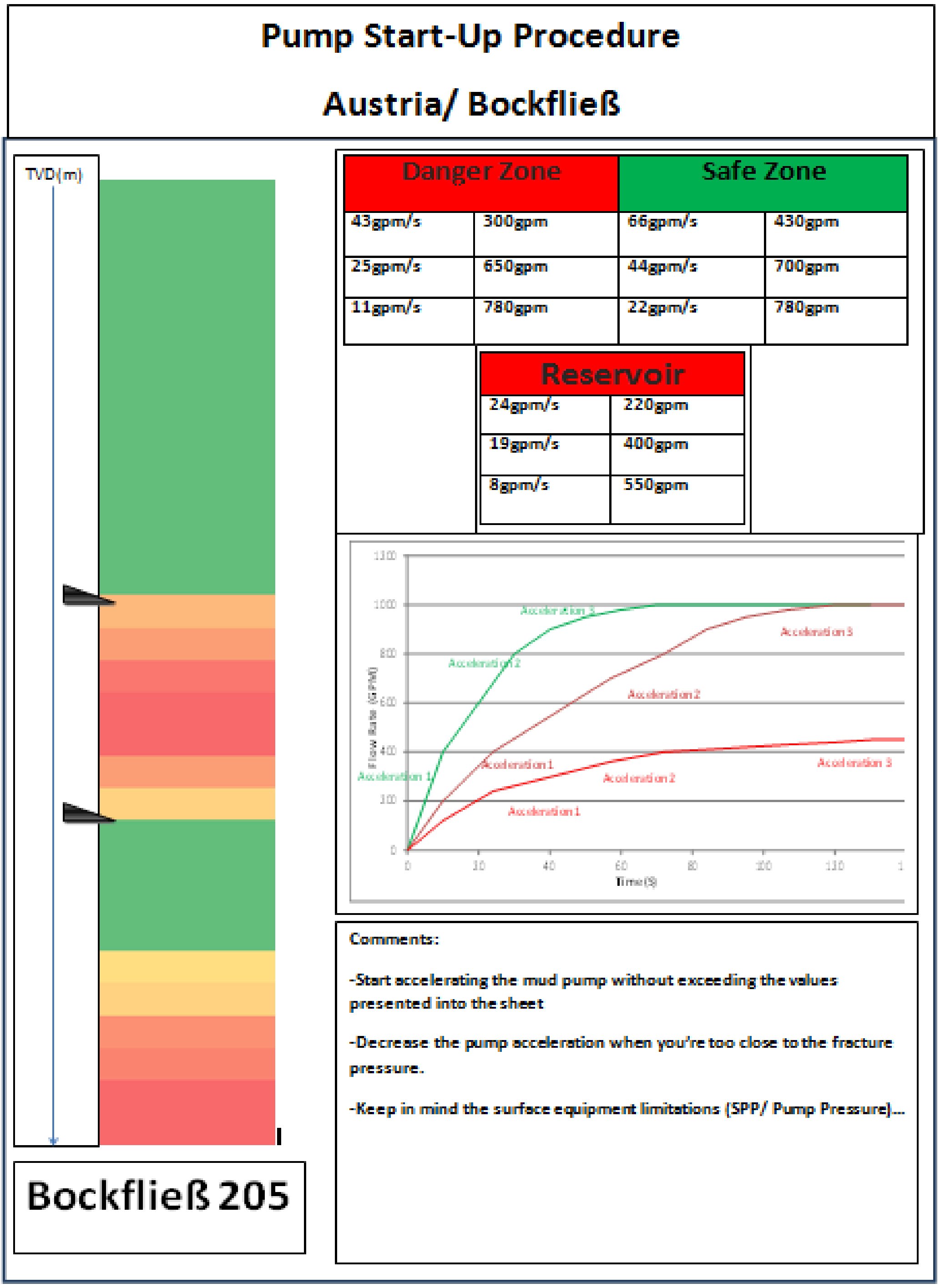
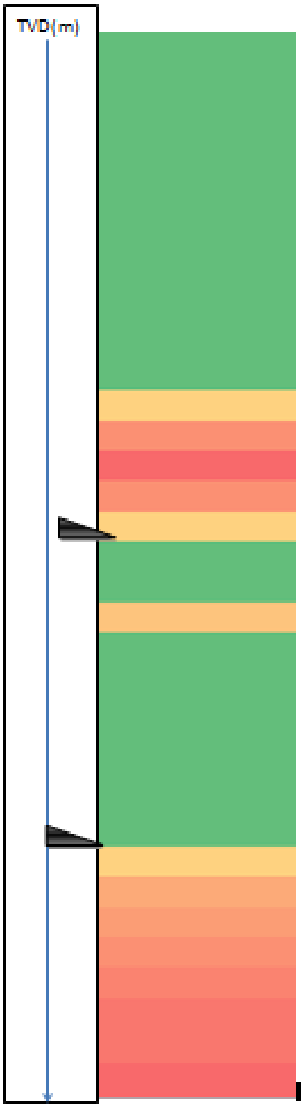


