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Dual gradient drilling simulations

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Preface

This report is the result of my master thesis carried out during my 4th semester at the Department of Petroleum Engineering and Applied Geophysics at the Norwegian University of Science and Technology in Trondheim. The topic was suggested by Professor John-Morten Godhavn.

The main objective of this project was to explore the properties of the Low Riser Return System by building a model for simulating the effect of change in pump rates of bottom hole pressure. The model was then used to simulate some preferred scenarios.

I would like to address my acknowledgments to Professor John-Morten Godhavn for his support during the work on this thesis.

Trondheim 13th of May, 2011

Kjartan Örn Sigurjónsson

Summary

The system studied in this thesis is called the Low Rise Return system and uses a partly filled marine drilling riser with a variable mud level which is used control the bottom holes pressure.

Initially main components of the Low Riser Return System are listed and explained. Then the performance characteristics of the system are explored. Level movements in riser during level increase and decrease at constant mud pump rates are explained along with the effect of mud pump rate on maximum level increase and decrease rates.

A simple simulator is then presented that calculates the bottom hole pressure when pump rates are changed. The simulator includes a function that enables it to simulate lost circulation scenarios.

The simulator is used to simulate some preferred scenarios. First a pressure increase and decrease at constant mud pump rates are simulated. Then it is shown how a faster pressure decrease can be achieved by temporarily lowering the mud pump rate. Next simulations are shown where changes in mud level are used to compensate for changes in equivalent circulation density as mud pump rates are changed. Finally simulations are run that demonstrate how mud level can be reduced to cure lost circulation scenarios. Results and lessons learned are then discussed.

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1 Introduction

Earths remaining oil reserves are becoming ever harder to produce. This forces the industry to look for new way the technologies that enable drilling where it was not possible before and can improve recovery from aging reservoirs.

The system studied in this thesis is based on the LRRS system which is a MPD system patented by Ocean Riser Systems. The system is to be applied on floating drilling rigs and uses a partly filled marine drilling riser with a variable mud level which is used control the bottom holes pressure.

MPD systems are systems that allow a more accurate control the annular pressure profile and their goal is predominantly to keep bottom hole pressure (BHP) as close to a pre specified value as possible while performing different operations. This enables those systems to drill through narrow pressure windows not drillable before.

In this thesis main components of the Low Riser Return System are listed and explained. The description is limited to the components that effect the simulation model presented later.

Then the performance characteristics of the system are then explored. Level movements in riser during level increase and decrease at constant mud pump rates are explained along with the effect of mud pump rate on maximum level increase and decrease rates.

A simple simulator that calculates the BHP when pump rates are changed is then presented. The simulator includes a function that enables it to simulate lost circulation when bottom hole pressure exceeds the formation fracture pressure.

The simulator is used to simulate some preferred scenarios. First a couple of simulations related to commissioning test used for choked MPD systems are run. First a pressure increase and decrease at constant mud pump rates are simulated. Then it is shown how a faster pressure decrease can be achieved by temporarily lowering the mud pump rate. Lastly demonstrated how changes in mud level are used to compensate for changes in equivalent circulation density as mud pump rates are changed.

Finally simulations are run that demonstrate pressure is reduced to cure lost circulation scenarios. In the first simulations pressure is decreased by lowering the level in the riser at a constant MP rate. Then a combination of lowering the level and temporarily decreasing the MP to get a faster pressure reduction resulting in a smaller loss of drilling fluid is shown for comparison.

Results and lessons learned are finally listed and discussed.

2 System description

The system studied in this thesis is based on the LRRS system which is a MPD system patented by Ocean Riser Systems (Fossli & Sangesland, 2004). The system uses a partly filled marine drilling riser with a variable mud level which is used control the BHP. In the following sections keys system parameters will be explained. The description is kept simple and focuses mainly on parts directly influencing the model used for simulation. Parameters related to the well used for simulation are also shown.

2.1 Pressure control

Conventional systems have two means of controlling pressure that is with hydrostatic pressure control and frictional pressure control. Hydrostatic pressure control is the prime way and is done by changing the mud weight in the well. This involves costly addition of minerals to the mud but more importantly this is a lengthy process since the full effect of the new mud weight change is not seen until all the old mud has been circulated out of the well and replaced with the new one. Frictional pressure control on the other hand involves changing the circulation rate and consequently changing the annular friction pressure. The change in circulation rate causes a rapid change in BHP but its disadvantage is that the control is lost when drilling fluid circulation is stopped.

The LRRS can use both of those methods to control the well pressure but its primary way of controlling the well pressure is by adjusting the mud level in the riser. In a conventional system the mud level is fixed at the rotary kelly bushing (RKB). A schematic picture of the LRRS is shown in Figure 2.1

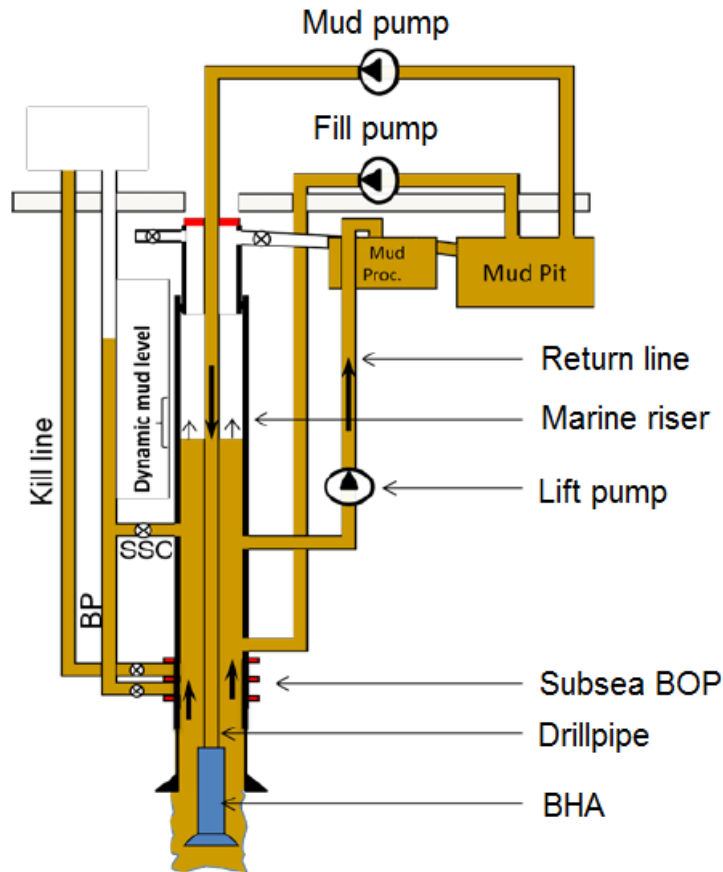


Figure 2.1 Schematic picture of the LRRS (Handal, 2011)

The LRRS uses a marine riser partly filled with mud and above the mud level it is filled with gas at approximately atmospheric pressure. No additional sealing device is used so under normal operating condition mud flow freely from the well into the riser. The pressure is increased by raising the mud level in the riser and decreased by lowering it.

When the blow out preventer (BOP) is closed drilling fluid is circulated from beneath the BOP to the riser through a bypass line. A choke is placed on the top of the bypass line and can be used to control the backpressure. The performance of the system with a closed BOP is not discussed in this thesis.

2.2 Pumps

The system uses three pumps to control the mud level in the riser. The conventional mud pump (MP) that pumps the mud down the drill string and back up the annulus to the riser. The mud is brought back to the surface using a subsea lift pump (LP) which pumps the mud along with the cuttings back to the rig through a separate return line. The third pump is the fill pump (FP), sometimes referred to as booster pump, which allows for the riser to be filled up more quickly when an increase in BHP is needed.

The simulations done do not include the effect of output pressure on pump performance. It further assumed that the pumps are able to provide all flow rates up to their stated maximum at the pressure needed.

Mud Pump (MP)

The MP is located on the rig. It pumps the mud down the drill string, through the bit and then the mud and cuttings up the annulus to the riser. This pump has to provide the highest pressure of the three pumps. A piston pump is therefore used for this purpose. The maximum flow rate is assumed to be 5000 l/min and ramp up and down times equal to be to 30 seconds.

Lift pump (LP)

The LP is located subsea. It pumps the mud and cuttings from the riser back to the rig through a separate return line. A centrifugal pump is used for this purpose. The maximum flow rate is assumed to be 4000 l/min and ramp up and down times to be equal to 30 seconds.

Fill pump (FP)

The FP is located on the rig. It is used to pump clean mud into the riser when an increase in mud level is needed. An increase in mud level can be accomplished without it by running the LP at a lower rate than the MP but the FP allows for a quicker level adjustment. A centrifugal pump is used for this purpose. The maximum flow rate is assumed to be 5000 l/min and ramp up and down times equal to 30 seconds. The flow rates and ramping times for the three pumps are summarized in Table 2.1.

Table 2.1 Shows maximum flow rates and the minimum time it takes to bring the pumps from no flow to their maximum rate (ramp up) and from maximum flow to no flow (ramp down)

Pump Name	Maximum flow rate [l/min]	Minimum ramp up/down time [s]
Mud pump	4000	30
Lift pump (Subsea)	5000	30
Fill pump	5000	30

2.3 Riser, drill sting and bottom hole assembly

The internal diameter (ID) of the riser and the outside diameter (OD) of the drill string determine the annular capacity of the riser. The annular capacity again determines how much the mud level changes for a given mud volume increase and thus the time it takes to change the mud level.

An additional pressure drop is experienced as the fluid passes the bottom hole assembly (BHA) compared to the drill string. This is caused by an increase in flow velocity around the BHA since it has a larger diameter than the drill string. The BHA is assumed to have an OD of 6,5 in and to be 75 m long. The dimensions related to the riser, drill string (DS) and BHS are summarized in Table 2.2.

Table 2.2 Shows OD, ID and the length of the riser DS and BHA

Name	OD [in]	ID [in]	Length [m]
Riser	21	19,5	360 (approximately)
Drill string	5	-	-
Bottom hole assembly	6,5	-	75

2.4 Well parameters

In the following sections the well parameters are put forth. The well used for simulation is based on a Statoil well located in the Troll field. The well is deviated with relatively long horizontal section. All depths are measured from the RKB. The air gap from the RKB to sea surface is 24 m and the distance from sea surface to sea floor is 337,6 m. The well trajectory is shown in Figure 2.2.

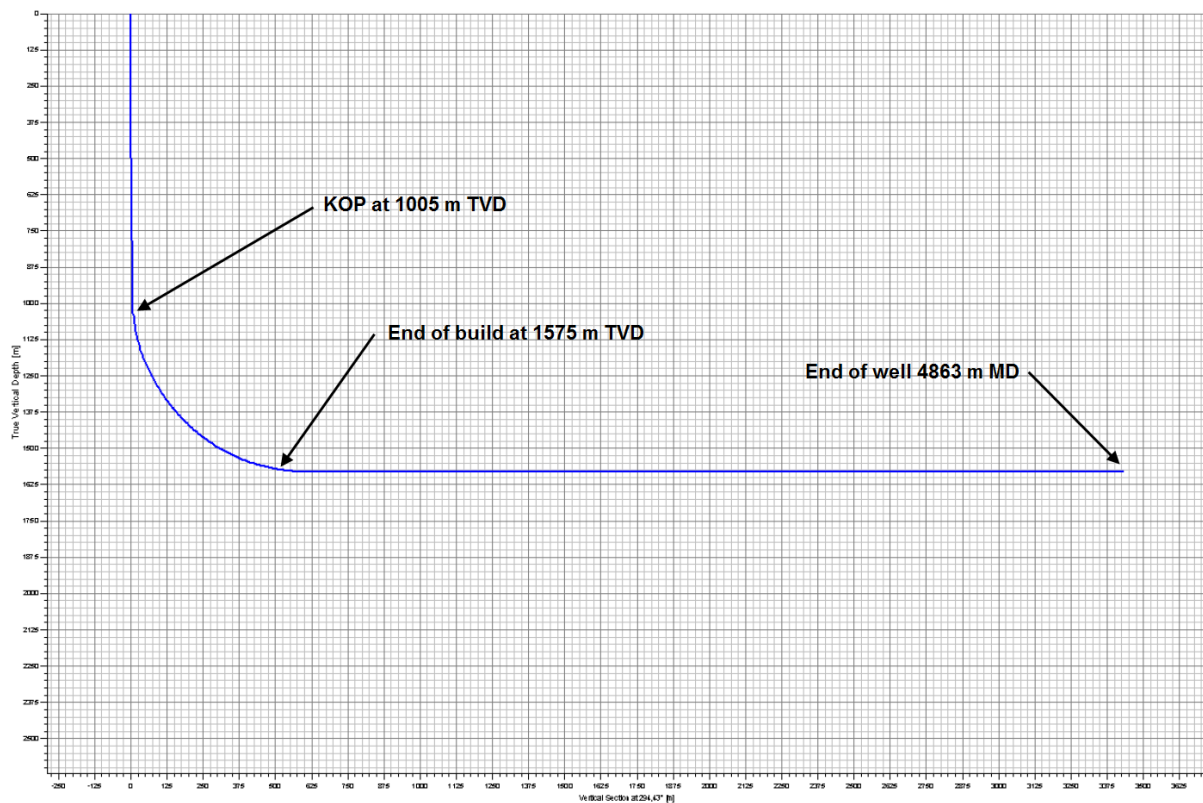


Figure 2.2 Shows the 2D trajectory of the well used for simulation (Statoil, 2011)

Casing length and sizes

Casing length and sizes are shown in Table 2.3. The most important diameters are the ones that define the size of the annulus while the annulus reservoir section is being drilled since they determine the flow velocity and thereby affect the pressure drop in their respective sections. Those diameters are written in bold text in the table for clarification.

Table 2.3 Shows casing and hole parameters of the well used for simulation

Hole Size [inch]	Casing OD [inch]	Weight [lb/ft]	TVD [m]	MD [m]	Interval [m MD]
36	30	-	426	426	362-426
24	18 5/8	87,5	949	949	362-949
17 1/2	13 3/8	72	1367	1449	362-1449
12 1/4	10 3/4	60,7	1526	1719	1719-1449
12 1/4	9 5/8	53,5	1582	1988	1988-1719
8 1/2	7	-	1582	4864	4864-1988

3 Performance characteristics of the LRRS

In the section below it is explained what limits the magnitude of the pressure compensation with level changes. It is shown how the level in the riser changes during increase and decrease but knowing how the level moves during increases and decreases plays a vital role if changes in ECD during MP rate changes are to be accurately compensated for. Fastest possible level increase and decrease is explained and finally the effect of MP rate on BHP is shown.

3.1 The magnitude of pressure compensation

Pressure is managed by changing the mud level in the riser. If pressure is to be increased the level is raised and if the pressure is to be decreased the level is decreased. The magnitude of the pressure change depends on two parameters namely the mud density ρ_{mud} and the level change h as shown in Equation 3.1.

$$P = \rho_{mud} \cdot g \cdot h \quad \text{Equation 3.1}$$

Where g is standard gravity. Given a certain mud weight the maximum pressure increase and decrease that the system can provide depends on how much the level can be increased or decreased. Here this maximum level change is called available riser length (ARL) and is explained in Figure 3.1.

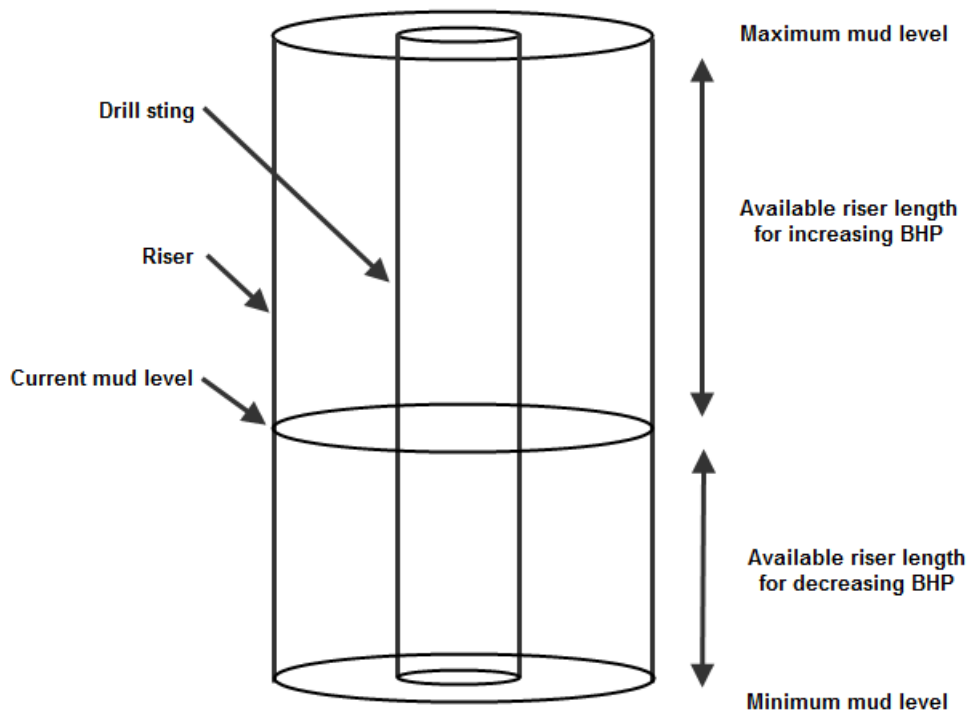


Figure 3.1 Shows the ARL for level increase and decrease.

During pressure increase the ARL is the distance from the current mud level to the maximum possible mud level accommodated by the riser. During a pressure decrease the ARL is the distance from the current mud level to the minimum possible mud level accommodated by the riser. Figure 3.2 shows the absolute value of the possible pressure change as a function of ARL.

