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MASTER'S THESIS

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Title of Master's Thesis:

Visualization and verification of how static and dynamic drilling parameters contribute to the bottom hole pressure while drilling a well.

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Summary

Even with all the talk about finding an alternative fuel, the demand for fossil fuel will not decrease for years to come. As the major oilfields are depleting and aging, this demand forces wells to be drilled in more hostile environment both with regards to location, where wells have to be drilled at deeper water depths, and the environment experienced in the reservoirs that allow for lesser margin of error. Such advanced and difficult wells are forcing the use of more advanced technology, as automated drilling and Managed Pressure Drilling (MPD). Common to both technologies are the use of hydraulic models or down hole pressure estimators to calculate down hole conditions, such as pressure, temperature, fluid density, etc. The calculations performed by these models does not always mirror the down hole measurements, and as a compensating factor, the hydraulic models is adjusted by a not fully understood factor to correlate the model to “reality”. This factor is not always related to a specific source. The aim of this thesis is therefore to find a way of splitting the adjustment factor into a stand alone factor for each of the contributing frictional terms, thereby provide more accurate input data for the hydraulic model that might reduce the need for such a factor.

Real time data from a well drilled in MPD mode on the Gullfaks field in 2009 was used for determining how much each of the drilling parameters contributed to the bottom hole pressure change experienced during start-up and break-up procedures. As the absolute pressure change most likely will be dependent on depth, the contributions to the bottom hole pressure change caused by the different drilling parameters was found as percentage of the total bottom hole pressure change for each run. This provided a basis for finding a mean value with a corresponding standard deviation of how much each of the drilling parameters contributed to the pressure build-up and decrease for the start-up and break-up cases respectively.

After these mean values were established, simulations performed in the simulating software Drillbench © was used to help verify which surrounding factors that could govern the distribution of how much each drilling parameter contributed to the bottom hole pressure change.

It was found that it was the magnitude of flow rate and RPM that most likely were the governing factors, and that the depth and whether there was cuttings present or not did not seem to affect the distribution of which drilling parameters that contributed the most.

Acknowledgement

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At last I would like to thank Professor Rune Wiggo Time from the University of Stavanger for providing me with valuable input on which methods that could be used to resolve the problem in hand.

Stavanger, 14th of June 2010

Gisle Vaaland

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1 Introduction

The primary reason for choosing to drill a well in MPD mode is because of a small operating window, commonly encountered either in depleted or HPHT reservoirs. A small operating window refers to narrow pressure margins between the pore and fracture pressure limits, which implies that there are a small margin of error. MPD operations therefore require a high degree of knowledge about the environment in the well, and how the controllable drilling parameters affect the BHP. Examples of such parameters are mud properties, flow rate, RPM, ROP etc. The effects that these parameters have on the BHP are not always straight forward, especially when there are interactions between them. This cause an uncertainty in the BHP calculations carried out in beforehand, which is transferred to the hydraulic model that is used to control the surface backpressure. Because of the small margin of error within MPD operations, these uncertainties should be reduced to a minimum, both for safety reasons, and for being able to drill even narrower operating windows in the future.

This first chapter is used to clarify the objectives of the thesis, and outline the method for resolving them.

The second chapter is used to give an introduction to why there is use for advanced drilling methods, such as MPD. It also gives a description of the basic concepts and variations of MPD, and the problems that it seeks to negate.

In the third chapter a short summary of the equipment common to MPD operations are outlined to illustrate the complexity of this drilling method compared to conventional drilling.

The fourth chapter is used for explaining the main factors that affect the bottom hole pressure during drilling. The fifth and sixth chapter consists of theory regarding probability relevant for this thesis and a description of the simulator tool used, respectively.

Finally, in chapter seven the actual case study with results and discussion are presented, and the eight chapter contain the conclusions drawn from the study.

1.1 Objectives

Due to little margin of error, there has been established a dedicated start up and break up procedure for the wells drilled in MPD mode that seeks to minimize the pressure fluctuations encountered when breaking circulation or overcoming the fluids yield point. As the mud telemetry is offline during these time spans, the hydraulic model does not have the opportunity to calibrate itself against real time data, which induces uncertainty to the calculation of the BHP.