Figure 39. Austria/Bockfliess Final Outcome

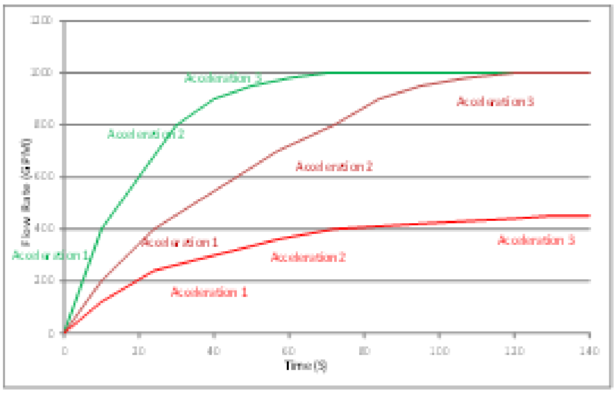
Pump Start-Up Procedure

Austria/ Erdpress



Danger Zone		Safe Zone	
38gpm/s	450gpm	45gpm/s	500gpm
30gpm/s	680gpm	33gpm/s	700gpm
10gpm/s	720gpm	25gpm/s	750gpm

Reservoir Area	
25gpm/s	300gpm
16gpm/s	500gpm
10gpm/s	550gpm



Comments:

-Start the pump as fast as possible to fill the void space in the new stands.

-Start accelerating the mud pump without exceeding the values presented into the sheet

-Decrease the pump acceleration when you're too close to the fracture pressure.

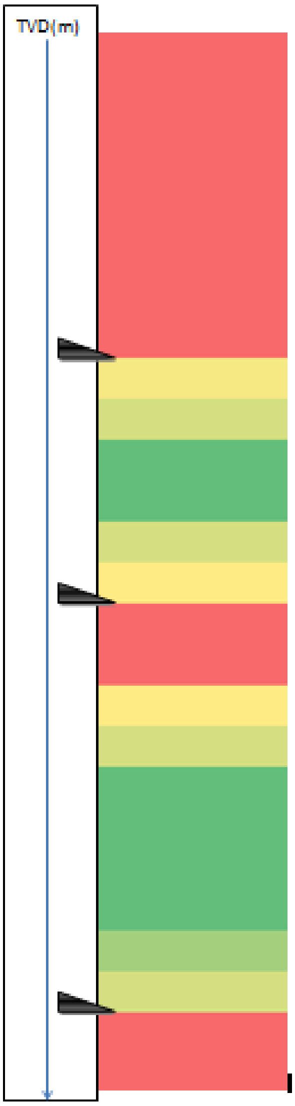
-Keep in mind the surface equipment limitations (SPP/ Pump Pressure)...