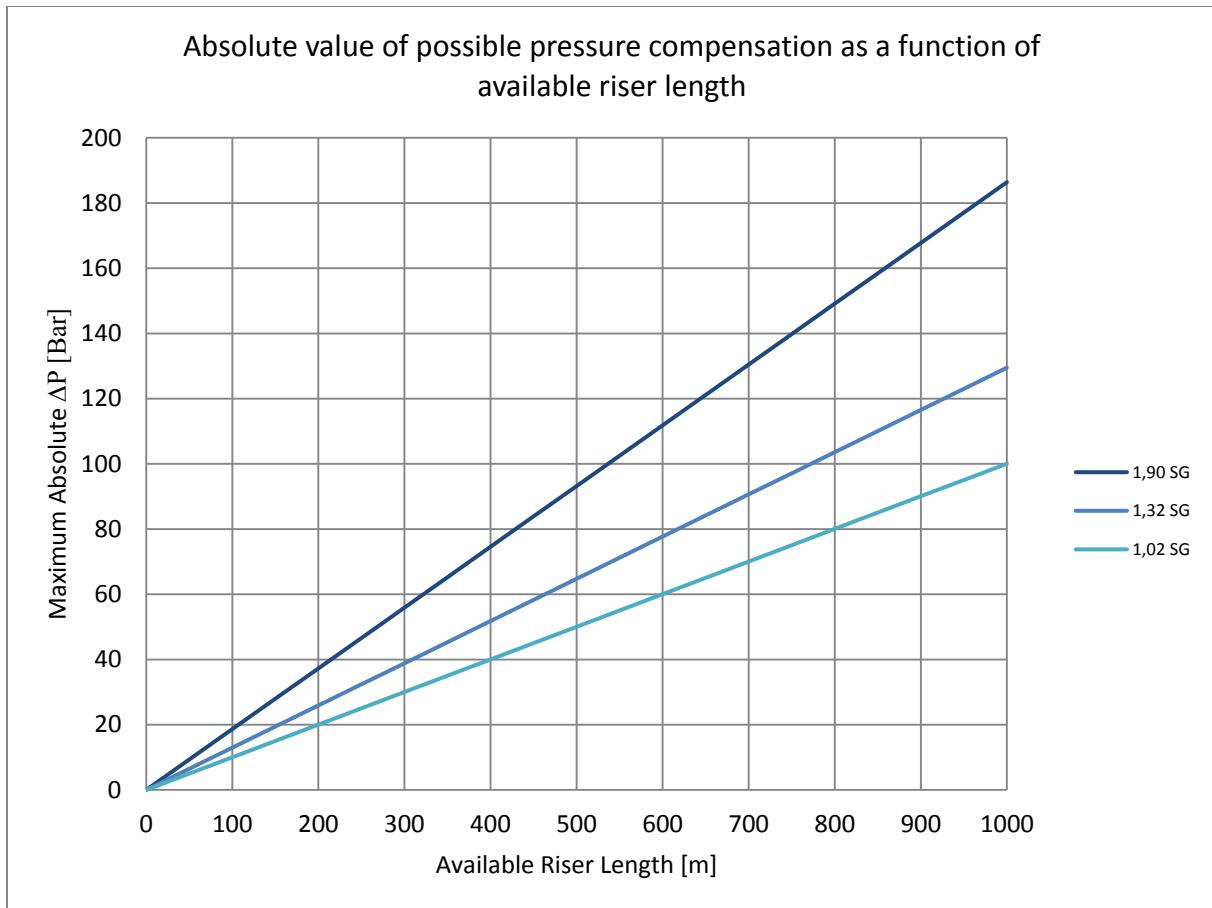


Figure 3.2 Shows the absolute value of the possible pressure compensation as a function of ARL for three different mud weights

Because the level in the riser is generally lower than the one in the drill string there exists a pressure imbalance. This imbalance will cause spontaneous u-tubing if the total pressure drop in the system becomes less than the pressure difference caused by the difference in mud level (Handal, 2011). Under normal operation u-tubing should be avoided because pressure behavior in the system becomes more difficult to predict. The additional annular flow rate caused by the u-tubing creates additional annular friction loss and the air that enters the drill string as the mud level drops and has to be circulated through the system. The minimum allowed mud level in the riser can therefore be restricted when the total pressure drop in the system is less than the maximum possible difference in level between the riser and drill string. This condition is not likely to pose problems during normal operation where the total pressure drop in the system is relatively high. It is however a concern and should be accounted for when the MP is shut down completely for example during connections (Hejna, 2010).

3.2 Mud level change in the riser during pressure changes at constant mud pump rate

The mud level in the riser is changed by controlling the individual pumps rates in such a way that the net flow into the riser becomes positive for a level increase and negative for a level decrease. No circulation loss is assumed for demonstrating the mud level movement so the net flow into the riser can be calculated using Equation 3.2.

$$\dot{q}_{riser} = \dot{q}_{mud} + \dot{q}_{fill} - \dot{q}_{lift} \quad \text{Equation 3.2}$$

When the system has reached its maximum level changing rate the level change in the riser becomes linear. It is however useful to know how the level changes while the pump rates are being ramped to this maximum rate. This gives information about how the MP rate should be changed so ECD changes can be compensated for by a movement of the mud level.

3.2.1 Mud level movement during a level increase

Initially the MP and lift pump are running at equal rates so the net flow into the riser is zero. When the BHP is to be increased as fast as possible while maintaining a constant MP rate the pumps should be ramped in the following manner

- The LP is ramped to zero flow
- The FP is ramped to maximum flow

The maximum level increasing rate is reached when ramping of both the pumps is complete. Before the pressure increase operation is complete the pumps have to be ramped down to their initial flow rates again so the net flow into the riser becomes zero. Figure 3.3 shows how the level in the riser changes during the ramping (up and down) of the LP and FP for three different MP rates.

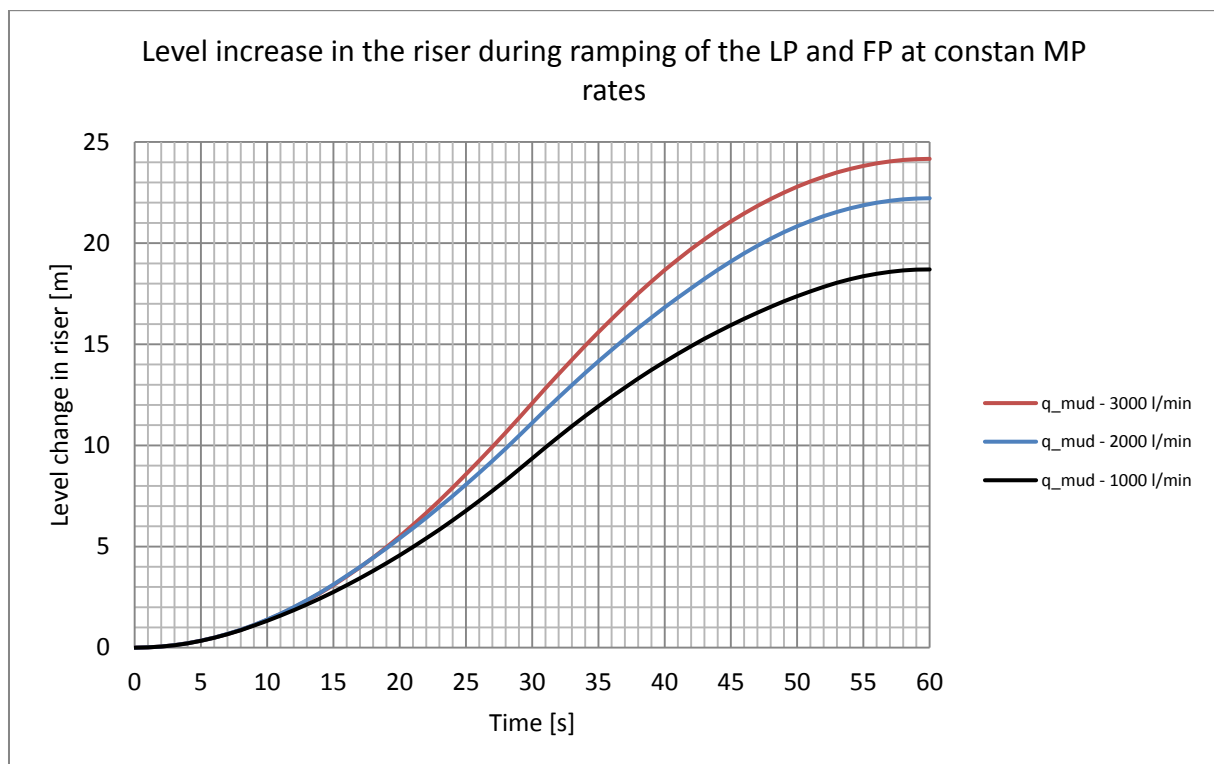


Figure 3.3 Shows how the level in the riser increases while the FP is ramped up and the lift pump is ramped down (0-30 sec) and then back to their initial rates (30-60 sec). This is shown for three different mud pump rates (q_{mud}).

The time it takes to reach maximum level increase rate and slow down again is determined by the time it takes to ramp the FP from no flow to its maximum rate. If a larger pressure

increase is needed than the one provided in the 60 second period an interval of constant rate comes in between the ramp up and down curves as shown in Figure 3.4.

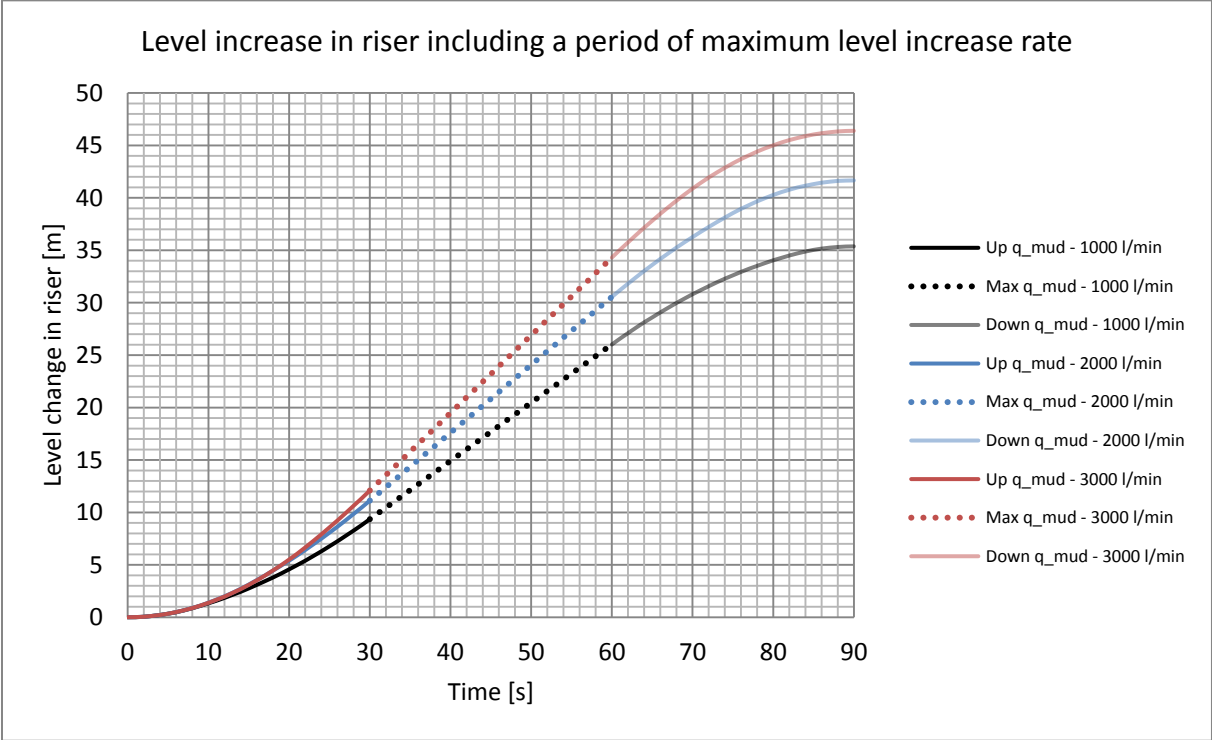


Figure 3.4 Shows the level increase in the riser for increases large enough so the system reaches maximum level increase rate. The level change at these rates are represented by the dotted lines (Max q) that separate the ramp up (Up) and down (Down) curves.

The effect of the constant MP rate can be seen on both Figure 3.3 and Figure 3.4. The higher the MP rate the higher the maximum level increase rate and the level increase during ramping of the LP and FP.

If a smaller pressure increase is needed than the one gotten after 60 seconds the pumps are ramped back to their initial rates before the maximum level increase rate is reached. An example of this is shown in Figure 11.2 in Appendix 11.2.

3.2.2 Mud level movement during a level decrease

Initially the MP and lift pump are running at equal rates so the net flow into the riser is zero. When the BHP is to be decreased as fast as possible while maintaining a constant MP rate the pumps should be ramped in the following manner

- The LP is ramped to maximum flow

The FP can only be used for a level increase so it is not running during a level decrease. The maximum level decrease rate is reached when the LP has reached its maximum flow rate. Before the pressure decrease operation is complete the LP has to be ramped down to its initial flow rate again so the net flow into the riser becomes zero. Figure 3.5 shows how the level in the riser changes during the ramping (up and down) of the pumps for three different main pump rates.

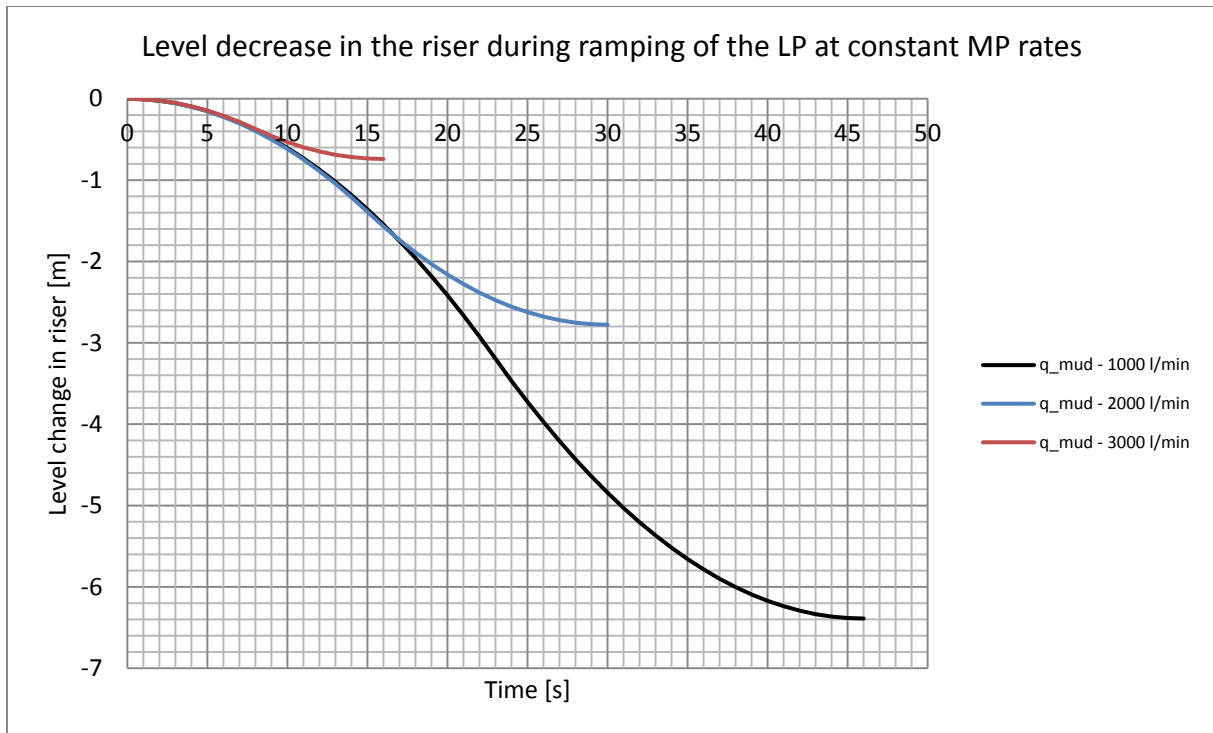


Figure 3.5 Shows how the level in the riser decreases while the lift pump is ramped up(0-23 sec) and back down again (23-46 sec). This is shown for three different MP rates(q_{mud})

The time it takes to reach the maximum level decrease rate depends on the time it takes to ramp the lift pump to its maximum flow rate. How long it takes to ramp the lift pump is determined by the initial flow rate of the MP since they are equal in the beginning and at the end of the operation. If a larger pressure increase is needed than the one provided by the ramp up and down period an interval of constant rate comes in between the ramp up and down as shown in Figure 3.6.

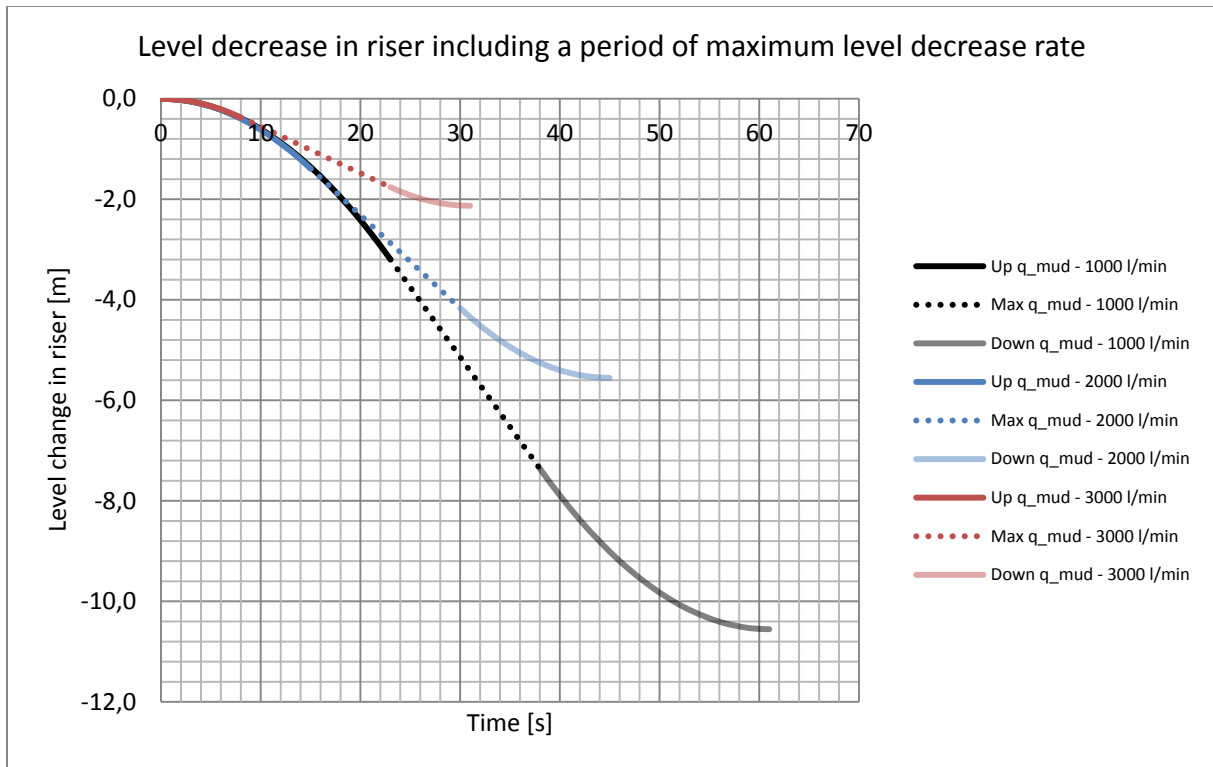


Figure 3.6 Shows the level decrease in the riser for decreases large enough so the system reaches maximum level decrease rate. The level change at these rates are represented by the dotted lines (Max q) that separate the ramp up (Up) and down (Down) curves.