The objective of this thesis is therefore to relate the pressure build up and pressure decrease for the start up and break up procedure, respectively, to the changes in drilling parameters for a well already drilled, to see if there is a trend to how much each drilling parameter influence the BHP change. With drilling parameters, controllable drilling parameters, such as rotation of the drillstring and flow rate is meant. The presence of cuttings has also been investigated. If there is found a correlation to the magnitude of the BHP change and each drilling parameter, a suggestion for how to establish this factor for new wells to be drilled should be outlined as the importance of an automated method for obtaining these factors is crucial for the coming MPD operation, since available drilling windows constantly decrease. The method for obtaining these factors will be tested on a real time model prior to an MPD operation this autumn.

To resolve this task, the BHP pressure measurements obtained from the well already drilled, which for confidentiality reasons is referred to as Well A for the remainder of the thesis, was plotted along with the changes in the drilling parameters. This enabled the possibility of relating the pressure changes seen in the BHP to the changes in the drilling parameters. Since the absolute value of the pressure change seen in the well due to changes in drilling parameters is expected to increase with depth, the changes in pressure for the different runs were given as percentage changes of the total pressure build up, or decrease. This enabled the possibility of comparing runs taken at different depths, providing a mean value for the effect to the total pressure change caused by each drilling parameter.

2 MPD

In the following an introduction to the basic concepts of MPD is given along with the different variations of MPD, and the reason for why MPD is considered to be the second most influential drilling technique for the coming years, only surpassed by directional drilling [1].

2.1 Conventional Drilling

Sources for this chapter is [2] unless stated otherwise.

In conventional drilling the BHP is defined, when circulating, as the sum of hydrostatic head provided by the mud weight (P_{MW}) and the annular friction pressure (P_{AF}) that depends on the pump rate, mud properties, wellbore geometry etc.:

$$BHP_{DYN} = P_{MW} + P_{AF} \qquad \text{(Eq. 1)}$$

During connections and other operations, were there is no circulation present, the P_{AF} can be assumed to be zero, leaving the hydrostatic head of the drilling mud to be the only parameter that influence the BHP:

$$BHP_{STAT} = P_{MW} \qquad \text{(Eq. 2)}$$

From equation 1 and 2, it can be seen that to alter the BHP, when drilling conventionally, one can either change the mud weight, or the pump rate. This leads to several disadvantages. One being that it takes time to change the drilling mud to achieve a different hydrostatic head. Another being that during conventional drilling one will always experience pressure changes in the wellbore during operations whenever breaking circulation, as delta P_{AF} is not equal to 0. This might lead to cyclic loading of the wellbore, which might cause fatigue related problems.

2.2 Underbalanced Drilling

Part of the definition for UnderBalanced Drilling (UBD) provided by The International Association of Drilling Contractors (IADC) Underbalanced Operations (UBO) states [3]: "Drilling with the hydrostatic head of the drilling fluid intentionally designed to be lower than the pressure of formations being drilled…". This part of the definition shows that the objective of UBD operations is to intentionally keep the BHP lower than the pore pressure of the formation. The main reasons for this is to protect, characterize and preserve the reservoir while drilling, which might lead to a higher productivity of the reservoir. There are also evidences suggesting that UBO minimizes pressure-related drilling problems, such as differential sticking and fluid losses; which can result in increased Rate Of Penetration (ROP). However, as the hydrostatic under-balance will encourage influx of formation fluid into the wellbore as the well is being drilled, the well has to be designed to handle the produced fluid as this reaches the surface. In addition to adding to the complexity of the system, this provides the need for flaring produced hydrocarbons, which is one of the main reasons why the offshore industry have been reluctant to implement UBD techniques. It is also a space demanding system, and with space being a limiting factor on off-shore installations, implementation of such a system could prove difficult. Drilling underbalanced is also prohibited in some jurisdictions due to the risk of uncontrolled formation fluid influx, the Norwegian continental shelf being one of those. [4]

2.3 Managed Pressure Drilling

The source for this chapter is [1] unless stated otherwise.