Erdpress 24

Figure 40. Erdpress-Austria Final Outcome

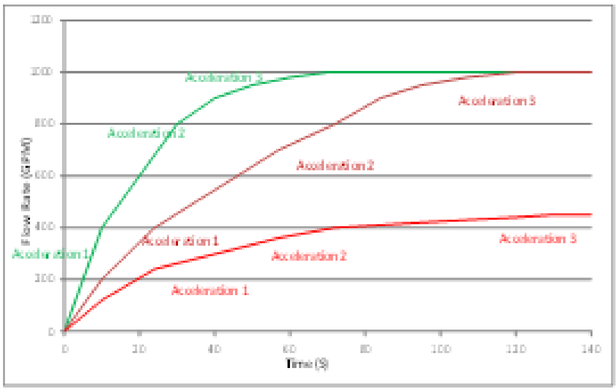
Pump Start-Up Procedure

Yemen/ Habban



Danger Zone		Safe Zone	
40gpm/s	500 gpm	45gpm/s	500 gpm
25gpm/s	650 gpm	32gpm/s	650 gpm
8gpm/s	730 gpm	15gpm/s	730 gpm

Reservoir Area	
20gpm/s	260 gpm
10gpm/s	300 gpm
5gpm/s	320 gpm



Habban 41-Sat-N01

Comments:

-Start the pump as fast as possible to fill the void space in the new stands.

-Start accelerating the mud pump without exceeding the values presented into the sheet

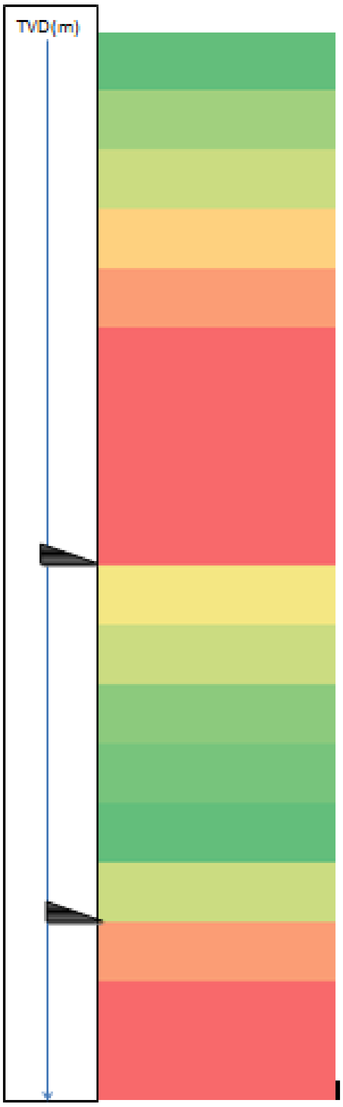
-Decrease the pump acceleration when you're too close to the fracture pressure.

-Keep in mind the surface equipment limitations (SPP/ Pump Pressure)...

Figure 41. Habban/Yemen Final Outcome

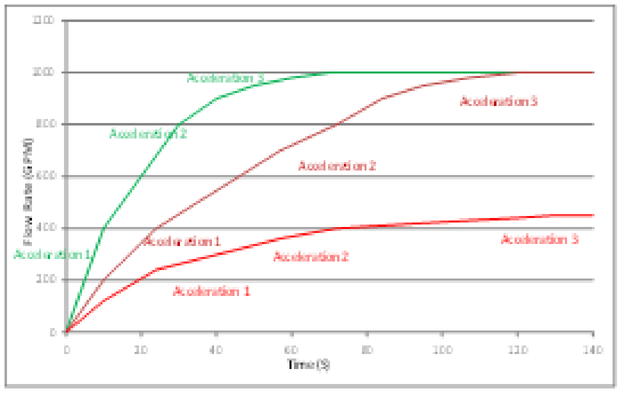
Pump Start-Up Procedure

Pakistan/ Latif-Miano



Danger Zone		Safe Zone	
35gpm/s	420gpm	48gpm/s	480gpm
25gpm/s	700gpm	35gpm/s	740gpm
15gpm/s	780gpm	15gpm/s	800gpm

Reservoir Area	
22gpm/s	220gpm
16gpm/s	420gpm
12gpm/s	500gpm



Comments:

-Start the pump as fast as possible to fill the void space in the new stands.

-Start accelerating the mud pump without exceeding the values presented into the sheet

-Decrease the pump acceleration when you're too close to the fracture pressure.

-Keep in mind the surface equipment limitations (SPP/ Pump Pressure)...

Latif-14

Figure 42. Latif-Miano Pakistan Final Outcome

Bibliography

A.Moore and A.Gillikin (2010). Eliminating Pressure Spikes after Connections and Trips to Improve ECD Control and Minimize Downhole Losses. AADE.