The effect of the constant MP rate on the level decrease can be seen on both Figure 3.5 and Figure 3.6. The higher the MP rate the lower the maximum level decrease rate and the level decrease during ramping of the LP.

If a smaller pressure increase is needed than the one gotten after 46 seconds the pumps are ramped back to their initial rates before the maximum level increase rate is reached. An example of this is shown in Figure 11.4 in Appendix 11.2.

3.3 Maximum level change in a given time at a constant mud pump rate

The maximum level increase or decrease that can be accomplished in a given time is determined by the level change curves. It is emphasized that those curves do not represent how the pressure changes with time. They show the maximum pressure that can be accomplished in any given time intervals given that the pumps are ramped back to their initial rate before the pressure change has been completed. The maximum level increase curve is shown in Figure 3.7 and the maximum level decrease curve is shown in Figure 3.8.

3.3.1 Maximum level increase

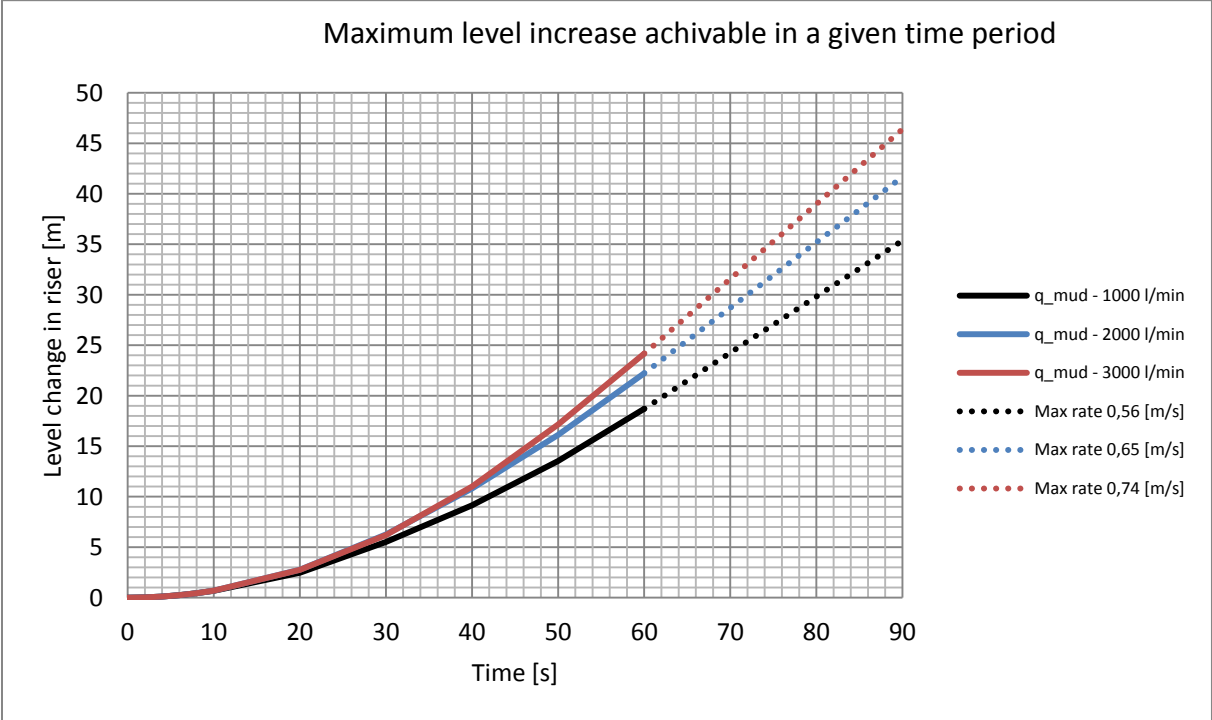


Figure 3.7 Shows the curves that define the maximum level increase that can be achieved in a given time period. This is shown for three different MP rates (q_{mud}).

The solid lines represent pressure changes that are complete in less time than it takes to reach maximum pressure increase rate. The dotted lines represent pressure changes where the maximum rate has been reached.

3.3.2 Maximum level decrease

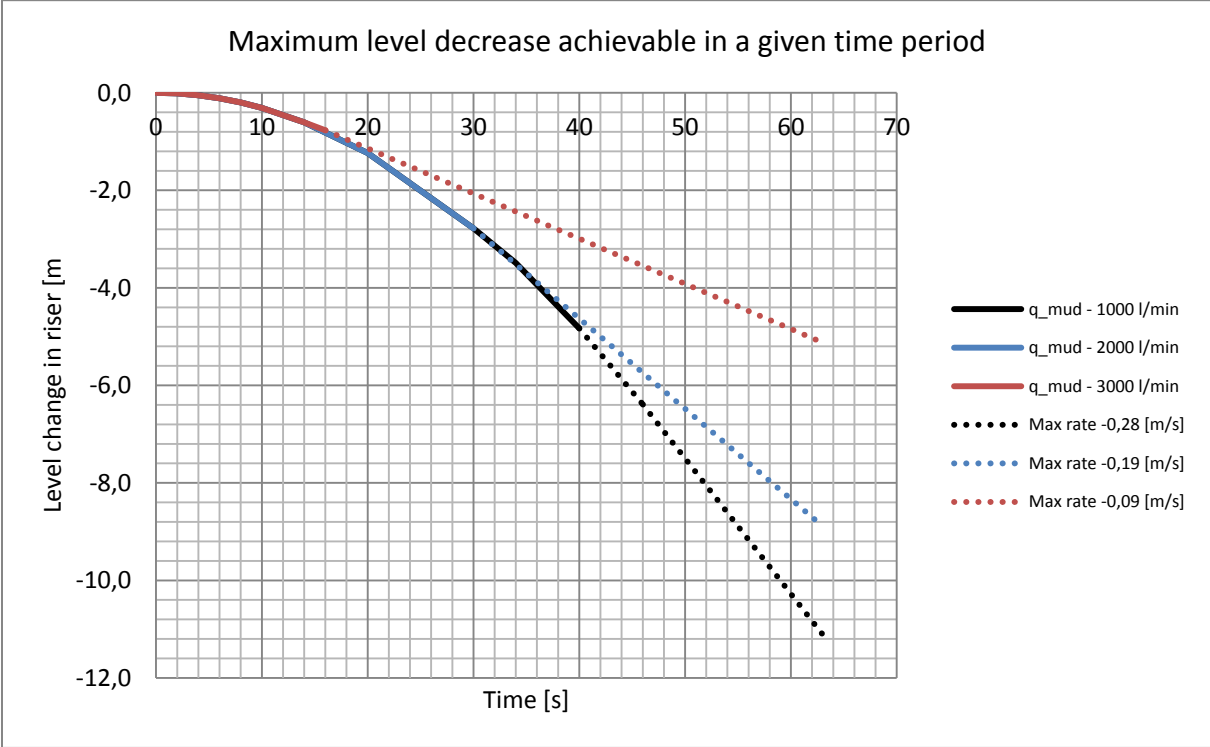


Figure 3.8 Shows the curves that define the maximum level decrease that can be achieved in a given time period. This is shown for three different MP rates (q_mud).

The solid lines represent pressure changes that are complete in less time than it takes to reach maximum pressure increase rate. The difference in time it takes to the maximum rate is caused by the initial MP rate as explained in section 3.2.2. The dotted lines represent pressure changes where the maximum rate has been reached.

3.4 Effect of mud pump rate changes on BHP

The BHP is the sum of the hydrostatic pressure caused by the TVD from the bottom of the hole to the mud level in the riser and the annular pressure drop caused by the mud flowing in the wells annulus. The size of the annular pressure drop depends amongst other things on the flow rate provided by the MP as shown by the equations in section 4.3. Figure 3.9 shows the total annular pressure drop as a function pump rate when the bit is located at 2263 m MD. The total annular pressure drop is the sum of the annular friction drop and the singularity losses related to sudden expansions. The figure is created using the simulator descried in section 4 and a mud with properties shown in Appendix 11.1.

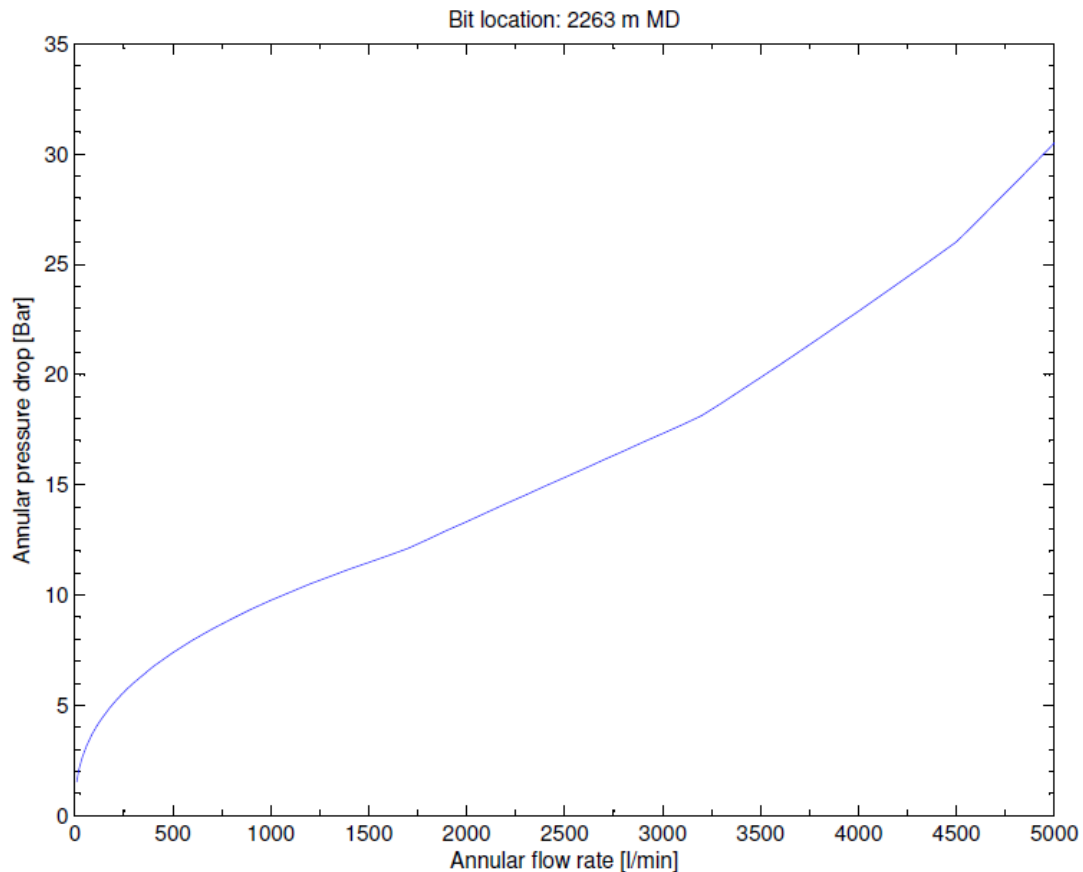


Figure 3.9 Shows the total annular pressure drop as a function of annular flow rate when the bit is located at 2263 m MD.

Changes in MP rates are often used in conventional systems to temporarily effect the BHP and this can also be euthanized in the LRRS system as mentioned in section 2.1. An interesting property of changing pressure by varying the MP rate is that the pressure changes can be made considerably faster than when relying only on the change in riser level. If the pump rate is for example 1800 l/min frictional pressure drop is about 12,5 bar according to Figure 3.9. If the rate is temporarily dropped to 1000 l/min frictional pressure drop drops to about 9,8 Bar and a 2,7 bar pressure decrease is achieved. Using the same assumptions as before and the pump specs listed in Table 2.1 dropping the rate from 1800 l/min to 1000 l/min takes about 5 seconds. From the information shown in Figure 11.5 Appendix 11.2 it can be seen that getting the same result by varying the mud level in the riser at a constant MP rate of 1800 l/s takes about 60 seconds. Combining those two methods, that is changing the MP rate temporarily to get a wanted pressure change and the returning it back to the initial one at a rate slow enough so the mud level change can keep the BHP constant, could improve the response of the system. This is demonstrated in more detail in section 5.3

4 Simulator description

The simulator is written in Matlab by Math Works and is made up of a main script and a couple of functions. The main module reads input data, such as pump rates, casing parameters and mud properties, from a Microsoft Excel document and calculates the BHP by calling the functions. An Excel document was selected as an input method to make modifications of input parameters less cumbersome.

In this section the simulator components will be put forth, the functions will be explained in more detail and the most important equations will be listed.

4.1 Excel input document

The Excel input file has two main components, the main page and the pump rate page. Screenshots from both pages are shown in Appendix 11.3

On the main page the user inserts the following parameters

- Casing sizes and setting depths
- Hole diameter in the uncased section
- Riser diameters
- Drill string diameter
- Diameter and length of the BHA
- Water depth
- Initial mud level in the riser
- Mud density
- Viscometer readings

Some simple calculations are made in the Excel document itself. Imperial units are commonly used in the industry and can be entered but are changed automatically to SI units which are read by the simulator. Internal diameters of casings are also calculated using Equation 4.1

$$ID = OD - 2 \cdot T \quad \text{Equation 4.1}$$

Where OD is the outside diameter of the casing and T is the standard wall thickness for the given casing weight according to The Drilling Data Handbook (Gabolde & Nguyen, 1999).

The viscometer readings entered are fitted to a rheological model in order to be able to determine the relationship between the shear stress and shear rate at all flow velocities. This is done in the Excel document using the power law model defined by Equation 4.2

$$\tau = K \cdot \dot{\gamma}^n \quad \text{Equation 4.2}$$

Where τ is the shear stress and $\dot{\gamma}$ is the shear rate. The power law exponent n and the consistency index K are calculated using Excel's built in regression tool and read in by the main module.

On the pump rate page the user manually enters flow rates for the MP, LP and FP.

4.2 Main script

The purpose of the main script is to twofold

1. Read the user input from the Excel document
2. Run the simulation by calling functions and combining results

The calculations carried out in the main module are mostly involve combining the results from the functions to calculate the annular flow rate, mud level in the riser and the BHP which is calculated using Equation 4.3. When a simulation has been run and the results are ready the main script plots the data.

$$P_{bh} = P_{hydrostatic} + P_{loss} \quad \text{Equation 4.3}$$

Where $P_{hydrostatic}$ is the hydrostatic pressure caused by the mud column in the annulus and P_{loss} is the annular pressure drop.

The Main script code is shown in Appendix 11.4.1.

4.3 Function: Annular pressure drop

The annular pressure drop function calculates the pressure drop as the drilling fluid flows through the annulus from the bottom of the hole to the riser. The equations used to calculate the pressure drops are taken from the book Drilling fluid Engineering (Skalle, 2010).

Annular pressure drop for laminar flow is calculated using Equation 4.4

$$\Delta p_{a,lam} = 4K \left(\frac{12\bar{v}}{d_o - d_i} \cdot \frac{2n + 1}{3n} \right)^n \cdot \frac{L}{d_o - d_i} \quad \text{Equation 4.4}$$

Where \bar{v} is the average annular flow calculated using Equation 4.5, d_o and d_i are the large and small diameters defining the annulus and L is the length of the annulus.

$$\bar{v} = \frac{\dot{q}_{ann}}{\frac{\pi}{4} \cdot (d_o^2 - d_i^2)} \quad \text{Equation 4.5}$$

Where \dot{q}_{ann} is the annular flow rate. Annular pressure drop for turbulent flow is calculated using Equation 4.6

$$\Delta p_{a,turb} = a \cdot N_{Re}^{-b} \cdot \frac{4L}{d_o - d_i} \cdot \frac{1}{2} \rho \bar{v}^2 \quad \text{Equation 4.6}$$

Where ρ is the mud density and

$$a = (\log(n) + 3,93)/50 \quad \text{Equation 4.7}$$

$$b = (1,75 - \log(n))/7 \quad \text{Equation 4.8}$$

The Reynolds number is calculated using Equation 4.9

$$N_{Re} = \frac{d_o - d_i^n \cdot \bar{v}^{2-n} \cdot \rho}{K_a \cdot (12^{n-1})} \quad \text{Equation 4.9}$$

Where

$$K_a = K \cdot \left(\frac{2n + 1}{3n} \right)^n \quad \text{Equation 4.10}$$

It is sometimes assumed that the flow pattern suddenly changes from laminar to turbulent at a discrete Reynolds number such as $N_{Re} = 2100$. In reality the change occurs over the range of numbers from 2000 to 4000. To avoid discontinuity in the annular friction function output it is assumed that the flow pattern changes from laminar to turbulent when the laminar and turbulent equations yield the same frictional pressure drop (Bourgoyne et.al. 1986).

The annular pressure drop function code is shown in Appendix 11.4.2.

4.4 Function: Singularity loss, sudden expansions

The function calculates the pressure drop caused by sudden expansions. Pressure loss through restrictions such as valves, bends, pipe entrances and sudden expansions are called singularity losses. Inertia effects will dominating compared to viscous effects and losses are determined experimentally. Sudden expansions in the system being simulated are found when casing diameters get bigger as the fluid travels up the annulus. A pressure loss is also experienced when the mud passes the point where the BHA ends and the normal drill string diameter continues. The pressure loss is determined using Equation 4.11 (Skalle, 2010)

$$\Delta p_{expansion} = K_{L,expansion} \cdot \left(\frac{1}{2} \rho \bar{v}^2 \right) \quad \text{Equation 4.11}$$

Where

$$K_{L,expansion} = \left(1 - \frac{A_1}{A_2} \right)^2 \quad \text{Equation 4.12}$$

Where A_1 and A_2 are the smaller and larger cross sectional area respectively. It should be noted that the singularity losses account for a negligible amount of the total drop for the simulated cases.