Managed Pressure Drilling (MPD) is a sub-technology of UBO which offers a method for drilling overbalanced, or even balanced, using underbalanced MW.

In the mid 1960 the Rotating Control Device (RCD) was introduced in the USA. This, together with a dedicated drilling choke and a drillstring non-return valve, enabled the practice of drilling with compressible fluids as gas, air, mist and foam. This is now referred to as Performance Drilling, and is considered the forefather for both UBD and MPD. After the expansion of UBD with mud and nitrated fluids in the 1990s, the use of RCD evolved and the industry learned to use the RCD to more precisely manipulate the annular hydraulic pressure profile when drilling with a conventional drilling system. This led to the ability of drilling with an Equivalent Circulating Density (ECD) close to, or even below the pore pressure without allowing the influx of formation fluid into the wellbore. There were several different approaches for achieving this kind of controlled drilling, and in 2003 the assortment of techniques were recognized as a technology within it self as MPD.

Although similar to UBD, MPD differs in the way that it does not allow influx of formation fluid into the wellbore by staying just above the pore pressure, as seen in Figure 1.

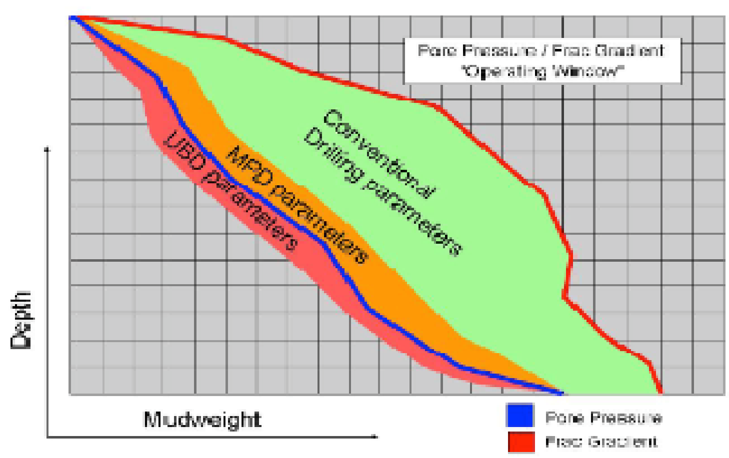

Figure 1 Pressure gradients for UBD, MPD and conventional drilling [5]

The IADC UBO and MPD Committee define MPD as [3]:

"MPD is an adaptive drilling process used to precisely control the annular pressure profile throughout the wellbore. The objectives are to ascertain the downhole pressure environment limits and to manage the annular hydraulic pressure profile accordingly. It is the intention of MPD to avoid continuous influx of formation fluids to the surface. Any influx incidental to the operation will be safely contained using an appropriate process.

Notes added to this definition are:

• MPD process employs a collection of tools and techniques which may mitigate the risks and costs associated with drilling wells that have narrow downhole environmental limits, by proactively managing the annular hydraulic pressure profile.

• MPD may include control of back pressure, fluid density, fluid rheology, annular fluid level, circulating friction, hole geometry or combinations thereof.

• MPD may allow faster corrective action to deal with observed pressure variations. The ability to dynamically control annular pressures facilitates drilling of what might otherwise be economically unattainable prospects."

MPD can be divided into two main categories [6]:

2.3.1 Reactive MPD

Meaning that MPD is used as a contingency if something unexpected, as surprise pressure regimes should occur. When drilling with reactive MPD, one has all the equipment to drill in MPD mode installed, but it is only utilized after encountering a problem. The well is therefore planned conventionally with regards to well construction and fluid programs, with the possibility of practicing MPD if something were to happen. This category of MPD is related to normal operating windows, meaning that there is a large enough margin between the pore pressure and the fracture pressure to drill the well using conventional methods.