Glossary.oilfield.slb.com. (2017). make a connection - Schlumberger Oilfield Glossary. [online] Available at: http://www.glossary.oilfield.slb.com/Terms/m/make_a_connection.aspx [Accessed 10 Aug. 2017].

Geologie.vsb.cz. (2017). Practice. [online] Available at: http://geologie.vsb.cz/DRILLING/drilling/practice.html [Accessed 10 Aug. 2017].

Cayeux, E., Daireaux, B. and Dvergsnes, E. (2011). Automation of Mud-Pump Management: Application to Drilling Operations in the North Sea. SPE Drilling & Completion, 26(01), pp.41-51.

Drilling Fluid Reference Manual. (2006). Baker Hughes, pp.7-14.

Glossary.oilfield.slb.com. (2017). gel strength - Schlumberger Oilfield Glossary. [online] Available at: http://www.glossary.oilfield.slb.com/Terms/g/gel_strength.aspx [Accessed 4 Aug. 2017].

Hossain, M. and Al-Majed, A. (n.d.). Fundamentals of sustainable drilling engineering.

IADC Drilling Manual. (2014). IADC.

Mixing of Thixotropic Fluids. (1982). .

Riddoch, J., Wuest, C. and Shaun, J. (2016). Managing Constant Bottom Hole Pressure with Continuous Flow Systems. Society of Petroleum Engineers. [online] Available at: https://www.onepetro.org/conference-paper/OTC-26752-MS.

Thonhauser, G. and Lüftenegger, M. (2017). Drilling Hydraulics Monitoring and Problem Detection.

using downhole annular pressure measurements to improve drilling performance. (1998). [online] Available at: https://www.slb.com/resources/publications/industry_articles/oilfield_review/1998/or1998win04_downhole_annular_pressure.aspx [Accessed 4 Aug. 2017].

Zoellner, P., Thonhauser, G., Lueftenegger, M. and Spoerker, H. (2011). Automated Real-time Drilling Hydraulics Monitoring. SPE/IADC Drilling Conference and Exhibition.

Acronyms

ESD	Equivalent Static Density
ECD	Equivalent Circulating Density
TVD	True Vertical Depth
SPP	Stand Pipe Pressure
GRF	Geology, Rheology and Geo-Pressure Margin Factor

Symbols

μ	Viscosity	[Cp]
γ	Shear Rate	[m]
τ	Shear Stress	[m]
ΔP	Pressure Losses	[Psi]
P_gsds	Pressure Required To Break The Gel Strength Inside The Drill String	[Psi]
P_gsa	Pressure Required To Break The Gel Strength In The Annulus	[Psi]
P_gst	Total Pressure Required To Break The Gel	[Psi]
L	Measured Depth	[Psi]
ID	Internal Diameter	[ft]
Y	Gel Strength	[Inch]
Dh	Hole Diameter	[lb/100ft²]]
OD	Drill String Outside Diameter	[Inch]
ε_G	Geological Factor	[Inch]
ε_R	Rheological Factor	[-]
ε_{GP}	Geo-Pressure Margin Factor	[lb/100ft²]]
$P_{(MD)}$	Calculated Pressure at Measured Depth	[ppg]
P_0	Initial Pressure at The previous Casing Shoe	[Psi]
MD_0	Measured Depth of The Previous Casing Shoe	[Psi]
MD	Measured Depth Of The Calculated Pressure	[ft]
ρ	Mud Density	[ft]
g	Gravitational Acceleration	[ppg]
θ	Wellbore Deviation Angle at Measured Depth	[m/s²]
$\frac{dK}{ds}$	Annular Frictional Pressure Loss Gradient	[°]
$\Delta p_{OH_{DC}}$	Pressure Losses in Open Hole-Drill Collar	[Psi/ft]
$\Delta p_{OH_{HWDP}}$	Pressure Losses in Open Hole-Heavy Weight Drill Pipe	[Psi]
$\Delta p_{OH_{DP}}$	Pressure Losses in Open Hole- Drill Pipe	[Psi]
		[Psi]

List of Figures

List of Tables