The singularity loss function code is shown in Appendix 11.4.3.

4.5 Function: Mud level

The function calculates the mud level in the riser. The mud level in the riser is controlled by the pump rates. The net flow into the riser in a system experiencing fluid loss is

$$\dot{q}_{riser} = \dot{q}_{ann} + \dot{q}_{fill} - \dot{q}_{lift} \quad \text{Equation 4.13}$$

Where \dot{q}_{ann} is the annular flow rate, \dot{q}_{fill} is the FP rate and \dot{q}_{lift} is the LP rate. It is assumed that the drilling fluid is incompressible and that the effects of well expansion can be

discarded. The effects of pump rate changes therefore affect the level in the riser immediately. The level change in the riser is calculated using Equation 4.14

$$\Delta Level_{riser} = \frac{\bar{q}_{riser} \cdot \Delta t}{\frac{\pi}{4} \cdot (d_{i,riser}^2 - d_{o,string}^2)} \quad \text{Equation 4.14}$$

Where \bar{q}_{riser} is the average flow rate over the time Δt , $d_{i,riser}$ is the internal diameter of the riser and $d_{o,string}$ is the external diameter of the drill sting.

The Mud level function code is shown in Appendix 11.4.4.

4.6 Function: Lost circulation

The lost circulation function calculates the lost circulation if the BHP becomes greater than the defined formation fracture pressure. It is assumed the severity of the circulation loss is changes linearly with the difference between the BHP and formation fracture pressure as shown in Equation 4.15

$$\dot{q}_{loss} = C \cdot (P_{bh} - P_{frac}) \quad \text{Equation 4.15}$$

Where C is the loss coefficient and P_{frac} is the formation fracture pressure. If the BHP is smaller than the formation fracture no pressure loss is experienced and the annular flow rate given by Equation 4.16 becomes equal to the MP rate \dot{q}_{mud} .

$$\dot{q}_{ann} = \dot{q}_{mud} - \dot{q}_{loss} \quad \text{Equation 4.16}$$

The Mud level function code is shown in Appendix 11.4.5.

5 Simulations: Commissioning Tests

In this section simulation results from test scenarios are presented. These demonstrate how pump rates are manipulated to get predefined results and give an idea of the performance that can be expected out of the LRRS. The scenarios are based on some of the commissioning tests that were suggested for and run on a choked MPD system (Godhavn, 2009) (Godhavn & Knudsen, 2010).

First the two tests are performed at constant MP rates. A pressure increase and a pressure decrease. Next a test is run that shows how a decrease in bottom BHP can be achieved faster than by only manipulating the mud level by temporarily decreasing the MP rate. Finally two tests are run that show how the MP rate can be increased and decreased while keeping the BHP as stable as possible.

All simulations are run with the bit located at 2263 m MD. This means that the bit is located 275 m into the 8,5 inch uncased section of the well. The mud has a density of 1320 kg/m³ and the rheological properties are shown in Table 11.1 in Appendix 11.1.

5.1 BHP increase at a constant mud pump rate

A 5 bar increase in BHP is made by increasing the level in the riser while the MP is run at a constant rate of 1800 l/min. This is done by temporarily increasing the FP rate and decreasing the LP rate. The increase is performed as fast as possible. The simulation results are shown in Figure 5.1 and the key results are listed in Table 5.1.

Process description

- The MP and the FP are initially running at the same rate (1800 l/min). The LP is off and the net flow into the riser is zero.
- As the test starts the LP is ramped down and the FP is ramped up. The net flow into the riser becomes positive and the level starts to increase.
- The LP rate reaches zero at 14 seconds
- The FP rate reaches its maximum rate (5000 l/min) at 30 seconds
- The system is running at its maximum level increase rate (0,63 m/s) from 30-58 seconds
- The ramp down of the LP is started at 58 seconds while the FP is still off. The net flow into the riser starts to decrease.
- The ramp up of the FP is started at 74 seconds
- The ramp up LP to its initial rate of 1800 l/min and the ramp down of the FP to zero is finished at 88 seconds. The test is finished.

Table 5.1 Simulation results for 5 Bar BHP increase at a constant MP rate

Time	88 seconds
Level increase	39,18 m
Pressure increase	5,09 Bar

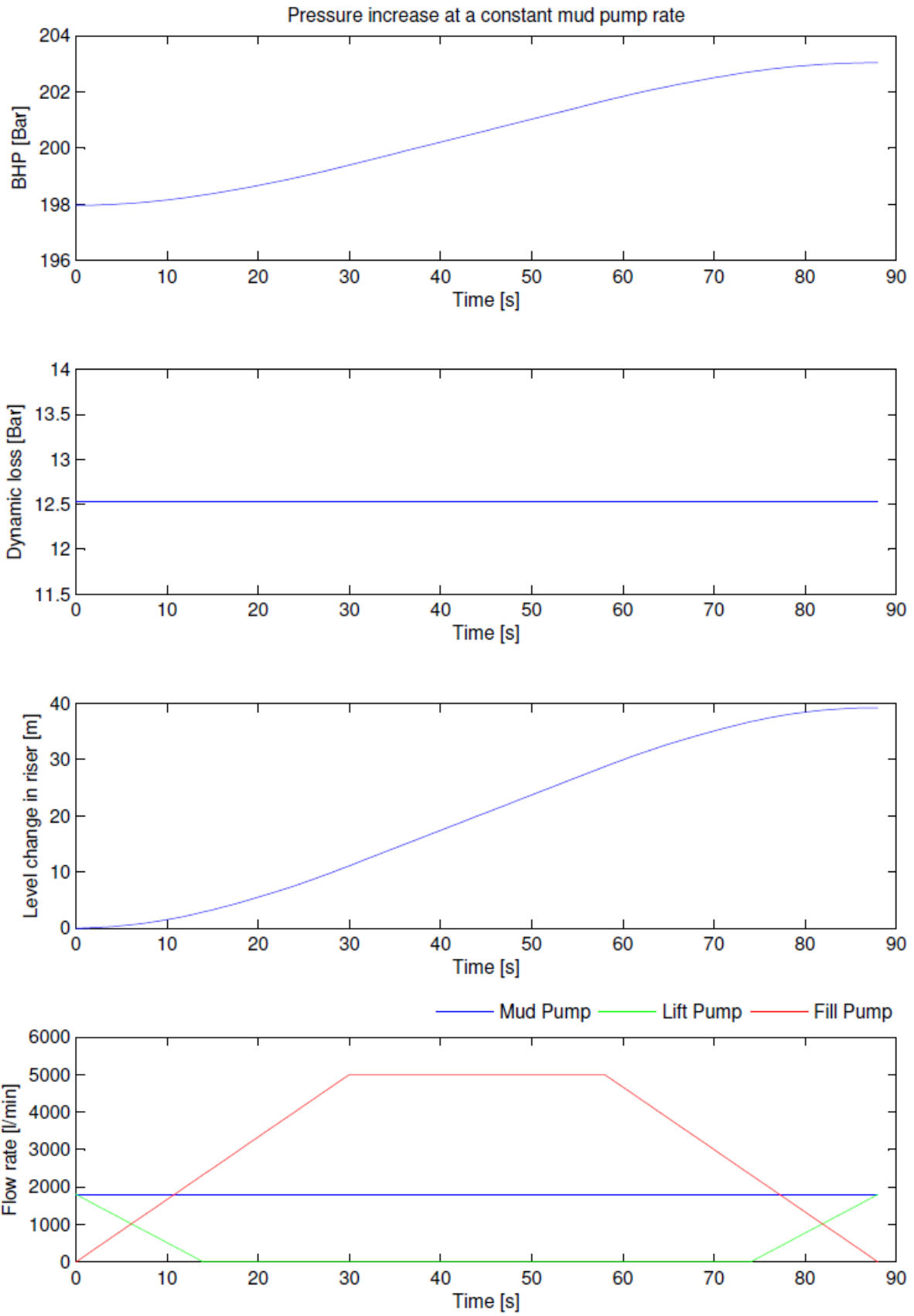


Figure 5.1 Shows the result from a simulation of 5 bar pressure increase at a constant MP rate of 1800 l/min

5.2 BHP decrease at a constant mud pump rate

A 5 bar decrease in BHP is made by decreasing the level in the riser while the MP is run at a constant rate of 1800 l/min. This is done by temporarily increasing the LP rate. The decrease is performed as fast as possible. The simulation results are shown in Figure 5.2 and the key results are listed in Table 5.2.

Process description

- The MP and the FP are initially running at the same rate (1800 l/min). The LP is off and the net flow into the riser is zero.
- As the test starts the LP is ramped up and the net flow into the riser becomes negative and the level starts to decrease.
- The LP reaches maximum pump rate (4000 l/min) at 17 seconds.
- The system is running at its maximum level decrease rate (0,204 m/s) from 17-189 seconds.
- The ramp down of the LP is started at 189 seconds. The net flow out of the riser starts to decrease.
- The LP is reaches its initial rate (1800 l/min) at 206 seconds. The net flow into the riser is zero. The test is finished.

Table 5.2 Simulation results for 5 Bar BHP decrease at a constant MP rate

Time	206 seconds
Level decrease	-38,5 m
Pressure increase	5,01 Bar

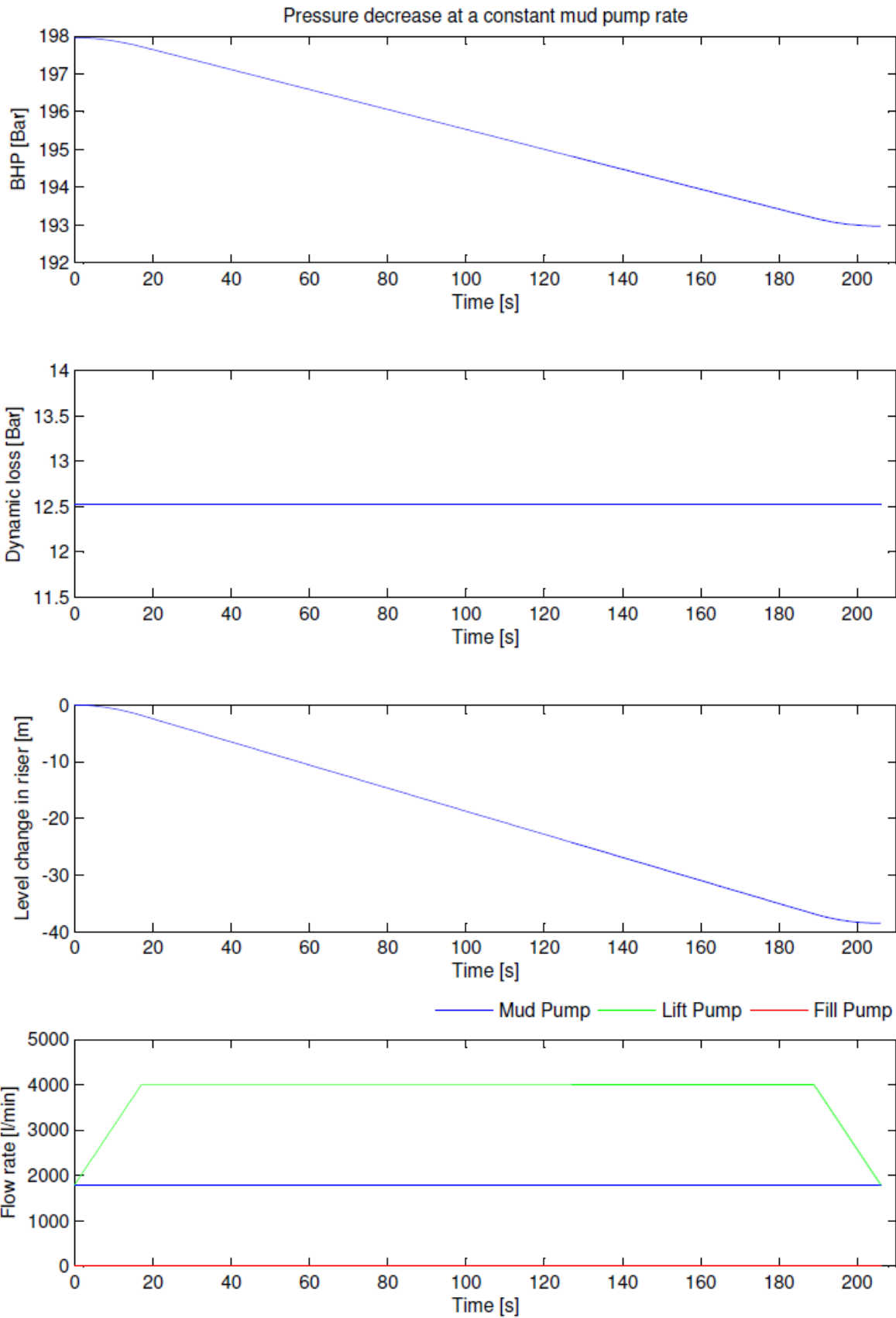


Figure 5.2 Shows the result from a simulation of 5 bar pressure decrease at a constant MP rate of 1800 l/min

5.3 5 bar pressure decrease with mud pump manipulation

A 5 bar pressure decrease is performed by quickly dropping the MP rate and thereby reducing the annular pressure loss. The MP is then ramped back to its initial rate while the riser in ECD is compensated for by a decrease in mud level. The simulation results are shown in Figure 5.3 and the key results are listed in Table 5.3.

Process description

- The MP and LP are initially running at the same rates so the net flow into the riser is zero
- The MP rate is dropped quickly from 1800 l/min to 550 l/min in 8 seconds while the LP is ramped up to its maximum rate of 4000 l/min in 17 seconds
- At 8 seconds the wanted pressure decrease of 5 bars has been achieved.
- The LP is run at its maximum rate from 17-143 seconds and it then ramped down to its initial rate of 1800 l/min
- The MP is ramped back to its initial rate from 17-160 seconds in such a way that the level decrease caused by the LP is able to compensate for the increasing ECD.
- At 160 seconds the MP and LP are running at the same rate, no net flow is into the riser and the simulation is finished.

Table 5.3 Simulation results for 5 Bar BHP where the MP rate is manipulated for a faster pressure decrease

Time to 5 bar decrease	8 seconds
Total time of operation	160 seconds
Pressure decrease	5 bar

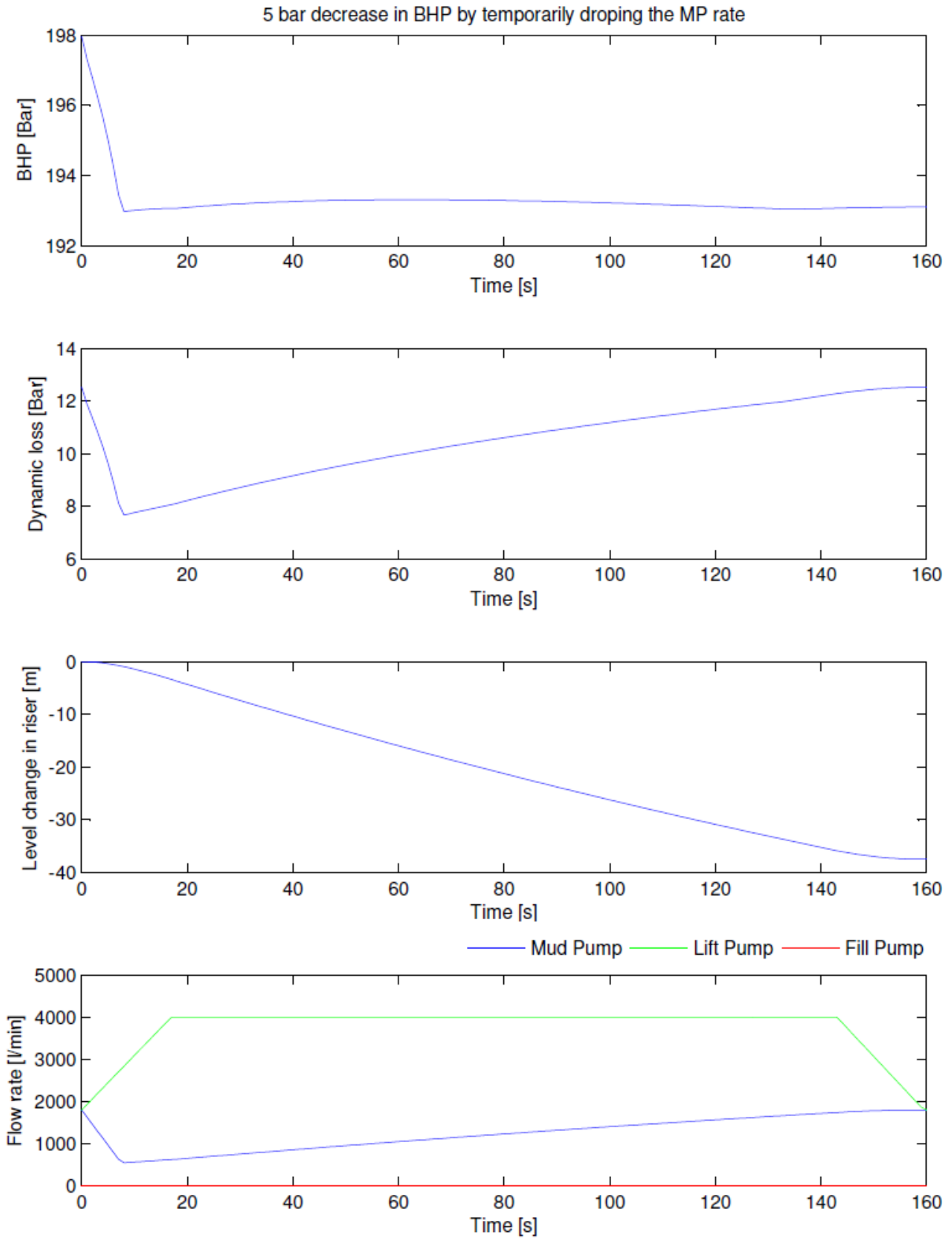


Figure 5.3 Shows the simulation results for a 5 bar pressure decrease where the MP rate is manipulated to get a faster pressure decrease

5.4 Mud pump rate decrease with a minimum change in BHP

When the MP rate is lowered a decrease in ECD is experienced due to the decrease in annular flow rate. The change in total annular pressure loss from 1000 – 1800 l/min is show in Figure 5.4. If the BHP is to be kept close to constant this decrease in ECD has to be compensated by increasing the mud level in the riser.