2.3.2 Proactive MPD

Meaning that the operation is planned to take full advantage of the ability to more precisely manage the annular pressure profile, with designing the fluid, casing and open hole drilling plan to MPD mode. The proactive MPD method is often referred to as "walk the line" category of MPD technology, and is the MPD method that has been used for most offshore applications. This category of MPD is related to drilling narrow operating windows, where the pressure margins between pore and frac gradients are to small to be drilled using conventional methods.

While reactive MPD has been practiced on problem wells for several years, it is only during the last couple of years that proactive MPD have been taken into use.

2.3.3 Variations of MPD

[7], [8] and [9] are the sources for the following sub-chapters unless stated otherwise.

Under the MPD technology there are four main subcategories taking different approaches to walking the line. These categories are sometimes, but not often, used on the same problem well to ensure that the well can be drilled safely. This combining of MPD variations is expected to become more frequent in the future, as prospects are becoming more difficult to drill. An outline of the four variations follows.

2.3.3.1 Returns Flow Control

This method is implemented for HSE reasons only, and is achieved by adding a RCD to the conventional drilling operation. The RCD allows for diverting the return mud into a closed loop system, instead of the conventional open to atmosphere system. The RCD prevents toxic vapors to enter the drill floor. Another problem with the open to atmosphere system is that explosive vapors can escape from the cuttings in the return mud, to trigger atmospheric monitors and/or automatically shut down production elsewhere on the platform.

2.3.3.2 Dual Gradient Drilling

The intent of Dual Gradient Drilling is often not to manipulate the pressure at the bottom of the well, but to avoid a gross overbalance that might cause a danger of fracturing the formation further up in the well, usually under the previous casing shoe, see Figure 2.

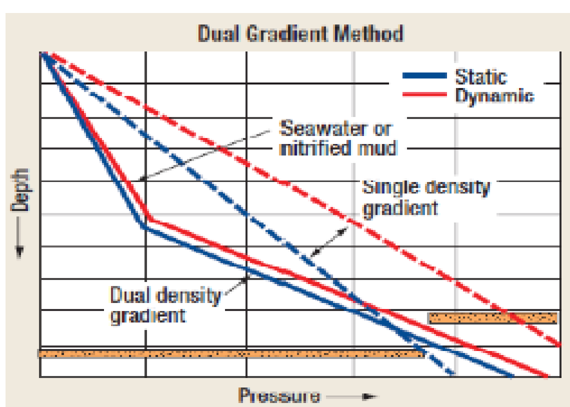

Figure 2 The dual gradient variation of MPD [10]

There are several ways of achieving Dual Gradient Drilling. For example, a parasite string attached to either the casing or the raiser can be inserted to a predetermined depth. A lighter fluid is then injected through this string into the annulus, and this lowers the pressure gradient from that point to the surface.

Another commonly used method is the use of subsea pumps to artificially lift returns from the seabed to surface through separate, dedicated return lines. The drilling riser is in this case filled with seawater to prevent it from collapsing. This tricks the well into thinking that the riser is shorter than it actually is, resulting in two pressure gradients.

2.3.3.3 Pressurized MudCap Drilling

The purpose of Pressurized MudCap Drilling is to allow drilling in areas where one is experiencing severe, or near total lost circulation. By applying backpressure, and pumping heavy mud down the backside of the RCD, one can fill up the annulus down to a predetermined depth. This will create a pressurized mudcap, see the yellow mud column in Figure 3, that will work as a seal in the annulus, forcing the drilling fluid out into the fractured formation. By using a lighter, less expensive fluid, like seawater, as drilling fluid, one can both achieve a higher ROP, and minimize the cost and the environmental damage. [11], [6]

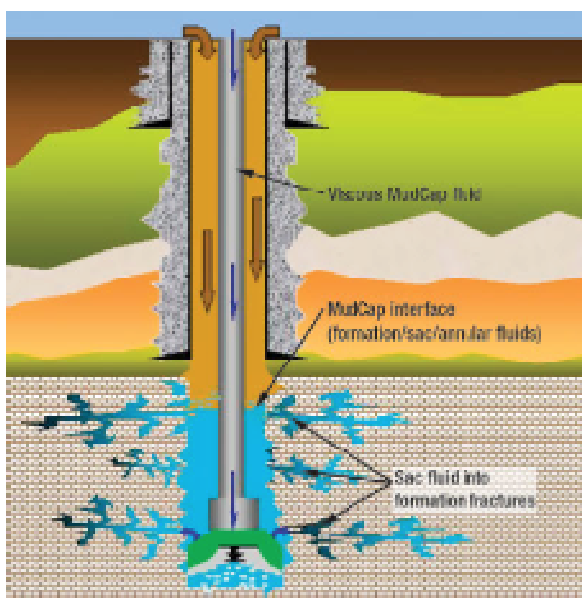

Figure 3 Pressurized Mudcap Drilling [11]

2.3.3.4 Constant BHP

Constant BHP (CBHP) operations are allowing prospects with narrow, or even unknown margins between the pore pressure and frac gradient to be drilled. This MPD method takes advantage of the benefit that the closed drilling mud system provides, by installing a choke valve on the return mud that can be used for creating surface backpressure, P_{BP}. This provides the conventional drilling operations with an extra variable to control the BHP as can be seen from Equation 3 and 4:

$$BHP_{DYN} = P_{MW} + P_{AF} + P_{BP} \qquad \text{(Eq. 3)}$$

$$BHP_{STAT} = P_{MW} + P_{BP} \qquad \text{(Eq. 4)}$$

By being able to adjust the backpressure accurately one can achieve a near constant ECD, regardless to whether there is circulation or not. The ability to adjust the backpressure also offers the advantage of not changing the drilling fluid in order to ensure overbalance in the wellbore. This allows for a lighter than conventional fluid program, where the drilling fluid actually can be hydrostatically underbalanced, which allows more flexibility to surprise pressure regimes during drilling. [11]

As it is this variation of MPD that have been used to drill the well that is to be investigated in this thesis, when referring to MPD, it is CBHP MPD that is meant, unless specified otherwise.

2.4 Reasons for MPD

Sources for this chapter is [12] and [13] unless stated otherwise.

MPD is considered by many experts in the industry to be the second most influential technologies, only surpassed by directional and horizontal drilling, over the next twenty years. The reason for this is the many opportunities that MPD provides. As of today, approximately half of the offshore reservoir prospects are unreachable with conventional drilling methods, due to either the economic or the operational aspect. By applying MPD technology, several of these prospects can be drilled both with regards to the economical, as MPD reduces Non Productive Time (NPT), and with regards to the operational, as MPD provides a much better and more flexible control of the pressure profile in the wellbore.

2.4.1 Narrow operation windows

As the easy reachable oil is more or less gone, the drilling environment is becoming more hostile, meaning that one have to drill in either deep water conditions, through HPHT reservoirs or re-drilling in aging, depleted fields. These hostile environments often make it impossible to reach the reservoir using conventional drilling methods, and various methods of innovative drilling methods, for example MPD, have to be implemented in order to drill the prospect.

For the well to be investigated in this thesis it was over-pressurized formation due to water injection that was the reason why it could not be drilled using conventional methods. The well is a sidetrack from a well that has been produced, with the aid of water injection, for quite some time. In Figure 4 the spike in pore pressure clearly illustrates how the operating window has narrowed from when the main well was drilled.