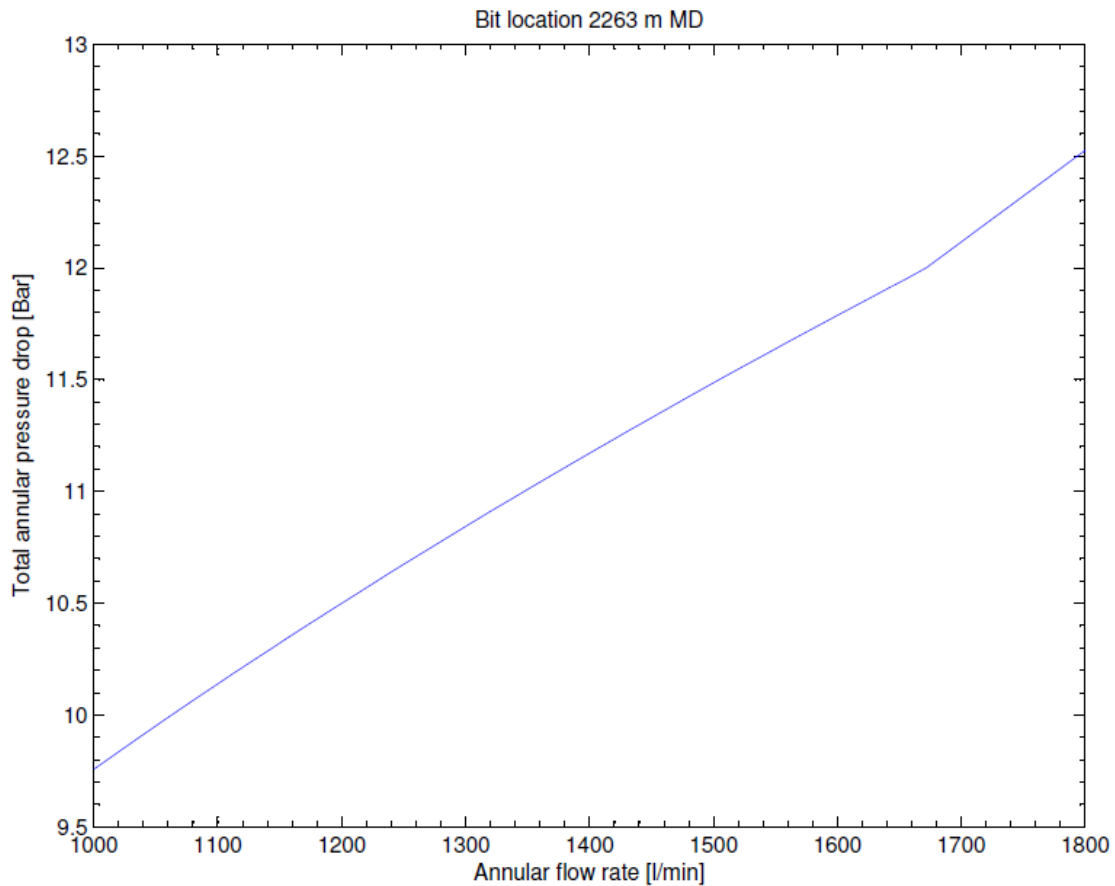


Figure 5.4 Shows the total annular pressure drop as a function of annular flow rate from 1000-1800 l/min when the bit is located at 2263 m MD.

It is not enough that the BHP is at the initial value at the end of the interval. It should also be kept constant while the change in MP rate is taking place. By comparing the change in friction with MP rate in Figure 5.4 and the fastest possible change in riser level shown in Figure 11.3 Appendix 11.2 it is clear that if the MP is ramped down as fast as possible the resulting change in ECD occurs faster than the system is able to compensate for by increasing the mud level. The rate at which the system can increase the level in the riser therefore becomes the limiting factor when decreasing the MP rate at a constant BHP.

Since the change in mud level is the limiting factor the LP and FP can be run in such a way that the level increase needed to balance the expected loss in ECD is achieved as fast as possible. The approximate change in riser level as a function of time during ramp up and down of LP and FP this operation has a similar form as the 60 second curve shown in Figure 11.2 Appendix 11.2. The only difference is that the MP rate will be decreasing resulting in a

downwards shift of the whole curve as indicated by Figure 3.6. The shift increases from the beginning to the end because of the decreasing MP rate.

The BHP is kept constant during the change in MP rate if the change in ECD mirrors the increase in mud level in the riser. Since the annular friction changes approximately linearly over the range 1000 l/min – 1800 l/min the ECD change will mirror the level change in the riser when the change in MP rate follows a curve identical to the level increase curve.

The simulation result is shown in Figure 5.5 and the key results are listed in Table 5.4

Process description

- Initially the MP and LP are running at the same rate, 1800 l/min, while the FP is at zero and the net flow into the riser is therefore zero
- As the test is started the LP is ramped down to zero as fast as possible while the FP is ramped up to its maximum rate, 5000 l/min, as fast as possible. The MP ramp down procedure is started right away and the rate decrease follows a curve that mirrors the expected level increase curve.
- The net flow into the riser is now positive and the level starts to increase at an increasing speed. The LP reaches zero at 14 seconds and the FP reaches its maximum at 30 seconds
- The maximum level changing rate is kept from 30-32 seconds
- FP rate is ramped down from 33-62 seconds at maximum ramp down rate to zero flow
- The LP ramp up is started at 54 seconds and reaches the final MP rate of 1000 l/min at 62 seconds. The net flow into the riser is now zero and the simulation is finished.

Table 5.4 Simulation results for MP rate decrease with a minimum change in BHP

Initial BHP	198,0
Final BHP	198,0
Max BHP during MP rate change	198,1
Min BHP during MP rate change	197,9
Total level increase	21,3 m
Time	65 seconds

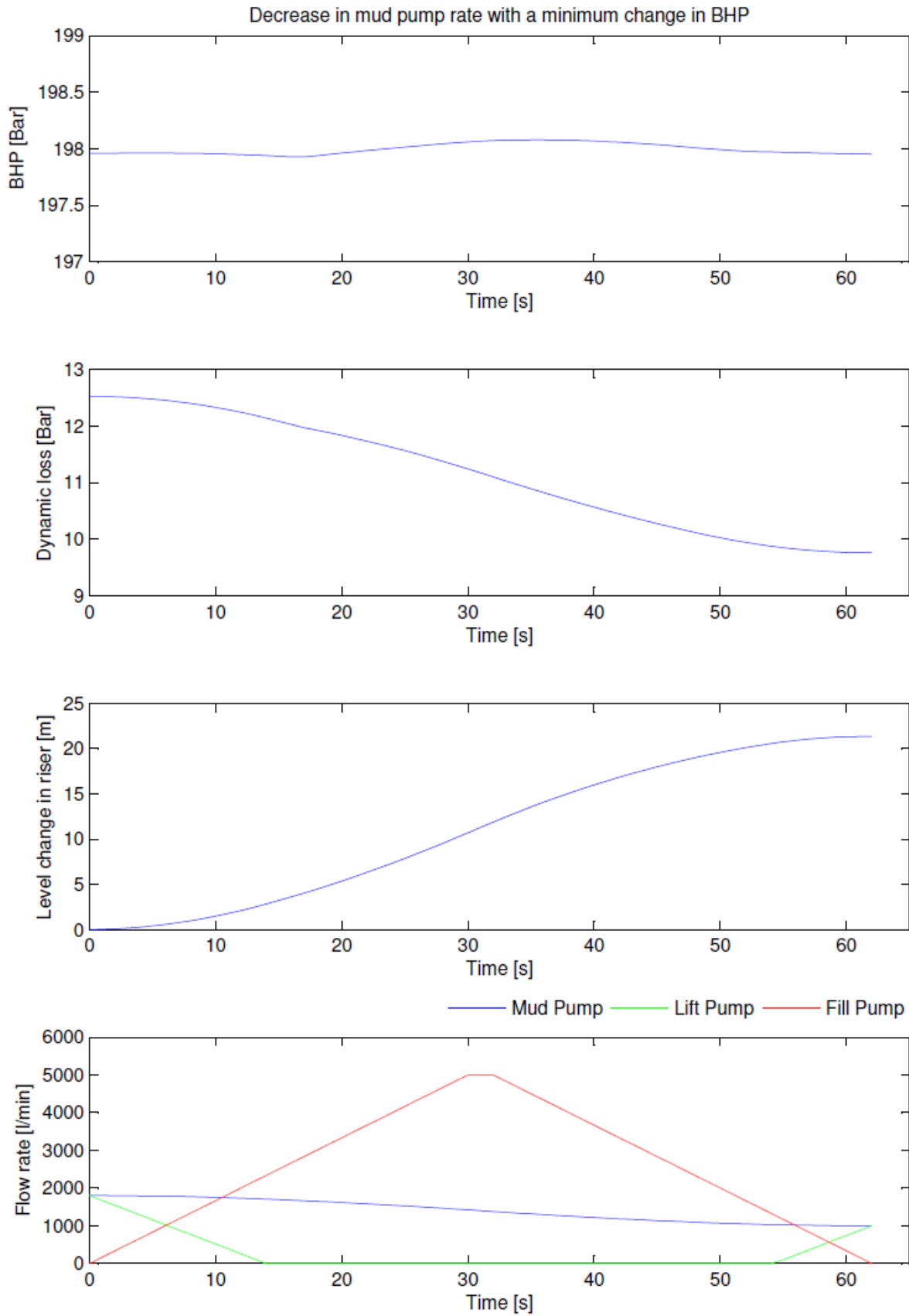


Figure 5.5 Shows the results from a simulation of changing the MP from 1800-1000 l/min with a minimum change in BHP.

5.5 Mud pump rate increase with a minimum change in BHP

When the MP rate is increased an increase in ECD is experienced due to the increase in annular flow rate. The change in annular friction from 1000 – 1800 l/min is shown in Figure 5.4. If the BHP is to be kept close to constant this decrease in ECD has to be compensated by decreasing the level in the riser.

As was true for the rate decrease above it is not enough that the BHP is at the initial value at the end of the interval. It should also be kept constant while the change in rate is taking place. By comparing the change in friction with MP rate in Figure 5.4 and the fastest possible decrease in riser level shown in Figure 11.5 it is clear that if the MP is ramped up at its maximum rate the resulting change in ECD occurs faster than the system is able to compensate for by moving the mud level down. The rate at which the system can lower the level in the riser therefore becomes the limiting factor when decreasing the MP rate at a constant BHP.

Since the speed of mud level change is the limiting factor the LP can be run in such a way that the level change needed to balance the expected loss in ECD is achieved as fast as possible. The approximate change in riser level as a function of time during the ramp up and down is very similar in form as the 46 second curve in Figure 11.4. The only difference is that the MP rate will be increasing at the same time which results in an upward shift of the whole curve since increase in MP rate increases the net flow into the riser. The shift increases from the beginning to the end because of the increasing MP rate.

A constant BHP is kept during the operation if the change in ECD mirrors the change in mud level in the riser. Since the annular friction changes approximately linearly over the range 1000 l/min – 1800 l/min the ECD change will mirror the level decrease in the riser when the change in MP rate follows a curve identical to the level decrease curve.

The simulation result is shown in Figure 5.6 and the key results are listed in Table 5.5

Process description

- Initially the MP and LP are running at the same rate, 1800 l/min, while the FP is at zero and the net flow into the riser is therefore zero.
- As the test is started the LP is ramped up to its maximum rate, of 4000 l/s, as fast as possible. The MP ramp down procedure is started right away and the rate decrease follows a curve that mirrors the expected level decrease curve.
- The net flow into the riser is now negative and the level starts to decrease at an increasing speed.
- The LP reaches 4000 l/s at 23 seconds and the maximum level decreasing rate is kept for the interval from 23 - 91 seconds.
- The LP rate is ramped down during the interval from 91 - 108 seconds at maximum ramp down rate to 1000 l/min. At 108 second the MP and LP meet at 1000 l/min. The net flow into the riser is now zero and the simulation is finished

Table 5.5 Simulation results for MP rate increase with a minimum change in BHP

Initial BHP	195,2
Final BHP	195,2
Max BHP during MP rate change	195,2
Min BHP during MP rate change	195,1
Total level increase	21,1 m
Time	108 seconds

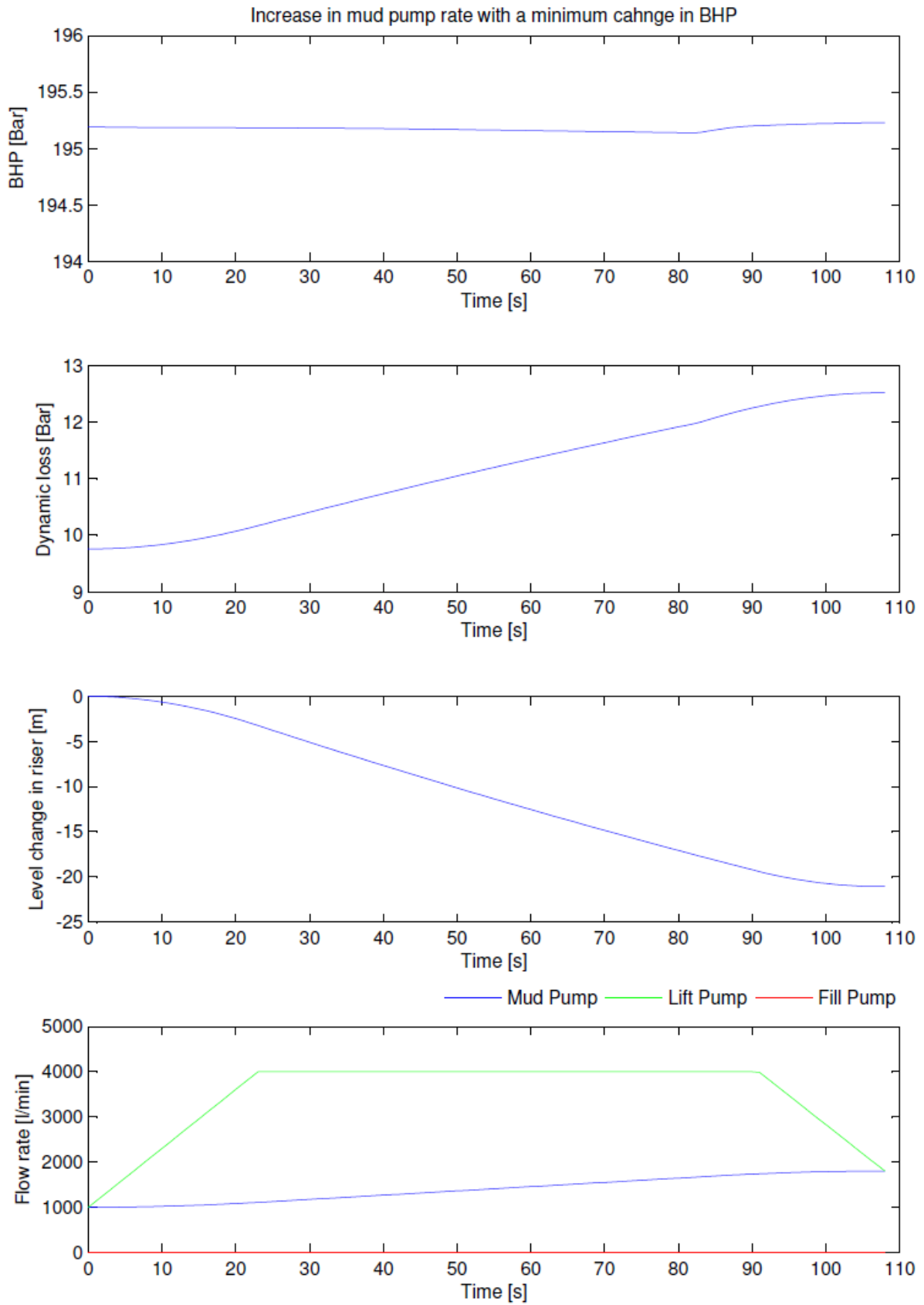


Figure 5.6 Shows the results from a simulation of changing the MP from 1000-1800 l/min with a minimum change in BHP.

6 Simulations: Lost circulation handling

Lost circulation is a total or partial loss of drilling fluid into highly permeable zones, cavernous formation and natural or induced fractures during drilling. Lost circulation causes reduced or total absence of fluid flow up the annulus when fluid is pumped through the drill string. The reduction in flow can be classified as seepage if the loss is less than 3 m³/hr (50 l/min) or partial loss if the loss is greater than 3 m³/hr but still some returns. Total loss results in no return of fluid through the annulus and in severe cases the hole may not even stay full if the pumps are turned off.

The immediate response to a lost circulation scenario is to lower the BHP with the hope of curing the loss. In a conventional system this means replacing the drilling fluid with a lighter one and/or decreasing the MP rate. In this section simulations are shown that demonstrate how the level in the riser can be reduced to lower the BHP and potentially cure a lost circulation.

6.1 Identification and effect of lost circulation

If the LRRS is running in an automatic mode with a focus on keeping a constant BHP the system will be attempting to keep the level in the riser stable. In the case of a lost circulation the level in the riser will start to drop which leads to lowering of the inlet pressure of the LP and the LP will then respond by lowering its pump rate (Handal, 2011).

The lost circulation causes reduction in annular flow which leads a decrease in ECD and lowering of BHP. This is seen by a reduction in the MP outlet pressure and the LP inlet pressure since the mud level in the riser starts to fall. The ability to measure LP inlet pressure can help the system to detect losses earlier than with conventional systems.

The magnitude of the ECD for a given circulation loss depends on the location of the loss zone. The biggest change in annular pressure drop is seen when the loss zone is located at the bit because the decrease in flow is the experienced along the total length of the annulus. If the loss zone is located behind/above the bit full annular flow is maintained from the bit to the loss zone and therefore the pressure loss remains unchanged in that section. The annular length after the loss zone on the other hand experiences the decrease in flow rate and annular pressure drop. Therefore the effect on ECD becomes smaller as the distance from the loss zone to the bit becomes larger.