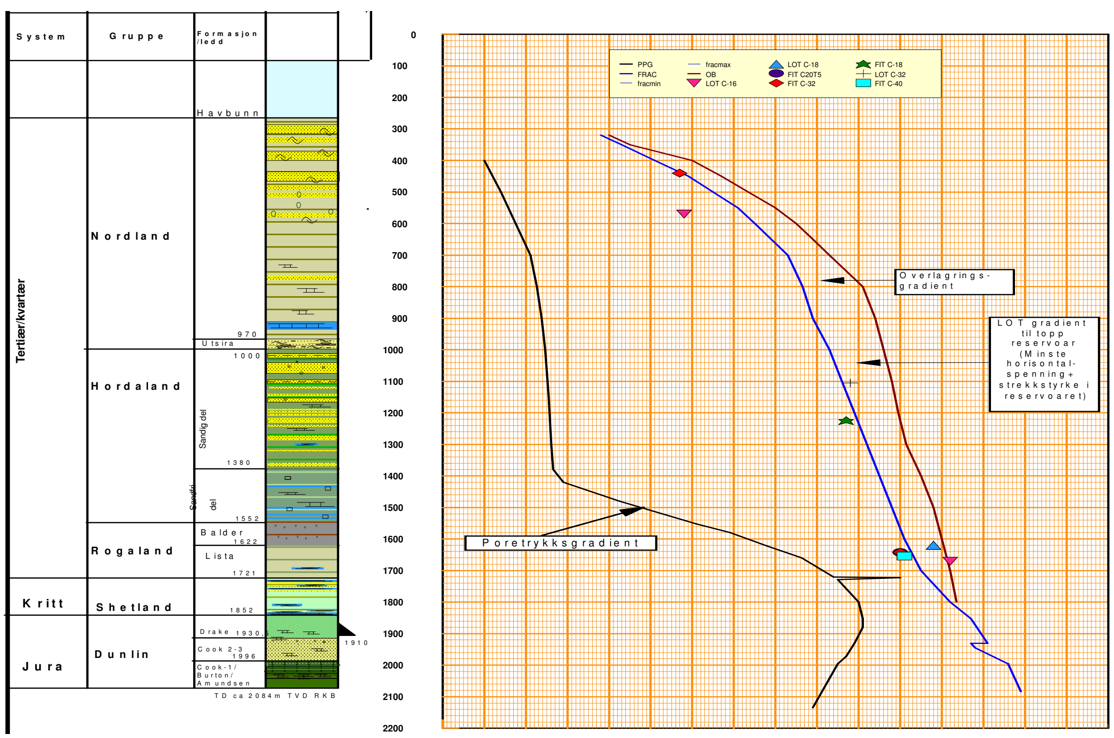

Figure 4 pressure distribution map of the top of the Shetland Group [40]

The problem with drilling conventionally through such narrow pressure margins between pore and frac pressure is the pressure changes that occur when going from dynamic to static conditions and visa versa. This will often lead to a kick-loss scenario, meaning that any stopping or starting of the pumps may cause the annulus pressure to exceed the pressure boundaries. When trying to drill, one will therefore experience lost circulation due to fracturing the formation, and encounter a kick due to influx of formation fluids when stopping for connections or tripping. This sort of problem can, when not having the ability to implement MPD, force the well to be Plugged and Abandoned.

2.4.2 NPT

The rental cost of the drilling rig is by far the most important cost contributor when drilling an offshore well. Being able to reduce NPT can therefore be the difference between a successful and an unsuccessful drilling operation. Figure 5 shows an overview of factors contributing to NPT taken from the Gulf of Mexico, and which factors that can be reduced, or even eliminated by the implementation of MPD.

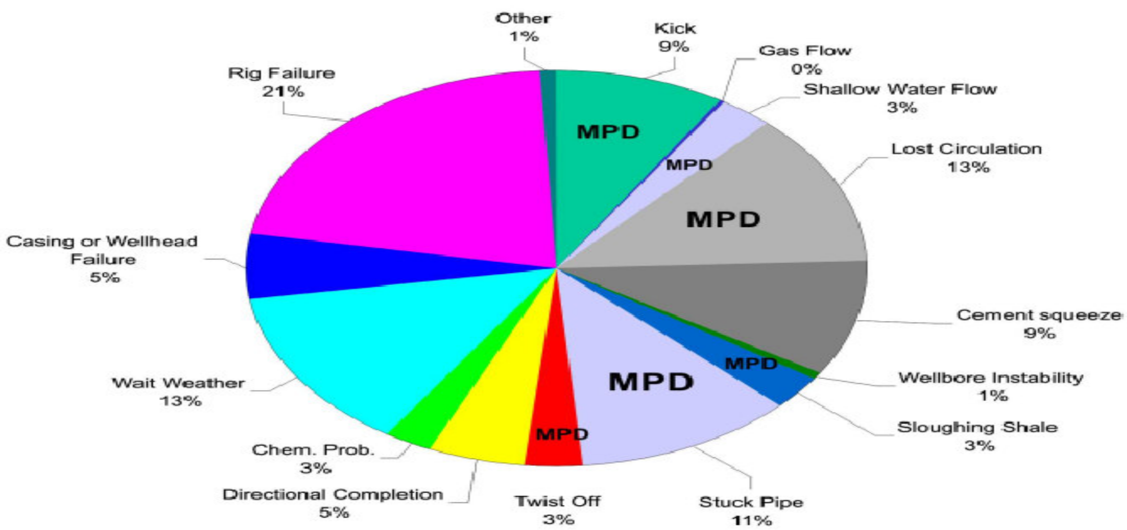

Figure 5 Problem incidents Gulf of Mexico shelf gas wells [**14**]

2.4.2.1 Kick and lost circulation

From Figure 5 it can bee seen that kick and lost circulation is responsible for respectively nine and thirteen per cent of the NPT. As explained earlier, these categories most often come as a consequence of the BHP either falling below the collapse pressure, or exceeding the fracture pressure. By having the ability to alter the BHP, as MPD provides, these problems would clearly be minimized, having the potential of improving NPT by 22 per cent alone.

2.4.2.2 Stuck pipe

Another huge area of improvement that MPD addresses is the NPT caused by stuck pipe situations. The main reason for experience stuck pipe is high differential pressure between the wellbore and the formation. A high overbalance, combined with a long open hole section increases the potential of experiencing stuck pipe. A solution to minimize the potential of stuck pipe when drilling conventionally is to set casing prematurely, which might lead to other problems later in the drilling operation. The possible benefits that are to be gained from MPD is therefore not only the eleven percent improvement in NPT caused by stuck pipe, but also the ability to drill longer open hole sections, which will reduce, among others, the time spent on setting casings.

2.4.2.3 Other improvements

From the figure one can also see that MPD addresses nearly half of the problems causing NPT, which is a quite significant improvement. Among these improvements are mud weighting, increased ROP, sloughing shale and multiple casings in trouble zones.

The mud weighting is minimized due to the fact that MPD utilizes surface back-pressure, and thereby allows for altering ECD without weighing up new mud. The ability of altering the ECD without replacing the mud is also beneficial during drilling, as it allows for longer sections to be drilled, and thereby reduces the need for multiple casings, especially in trouble zones.

By allowing an ECD that is closer to the pore pressure gradient, compared to conventional drilling, the over pressure is reduced, leading to a reduction of the differential pressure over the rock being drilled. This is shown to have a beneficial effect in breaking off and transporting a chip, resulting in a higher ROP. [15]

When experiencing a collapse pressure curve that is equal to, or greater than the pore pressure curve, formation can slough off and create stuck pipe situations. This is especially experienced when breaking circulation, for instance whenever making a connection, leading to cyclic loading of the wellbore. This cyclic loading is minimized when utilizing a proper program for the surface back-pressure applied during break-up and start-up procedures.

3 Equipment common to MPD operations

Sources for this chapter is [16] and [17].

Figure 7 shows a typical outlay of a closed circulation system used for MPD operations. The outlay is more complex, and contains more equipment than what is common to an ordinary open to atmosphere operation, which can be seen in Figure 6. This chapter will present the most important differences between the two outlays.

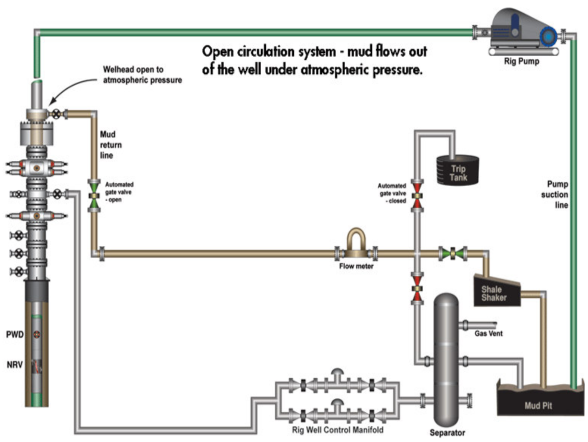

Figure 6 **Open circulation system** [17]