Indications of lost circulation are summarized as:

- Reduced inlet pressure for LP
- Reduced LP rate (if running in automatic constant level mode)
- Reduced MP pressure due to reduced frictional losses in the annulus

6.2 Simulated responses

To battle the lost circulation BHP is lowered. The pressure is lowered by running predefined step responses at a constant MP rate. The first step is identical to the one used for simulating a 5 Bar decrease in BHP in commissioning section. The second one is a 1 bar drop in BHP at constant MP rate and is run in series with the 5 bar step if it alone is not enough to heal the circulation loss.

All simulations are run with the bit located at 2263 m MD. This means that the bit is located 275 m into the 8,5 inch uncased section of the well. The mud has a density of 1320 kg/m³ and the rheological properties are shown in Table 11.1 in Appendix 11.1. The loss is assumed to happen at the bit for all simulated cases and it is assumed to change linearly with the difference between formation fracture pressure and BHP as shown with Equation 4.15. The loss constant *C* is equal to 50 l/min.bar for all simulations. The initial BHP is 198 bar in all cases but the formation fracture pressure is defined differently between simulations so different pressure decreases are needed to cure the losses.

6.2.1 Loss cured with a 5 bar step decrease

A circulation loss is cured by running the 5 bar step decrease described in section 5.2. Simulation results are shown in Figure 6.1 and key numbers are listed in Table 6.1.

Process description

- The MP and LP are running at 1800 l/s at the beginning and BHP is 198 bar
- Loss is introduced by a step in formation fracture after 20 seconds pressure form 200 bar to 194 bar and circulation loss is initiated
- After 30 seconds a 5 bar pressure decrease step is started
- The loss starts to decrease and is fully cured around 200 seconds as can be seen from the loss rate plot or the dynamic loss plot which shows a straight line indicating that initial annular flow rate has been restored.

Note

1. The sharp increase in dynamic loss at second 21 is because the lowering of the BHP caused by the decrease in annular friction is not registered in the fluid loss function until at second 22.
2. Running the 5 bar step, run to cure the loss, would result in a 5 bar decrease if run at a constant 1800l/min MP rate without any loss. In the simulated scenario the pressure decrease is slightly smaller because of the lost circulation.

Table 6.1 Simulation results for loss being cured with a 5 bar step decrease

Initial BHP	198,0 bar
Final BHP	192,8 bar
Loss during pressure decrease	210 liters
Total loss	289 liters

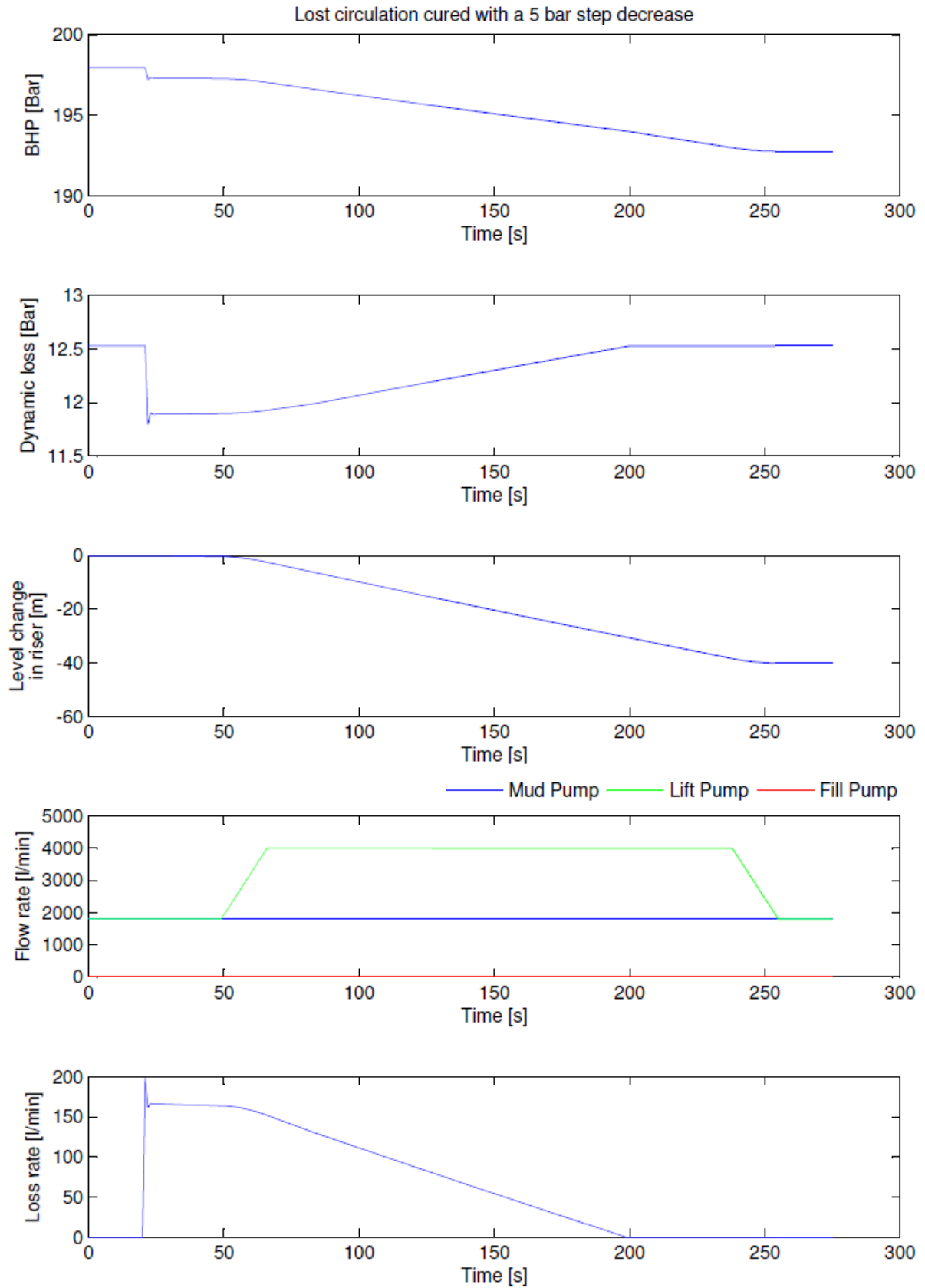


Figure 6.1 Shows the results from a simulation of lost circulation being cured with a 5 bar step decrease

6.2.2 Loss cured with a 5 bar step decrease followed by a 1 bar step

A circulation loss is cured by running the 5 bar step decrease described in section 5.2 followed by a similar 1 bar step since the loss is not completely cured after the first decrease. Simulation results are shown in Figure 6.2 and key numbers are listed in Table 6.2.

Process description

- The MP and LP are running at 1800 l/s at the beginning and BHP is 198bar
- Loss is introduced by a step in formation fracture after 20 seconds pressure form 200 bar to 192 bar and circulation loss is initiated
- After 30 seconds a 5 bar pressure decrease step is started
- The loss is not completely cured when the 5 bar step has been completed
- 30 seconds after the 5 bar step has completed a 1 bar step is run
- The loss starts to decrease and is fully cured around 315 seconds as can be seen from the loss rate plot or the dynamic loss plot which shows a straight line indicating that initial annular flow rate has been restored.

Note

1. The sharp increase in dynamic loss at second 21 is because the lowering of the BHP caused by the decrease in annular friction is not registered in the fluid loss function until at second 22.
2. Running the 5 and one bar steps, run to cure the loss, would result in a 5 and 1 bar decreases respectively if run at a constant 1800l/min MP rate without any loss. In the simulated scenario the pressure decreases are slightly smaller because of the lost circulation.

Table 6.2 Simulation results for loss being cured with a 5 bar step decrease followed by a 1 bar step

Initial BHP	198,0 bar
Final BHP	191,5 bar
Total loss	593 liters

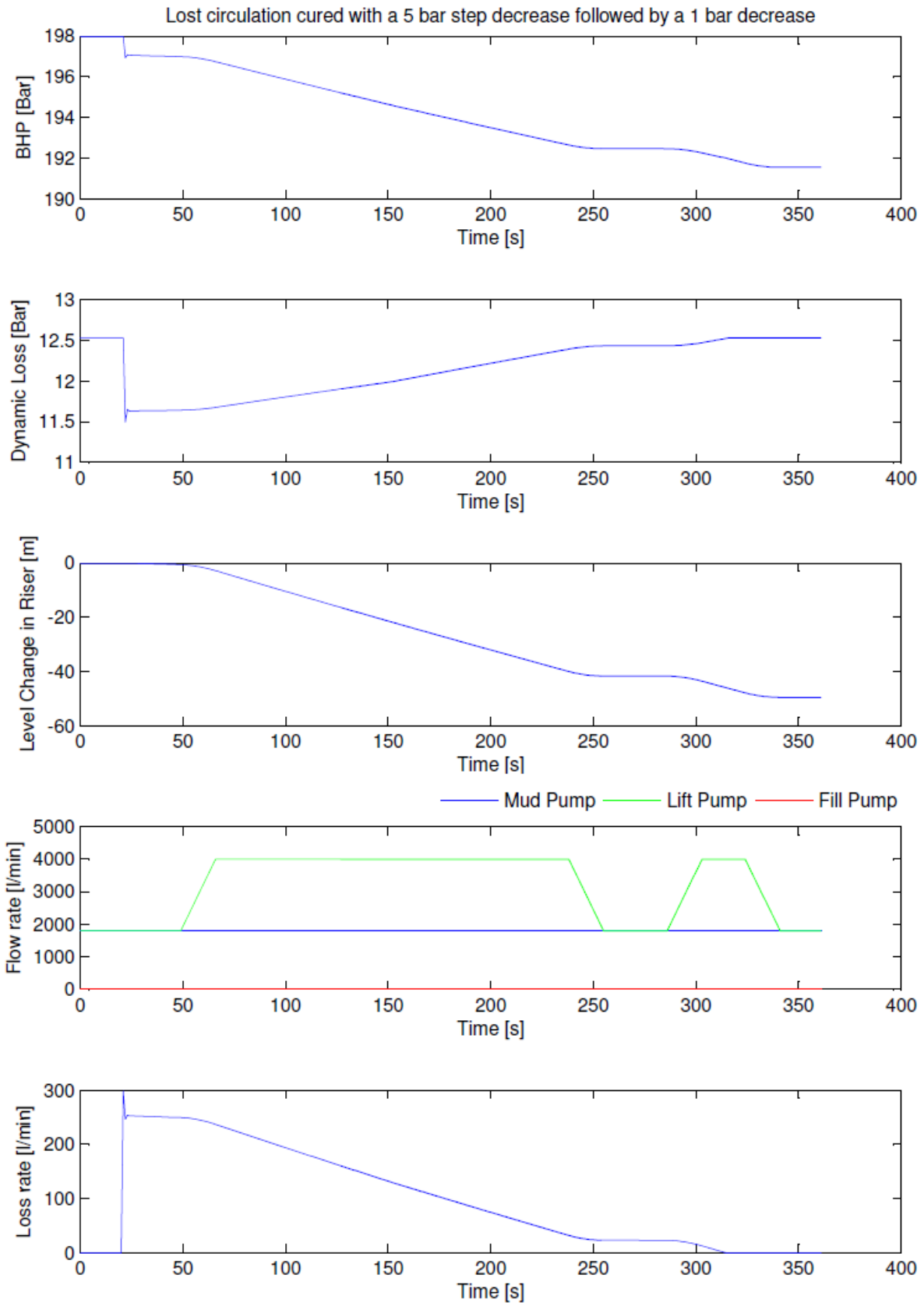


Figure 6.2 Shows the results of a simulation of lost circulation being cured with a 5 bar step decrease followed by a 1 bar step.

6.2.3 Loss cured 5 bar step response with MP variation

A circulation loss is cured by applying a 5 bar pressure decrease step. The lowering of pressure is done more quickly than in section 6.2.1 by manipulating the MP rate as shown in section 5.3. The simulation results are shown in Figure 6.3 and key numbers are listed in Table 6.3.

Process description

- The MP and LP are running at 1800 l/s at the beginning and BHP is 198bar
- Loss is introduced by a step in formation fracture after 20 seconds pressure form 200 bar to 194 bar and circulation loss is initiated
- After 30 seconds the response from section 5.3 is run
- The pressure is dropped 5 bars in 7 seconds and the loss is cured
- The LP is run at its maximum rate from 67-192 seconds and it then ramped down to its initial rate of 1800 l/min
- The MP is ramped back to its initial rate from 57-160 seconds is such a way that the level decrease caused by the LP is able to compensate for the increasing ECD.
- At 208 seconds the MP and LP are running at the same rate, no net flow is into the riser. The run continues to 229 seconds and then simulation is finished.

Table 6.3 Simulation results for loss being cured with a 5 bar step response by manipulating the MP rate

Initial BHP	198 bar
Final BHP	193 bar
Loss during pressure decrease	3,6 liters
Total loss	87,5 liters

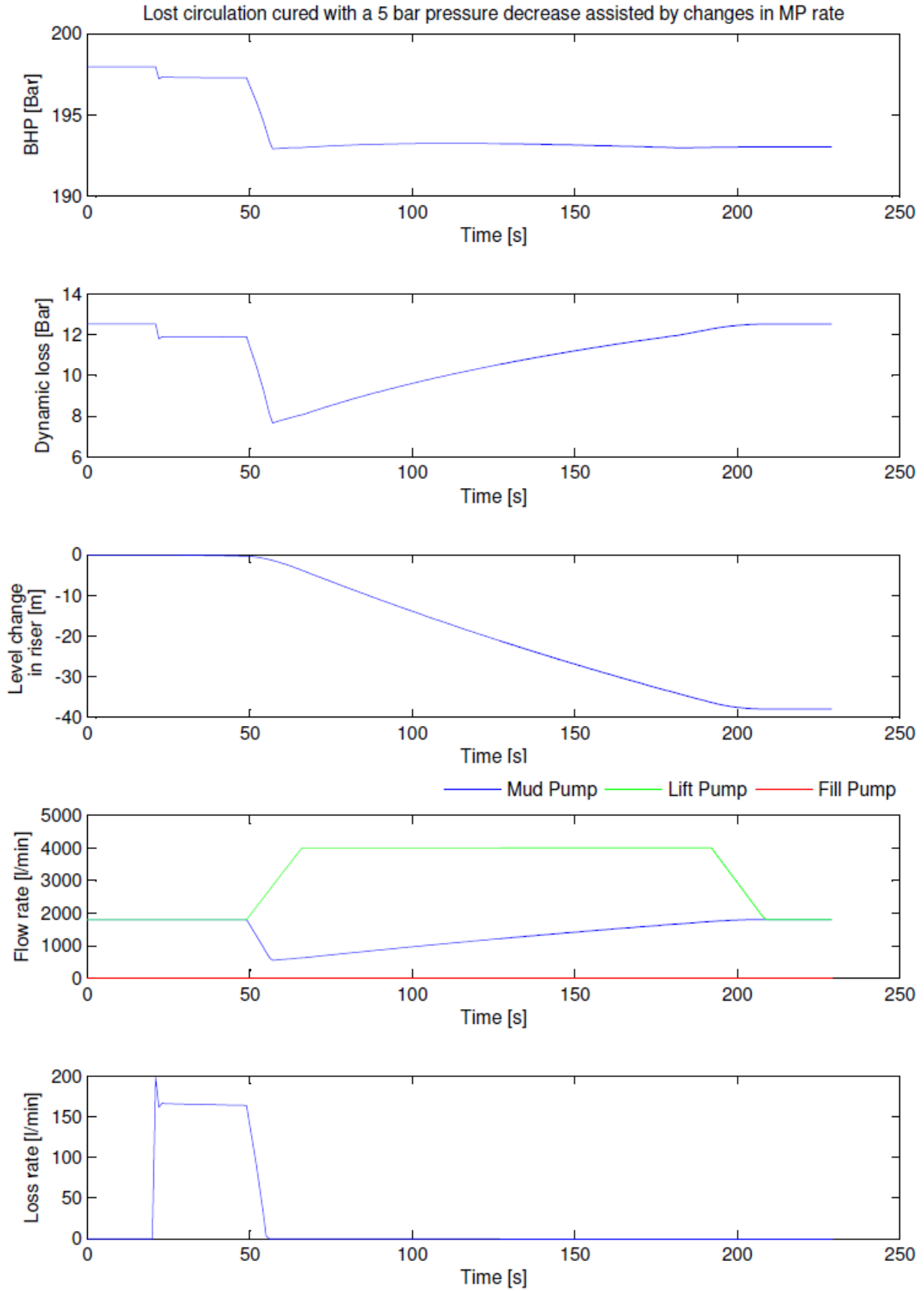


Figure 6.3 Shows simulation results for loss being cured with a 5 bar step response by manipulating the MP rate

7 Discussion

For better overview discussion is carried out for each section separately. A bullet point style is chosen to clearly separate different subjects and makes the writing more to the point. Topics are listed below.

7.1 Model limitations

The simplicity of the model poses some limitations. Some of the more critical ones are listed below and their effects discussed.

- All fluids are treated as incompressible and expansion (ballooning) of the wellbore is not accounted for. All changes in flow rates do therefore have immediate effects on BHP when in the real case time delays should be expected. The real response of pump rate changes is therefore expected to be slower. The simulation results can therefore be thought of as an upper performance limit for the given system specifications.
- The model does not include inertial effects. When a pump is shut down flow rate is assumed to stop immediately. In real life fluid will continue to flow due to inertial effects. This means that it becomes more complicated to control BHP at the end of operations. This could mean that the difference between maximum and minimum pressure during an operation which should be carried out at constant BHP could become larger.
- Pressure drop in the riser itself is not accounted for. This drop depends on the level in the riser but is relatively small even at the simulated highest level increase rates (less than 0,2 bar).
- The simulator cannot simulate the effect of u-tubing. U-tubing does no effect any of the scenarios included in this thesis but for scenarios where MP is stopped this feature should be included.

7.2 Performance characteristics

Below observations concerning system properties are discussed.

- System performance depends on pump capacity. It was demonstrated that the MP rate affects how fast pressure increases/decreases can be made at a constant MP rate. When the MP rate equals the LP rate no decrease in mud level can be made without lowering the MP rate. This indicates that a more powerful LP is needed if the MP is to be run at full capacity while still being able to decrease pressure by lowering the mud level. The LP capacity can be increased by using a bigger pump or by adding another one. The level increase on the other hand does not suffer from this problem. Level increases can even be made while the MP is turned off due to the FP.
- The level change curves provide information about how MP rate should be changed if a constant BHP is desired. It should be kept in minds that when the MP rate is increased the curves real curve will be shifted up compared to the ones presented and during a MP decrease they will be shifted down.

7.3 Simulations

The main observations and lessons learned from the run simulations are listed and discussed below.

- It was seen that the speed of level change can limit how fast the MP rates can be changed if it is to be done at constant BHP. This is especially true for high ECD situations. It should not be a problem during most normal operations but in the case of an unexpected shut down of the MP the level changes won't be able to keep up with the rapid loss in ECD. For wells with high ECD the difference can be large. To reduce the risk of a blow out the BOP can be closed and the fluid flow caused by u-tubing circulated through the bypass choke line. The SSC can then be used to control the BHP.
- A fast pressure decrease gotten by temporarily changing the MP rate was demonstrated and showed lowered the amount of drilling fluid loss when used to cure a circulation loss. Lowering the MP rate however translates into poorer well cleaning. If the MP rate is lowered for too long there is a risk of cuttings falling down and causing problems. Short decrease periods should be fine as long as mud viscosity is able to minimize accumulation of cuttings in the wellbore.
- Depending on the hierarchy on the rig using the MP to affect BHP could mean a transfer of MP control from the driller to DGD operator. This could be met with skepticism like is true for most changes to normal practices.
- Fast pressure decrease by manipulation of MP was demonstrated. Pressure increase can be had in the same way by increasing the MP rate. Because of the slower pressure increase and decrease rate offered by level changes it may be impossible to use them to compensate for the fast pressure variations caused by surge and swab. MP manipulation might be an option for compensating such pressure variations.
- Knowing the behavior of the annular pressure loss with a change in MP rate is key if it is to be well compensated for. It is the authors believe that effects of MP rate change has to be studied for each individual well as it is being drilled since modeling will never perfectly predict the pressure behavior. The author agrees with a comment made in previous report that an extensive pump study of different stages of a planned well can be of crucial high importance when applying the LRRS (Handal, 2011).

7.4 Comparison the back pressured chocked systems

- A choked MPD system can vary pressure in the well faster than with the LRRS since the choke can be closed in matter of seconds. This makes handling of unexpected scenarios easier.
- Pressure changes with the LRRS can be made faster (than with level changes) by varying the MP rate. The resulting pressure increase is however not uniformly distributed over the well. Higher pressure losses are for example experienced around the BHA. The pressure introduced by the choke is however experienced uniformly in the well like when pressure variations are made by moving the level in the riser.

- When used in floating drilling applications LRRS has the advantage of being able to use higher than normal density drilling fluids. This allows the system to include regulatory requirements of riser margin and trip margin. When using a closed loop MPD system with a surface BOP BHP is made up of hydrostatic pressure of the mud in the well plus the friction introduced by the choke. The mud weight is therefore lower than in conventional drilling and the margins mentioned before will difficult to maintain (Fossli & Sangesland 2004).

7.5 Words on automation

Pressure control in the LRRS involves manipulation and coordination of up to three pump rates. The effect on BHP when simultaneously changing different pump rates can be quite unclear. Humans do not excel at multi variable control so automated pump control is recommended (Breyholtz & Nygard, 2009).

Changes tend to be struggled against in the industry (Smith et.al 2001) and the response to automation is might not be any different. Automated steps such as those used to change pressures at constant MP rates could serve as a less polarizing introduction of automation. The operator would then simply select an automated step of the pressure variation he wants and the rest is performed by the system. This would be similar to the curing of the lost circulation in section 6

Automation has come so far in other industries that one could argue that partly automated steps are not worthwhile and the aim should be set on full automation right away.

8 Conclusion

- A simple simulation model that shows changes in BHP as pump rates are changed was successfully developed. The model includes a loss function for simulating how pressures can be decreased to cure lost circulation scenarios.
- Level changes in the riser while the system is being ramped to its maximum level increase and level decrease rates were explored.
- The time it takes to reach maximum level increase and level decrease rate depends on the MP rate. When the MP rate is equal to the LP rate level decrease becomes impossible at a constant MP rate. Level increase is possible at no MP flow because of the inclusion of the FP.
- Simulation of a 5 bar pressure increase and a 5 bar pressure decrease by moving the mud level in the riser at a constant MP rate were performed. Time to reach 5 bar increase was accomplished in 88 seconds and the 5 bar decrease in 206 seconds.
- A 5 bar decrease by a temporary decreasing the MP rate was performed. Time to reach a 5 bar decrease was 8 seconds and the MP was brought back to its initial rate in 152 seconds while keeping the BHP close to constant.
- Decrease and increase in MP rates from 1800-1000l/min and 1000-1800l/min at close to constant BHP were simulated. The decrease was accomplished in 65 seconds and the increase in 108 seconds. Maximum variation in BHP during the decrease was 0,1 bar and 0,1 bar during the increase.
- If the annular pressure loss is approximately linear over a certain flow rate range changes in MP within that range can be made at close to constant BHP if the MP rate change mirror the level changing curve in the riser that is gotten when the level is change to compensate for the expected change in ECD.
- The level change rate in the riser limits how fast MP rate changes can be made at constant BHP.
- Lost circulation scenarios were simulated and it shown how they could be solved by decreasing BHP by a mud level decrease at a constant MP rate. Two scenarios were shown. One where a single 5 bar decrease cured the loss and a second one where an initial 5 bar decrease followed by a 1 bar decrease were used.
- Lost circulation scenario where a temporary decrease in MP rate was used achieved a quicker 5 bar pressure decrease than is possible by only decreasing the mud level. Less mud is lost but hole cleaning is compromised because of the lower annular flow rate.
- Pressure increase and decrease with the LRRS are slow compared to a choked MPD system. The LRRS system has an advantage of being able to provide trip- and riser margins which might prove difficult with a choked system on a floating rig.
- Results from the simulated scenarios, especially from maintaining a constant BHP while changing MP rates, indicate that the system could in theory be used for drilling through narrow pressure windows. The system performance in the real world will however depend highly on the use of a high quality hydraulic model and the availability and quality of real time pressure data. High performance pump controllers are also of importance.

9 References

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10 Abbreviations

ARL	Available Riser Length
BHP	Bottom Hole Pressure
BOP	Blow-Out Preventer
DGS	Dual Gradient System
DS	Drill String
ECD	Equivalent Circulating Density
FP	Fill Pump
LP	Lift Pump
LRRS	Low Riser Return System
MD	Measured Depth
MP	Mud Pump
MPD	Managed Pressure Drilling
OD	Outside Diameter
SSP	Sub Sea Pump
RKB	Rotary Kelly Bushing
SI	International System of Units
TVD	True Vertical Depth

11 Appendix

11.1 Mud properties

The density of the mud used for the simulations is 1320kg/m^3 . Table 11.1 shows viscometer readings for the mud. Figure 11.1 shows Shear stress as a function of shear rate. The data has been fitted with the Excel's built in regression tool to determine the power law exponent n and the consistency index K .

Table 11.1 Shows the viscometer data for the mud used for simulation

RPM	θ	$\dot{\gamma}$ s^{-1}	τ [lb/100 ft ²]	τ [Pa]
600	140	1022	68	32,56
300	98	511	49	23,46
200	78	340	41	19,63
100	54	170	30	14,36
6	16	10,2	10	4,79
3	13	5,1	8	3,83

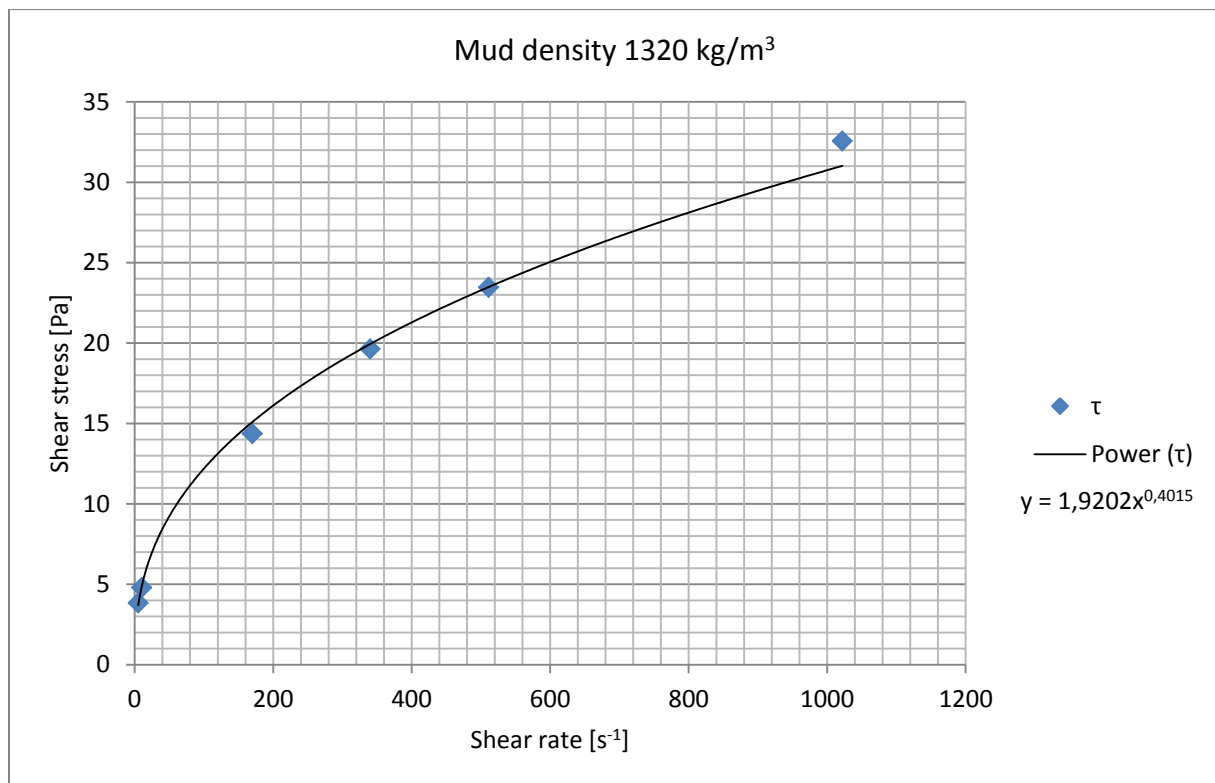


Figure 11.1 Shows shear stress as a function of shear rate for the mud used for simulation. $K=1,9202$ and $n = 0,4015$

11.2 Level change in riser and maximum level variation for 1800 l/min MP rate

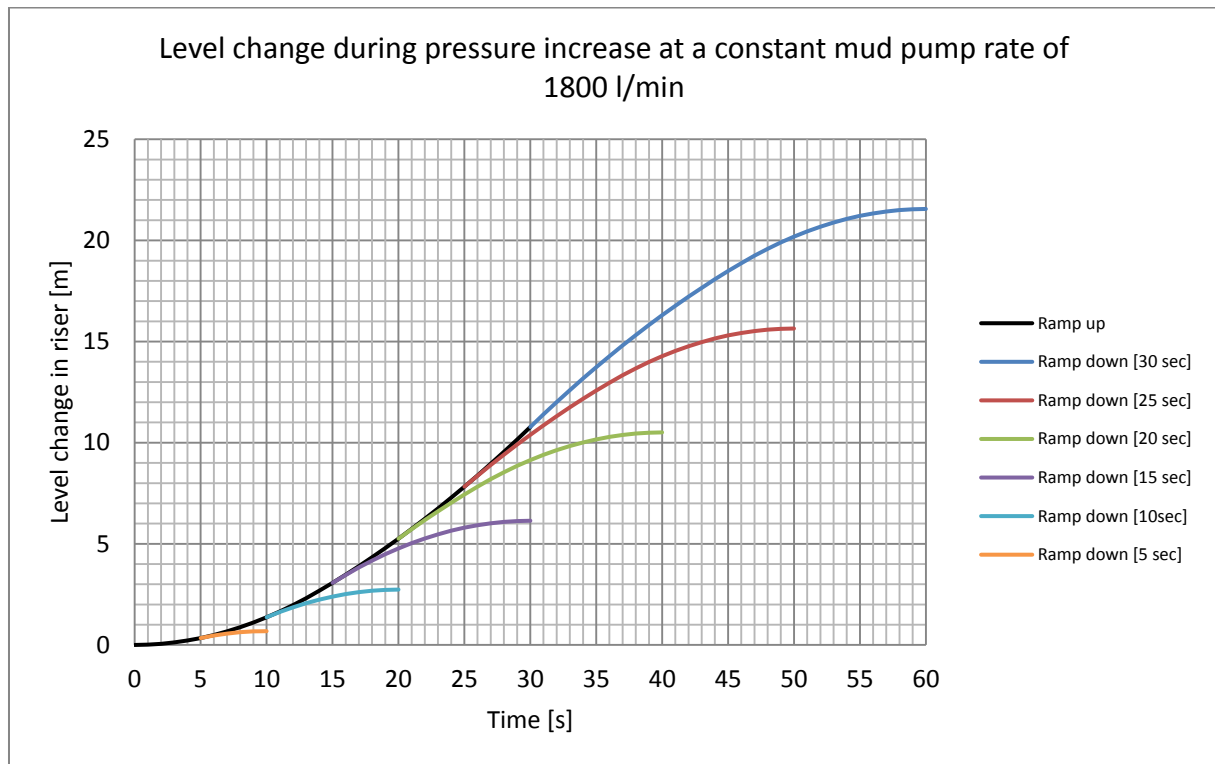


Figure 11.2 Shows level increase in the riser during pressure increase at a constant MP rate of 1800 l/min. All curves show level changes that are so small that the system is not able to reach maximum level increase rate. (The 60 second curve reaches it for at 30 seconds)

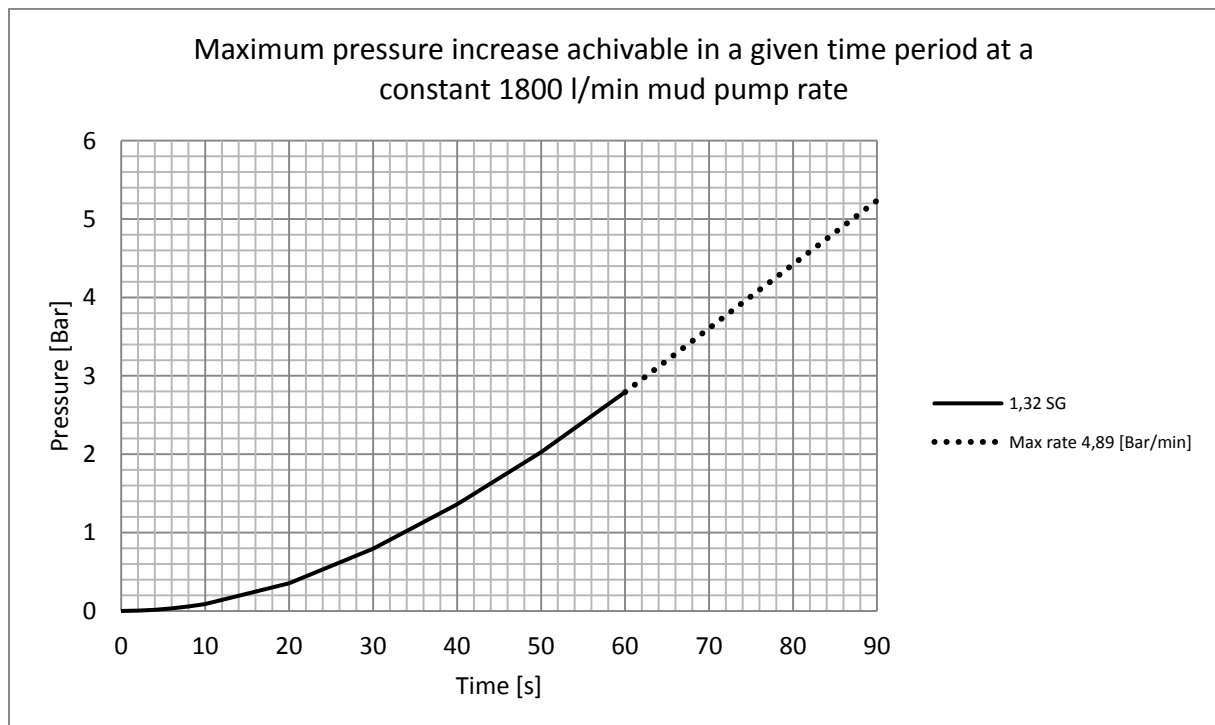


Figure 11.3 Shows the maximum pressure increase that can be achieved in a given time by increasing the mud level at a constant MP rate of 1800 l/min.

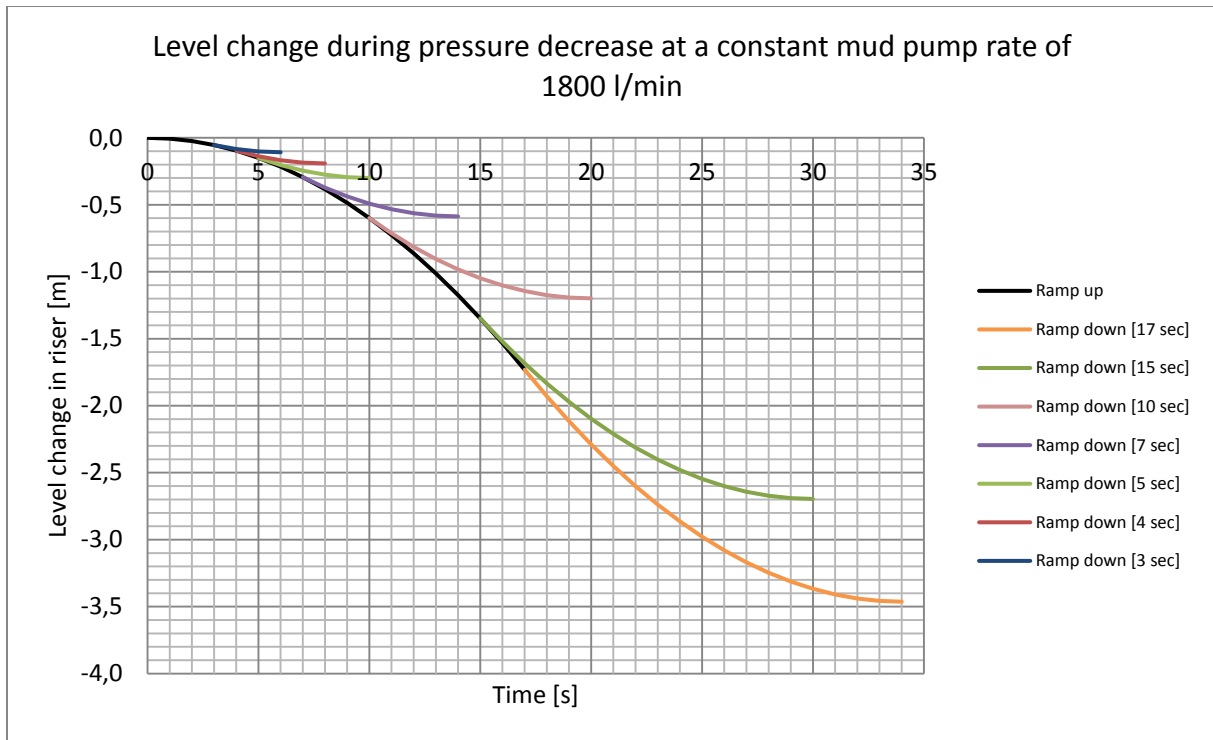


Figure 11.4 Shows level decrease in the riser during pressure decrease at a constant MP rate of 1800 l/min. All curves show level changes that are so small that the system is not able to reach maximum level decrease rate. (The 34 second curve reaches it at 17 seconds)

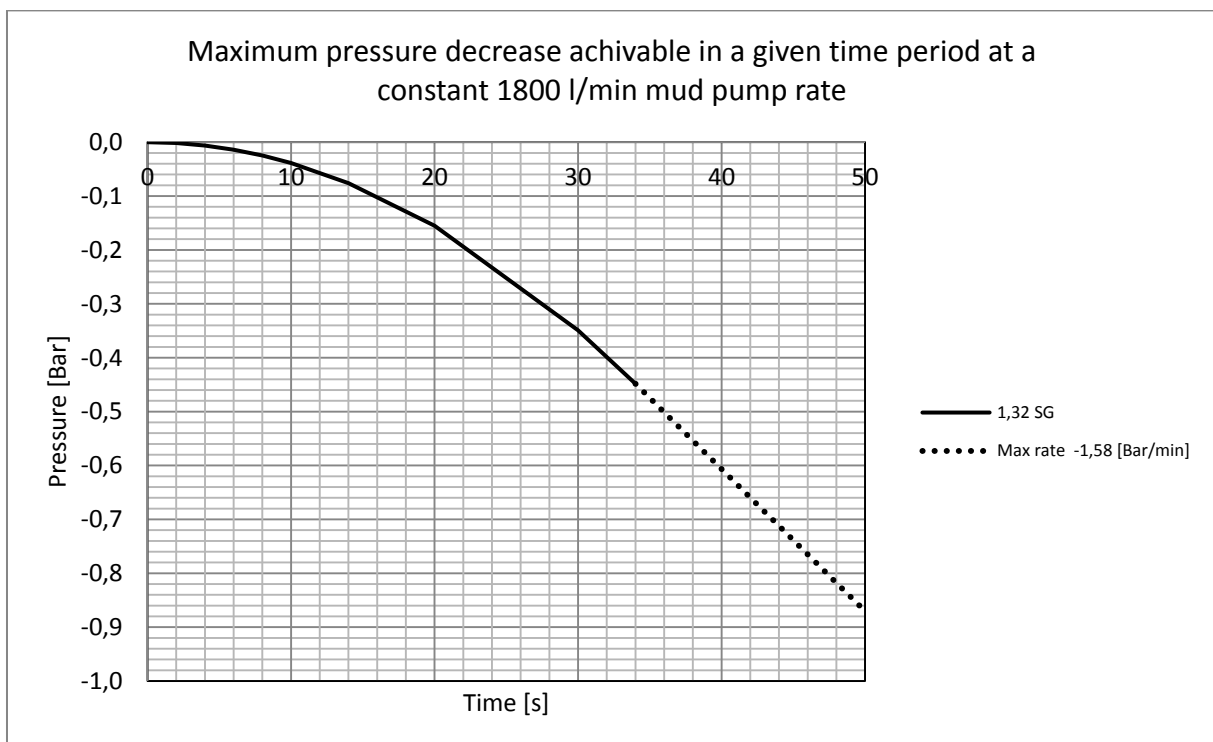


Figure 11.5 Shows the maximum pressure decrease that can be achieved in a given time by decreasing the mud level at a constant MP rate of 1800 l/min.

11.3 Excel input document

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Mud parameters						Well Parameters							
2	RPM	θ	γ	τ	τ		Casing size							
3			s^{-1}	[lb/100 ft ²]	[Pa]		MD Lower	MD Upper	TVD	Casing OD	Wall Thickness	Casing ID	Hole Diameter	Hole Diameter
4	600	140	1022	148,4	71,05		[m]	[m]	[m]	[in]	[in]	[m]	[in]	[m]
5	300	98	511	103,9	49,75		426	362	426	30		0,762	36	0,914
6	200	78	340	82,7	39,60		949	362	924	18,625	0,435	0,451	24	0,610
7	100	54	170	57,2	27,39		1449	362	1367	13,375	0,514	0,314	17,5	0,445
8	6	16	10,2	17	8,14		1719	1449	1526	10,75	0,545	0,245	12,25	0,311
9	3	13	5,1	13,8	6,61		1988	1719	1582	9,625	0,545	0,217	12,25	0,311
10						Bit Location	2263	1988	1582	7		0,178	8,5	0,216
11						Final MD	4864							
12		$\tau = K \cdot \dot{\gamma}^n$		n	0,4015									
13				K	1,9202									
14	Density of mud		hro_m	1320										
15							General	[m]	[in]					
16							The RKB	0						
17							Sea surface	24						
18							Sea floor	361,6		[m]	[in]			
19							Riser Parameters	Inner	Outside					
20							Diameter	0,4953	19,5	0,5334	21			
21							Initial Mud level	150						
22							Drill string							
23							Diameter			0,127	5			
24							Bottom hole assembly							
25							Diameter	0,1651	6,5					
26							Length	75						
27														
28														

Figure 11.6 Shows a screenshot of the Excel input document's main page.

	A	B	C	D
1	Time	Main Pump	Mud lift	Riser fill up
2	All	Flow rate q1	Flow rate q2	Flow rate q3
3	[s]	[m3/s]	[m3/s]	[m3/s]
4	0	0,0300	0,0300	0,0000
5	1	0,0300	0,0300	0,0000
6	2	0,0300	0,0300	0,0000
7	3	0,0300	0,0300	0,0000
8	4	0,0300	0,0300	0,0000
9	5	0,0300	0,0300	0,0000
10	6	0,0300	0,0300	0,0000
11	7	0,0300	0,0300	0,0000

Figure 11.7 Shows a screenshot of the Excel input document's pump rate page.

11.4 Matlab code

11.4.1 Main Script

```
% The main module of the program

% Clear all previous variables and command window
clc
clear all

% Write to the screen the simulator name and version
display('You are running DGDSIM verion May. 2012')

% Write the name of the excel file used for input and it's location
display('The excel file used for input is data.xls and is located in the
DGDSIM folder')
% Read in distance to Sea-Surface and Sea-floor [m MD] from RKB
Y_seasurface = xlsread('data','H16:H16');
Y_seafloor = xlsread('data','H17:H17');
% Read casing points (MD Lower, MD Upper) [m MD] from RKB
casing_points(:,1) = xlsread('data','G5:G10');
casing_points(:,2) = xlsread('data','H5:H10');
% Read the hole and casing diameters ID (D_casing, D_hole) [m]
Diameters(:,1) = xlsread('data','L5:L10');
Diameters(:,2) = xlsread('data','N5:N10');
% Possition of the bit MD and TVD [m] from RKB
Y_bit = xlsread('data','G10:G10');
Y_bit_TVD = xlsread('data','I10:I10');
% Possition of the mudline [m] from RKB
Y_mudline_initial = xlsread('data','H21:H21');
% Read in the power law coefficients (n,K)
n = xlsread('data','E11:E11');
K = xlsread('data','E12:E12');
% Tool string outer diameter [m]
d_ToolString = xlsread('data','H27:H27');
L_ToolString = xlsread('data','H28:H28');
% Drill pipe outer diameter [m]
d_DrillPipe = xlsread('data','J24:J24');
% Riser diameter [m]
d_riser = xlsread('data','H20:H20');
% Mud density [kg/m^3]
hro_mud = xlsread('data','E14:E14');
% Riser fluid density [kg/m^3]
hro_fluid = xlsread('data','E15:E15');

% Read the pump rates
% Mud Pump [m3/s]
q1_max = xlsread('data','O5:O5');
q1 = xlsread('data','Connection','B4:B3600');
% The annular flow equals the mud pump rate if tere is no loss [m3/s]
q_ann = q1;
% SubSea lift pump [m3/s]
q2_max = xlsread('data','O6:O6');
q2 = xlsread('data','Connection','C4:C3600');
% Fill pump / Booster pump [m3/s]
q3_max =xlsread('data','O7:O7');
q3 = xlsread('data','Connection','D4:D3600');

% Read the corrsponding time [s]
Time = xlsread('data','Connection','A4:A3600');
```

```

% ----- Start Simulation -----

for i = 1:1:length(q1)

    % Subtack lost circulation from the annular flow rate so effect is
    seen on ECD
    if 1<i
        q_ann(i) = q_ann(i) - q_loss(i-1);
    end

    % Pressure drop around the toolstring [Pa]
    % SingularityExpansion(q1,hro,d1,d2,d3)
    dP_tool_L(i) = AnnularPressureDrop(q_ann(i), n, K, hro_mud,
    Diameters(6,2), d_ToolString, L_ToolString);
    dP_tool_E(i) = SingularityExpTool(q_ann(i), hro_mud, d_DrillPipe,
    d_ToolString, Diameters(6,2));
    dP_tool(i) = dP_tool_L(i) + dP_tool_E(i);

    % Pressure drop in annulus 8 1/2" bare section [m], [Pa]
    L_section_1 = (Y_bit-casing_points(6,2))-L_ToolString;
    dP_ann_1(i) = AnnularPressureDrop(q_ann(i), n, K, hro_mud,
    Diameters(6,2), d_DrillPipe, L_section_1);

    % Pressure drop - sudden expansion going from 8 1/2" to 9 1/2" [Pa]
    % SingularityExpansion(q1,hro,d1,d2,d3)
    dP_Sing_exp_1(i) = SingularityExpansion(q_ann(i), hro_mud, d_DrillPipe,
    Diameters(6,2), Diameters(5,1));

    % Pressure drop in annulus 9 1/2 inch cased section [m], [Pa]
    L_section_2 = casing_points(5,1)-casing_points(5,2);
    dP_ann_2(i) = AnnularPressureDrop(q_ann(i), n, K, hro_mud,
    Diameters(5,1), d_DrillPipe, L_section_2);

    % Pressure drop - sudden expansion going from 9 1/2" to 10 3/4" [Pa]
    % SingularityExpansion(q1,hro,d1,d2,d3)
    dP_Sing_exp_2(i) = SingularityExpansion(q_ann(i), hro_mud, d_DrillPipe,
    Diameters(5,1), Diameters(4,1));

    % Pressure drop in annulus 10 3/4 inch cased section [m], [Pa]
    L_section_3 = casing_points(4,1)-casing_points(4,2);
    dP_ann_3(i) = AnnularPressureDrop(q_ann(i), n, K, hro_mud,
    Diameters(4,1), d_DrillPipe, L_section_3);

    % Pressure drop - sudden expansion going from 10 3/4" to 13 3/8" [Pa]
    % SingularityExpansion(q1,hro,d1,d2,d3)
    dP_Sing_exp_3(i) = SingularityExpansion(q_ann(i), hro_mud, d_DrillPipe,
    Diameters(4,1), Diameters(3,1));

    % Pressure drop in annulus 13 3/8 inch cased section [m], [Pa]
    L_section_4 = casing_points(3,1)-casing_points(3,2);
    dP_ann_4(i) = AnnularPressureDrop(q_ann(i), n, K, hro_mud,
    Diameters(4,1), d_DrillPipe, L_section_4);

    % Total pressure drop [Pa]
    dP_tot(i) = dP_tool(i) + dP_ann_1(i) + dP_ann_2(i) + dP_ann_3(i) +
    dP_ann_4(i) + dP_Sing_exp_1(i) + dP_Sing_exp_2(i) + dP_Sing_exp_3(i);

```

```

% Calculate the new mudlevel [m]
dY_mudline(i) = Level(q_ann(i), q3(i), q2(i), d_riser, d_DrillPipe);
Total_change = sum(dY_mudline);
Y_mudline(i) = Y_mudline_initial - Total_change;
Y_mudline_plot(i) = Total_change;

% Hydrostatic pressure [Pa]
P_hydro_mud(i) = hro_mud*9.81*(Y_bit_TVD - Y_mudline(i));

% Bottom hole pressure [Pa]
P_Bottom(i) = P_hydro_mud(i) + dP_tot(i);

% Run the Lost Circulation Function. It checks if BHP is high enough to
% cause lost circulation and calculates it if BHP is high enough.
q_loss(i) = Lost_Circulation(P_Bottom(i), Time(i));

end

% ----- Plots -----

% Total pressure drop
subplot(5,1,2), plot(Time, dP_tot/10^5)
xlabel('Time [s]')
ylabel('Dynamic Loss [Bar]')
% Bottom hole pressure
subplot(5,1,1), plot(Time, P_Bottom/10^5)
xlabel('Time [s]')
ylabel('BHP [Bar]')
% Change in mudline position in the riser
subplot(5,1,3), plot(Time, Y_mudline_plot)
xlabel('Time [s]')
ylabel('Level Change in Riser [m]')
% Pump rates
subplot(5,1,4), plot(Time, q1*60000, 'blue', Time, q2*60000, 'green', Time,
q3*60000, 'red')
legend('Mud Pump', 'Lift Pump', 'Fill Pump', 'Location', 'SouthEast')
xlabel('Time [s]')
ylabel('Flow rate [l/min]')
% Plot the loss rate
subplot(5,1,5), plot(Time, q_loss*60000)
xlabel('Time [s]')
ylabel('Loss rate [l/min]')

```

11.4.2 Function: Annular pressure drop

```
% The function calculates annular pressure drop and gives the result in
[Pa]
% Inputs:
% q1 - Annular flow rate [m^3/s]
% n - Power law exponent
% K - Consistency index
% hro - Mud density [kg/m^3]
% d0 - Smaller diameter [m]
% d1 - Bigger diameter [m]
% L - Length of section [m]

function [dP_ann] = AnnularPressureDrop(q1,n,K,hro,d0,d1,L)

V = q1/((pi/4)*(d0^2)-(d1^2));
% Reynolds number - Annular flow - for power law
d = d0-d1;
K_a = K*((2*n+1)/(3*n))^n;
Re_a = ((d^n)*(V^(2-n))*hro)/(K_a*12^(n-1));
N_re = Re_a;

% Pressure drop - Annular flow - Laminar
dP_a_lam = 4*K * ((12*V*(2*n+1))/((d0-d1)*3*n))^n * (L/(d0-d1));

% Pressure drop turbulent flow
a = (log10(n)+3.93)/50;
b = (1.75-log10(n))/7;
% Pressure drop - Annular flow - Turbulent
dP_a_turb = a*(N_re^-b)*((4*L)/((d0-d1)*2))*hro*V^2;

if dP_a_turb < dP_a_lam
dP_ann = dP_a_lam;
else
dP_ann = dP_a_turb;
end
```

11.4.3 Function: Singularity loss, sudden expansions

```
function [dP_SingularityExpansion] = SingularityExpansion(q1,hro,d1,d2,d3)

% Singularity losses caused by sudden area enlargements - Such as changing
% casing diameters
% d1-Drillstring, d2-smaller, d3-larger

% Calculate the two cross sectional areas [m^2]
A1 = (pi/4)*(d3^2 - d1^2);
A2 = (pi/4)*(d2^2 - d1^2);
% Calculate the loss coefficient
K_L_exp = (1-A1/A2)^2;
% Average flow velocity [m/s]
V = q1/A1;
% The pressure drop [Pa]
dP_exp = K_L_exp*(0.5*hro*V^2);
dP_SingularityExpansion = dP_exp;
```

11.4.4 Function: Mud level

```
% This function calculates the level of the mudline in the riser
function [dY_riser] = Level(q_mud, q_fill, q_lift, d_riser, d_pipe)

% The flow rate filling up the riser [l/s]
q_riser = q_mud + q_fill - q_lift;

% calculate the volume per unit length in the riser and drill pipe [m^2]
A_riser = (d_riser^2)*(pi/4);
A_pipe = (d_pipe^2)*(pi/4);

% Change in mud line level [m/s] but [m] if the resolution of time is 1 sec
dY_riser = q_riser/(A_riser-A_pipe);
```

11.4.5 Function: Lost circulation

```
% The Function calculates lost circulation if BHP is higher than the
defined fracture pressure [m^3/s]
% Input is bottom hole pressure BHP [Pa]

function [Q_loss] = Lost_Circulation(BHP, t)

% Change bottom hole pressure to [Bar]
% p_bh = 198 Bar @ 1800 l/min
P_bhp = BHP/(10^5);

% Introduce loss after 20 sec
if 20 < t
    % Formation Fracture Pressure [Bar]
    % For 5 bar step P_frac = 194 Bar and 192 Bar for the 5+1 Bar step
    P_frac = 194;
else
    P_frac = 200;
end

% Loss constant [l/min.Bar]
PI = 50;

% Check if bottom hole pressure is bigger than formatoin fracture pressure
if P_frac < P_bhp
    % Calculate lost cication [l/min]
    Q_loss = PI*(P_bhp - P_frac);
else
    % No fluid loss
    Q_loss = 0;
end

% Convert from [l/min] to [m^3/s]
Q_loss = Q_loss/60000;
```