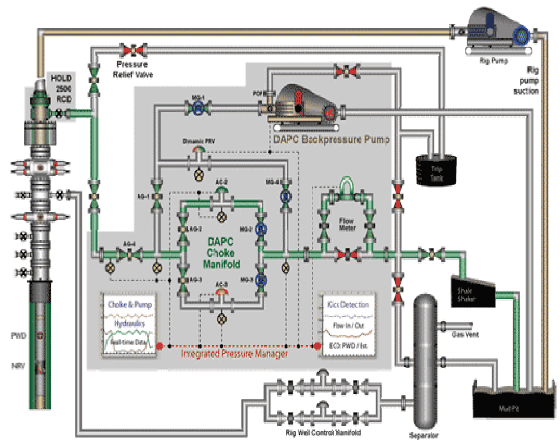

Figure 7 **Closed circulation system** [17]

3.1 Rotating Controller Device

All MPD operations rely on a Rotating Controller Device (RCD) as the primary pressure seal. The RCD ensures that the annulus is securely packed off from the surface both during static and drilling conditions.

As mentioned earlier the RCD is actually not a new device that has arisen together with the relative young MPD technology. It has been around, not changing too much, since the 1930s. The biggest difference lie in its application, where the old RCDs was used as a device for diverting air and gas during conventional drilling operations, the RCDs used in todays MPD operations are designed to be a pressure barrier with the capacity of holding 5000 psi while static and 2500 psi while rotating.

The modern day RCD comes in two variations, passive and active.

3.1.1 Passive system

The passive RCD system is the most common. It seals off the annulus using a seal element called “stripper rubber” which has a diameter ½ - 7/8 in. undersize to the drill pipe that provides a tight seal. When exposed to wellbore conditions the annular pressure further tighten the seal.

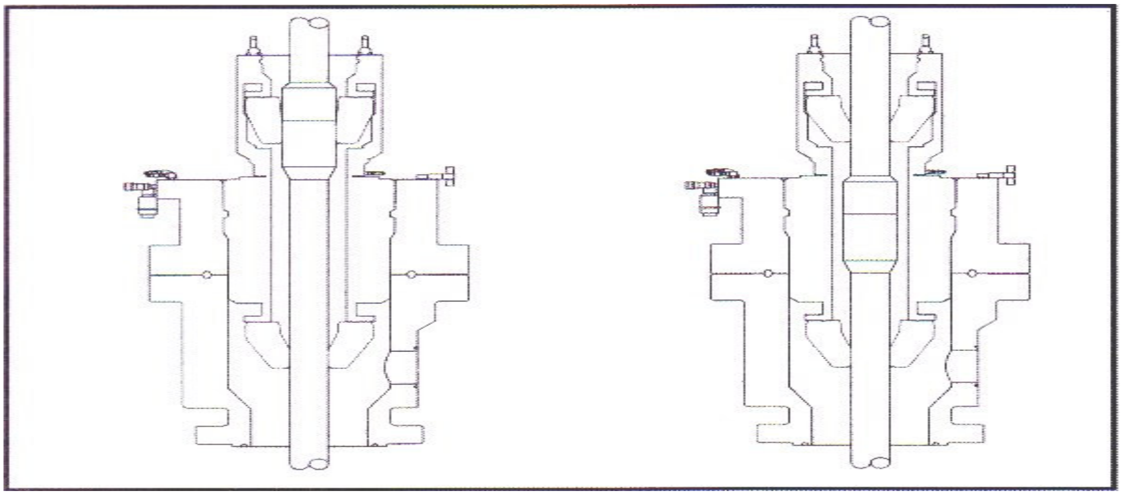

Figure 8 **Dual stripper units in a high-pressure RCD (courtesy of Weatherford International Ltd.)** [16]

Figure 8 shows the lay out for a dual seal system where the upper seal work as a contingency should the lower seal experience a leak. This dual system also has the advantage that when a connection is made, it can pass first through the upper, then the lower seal, always leaving one seal pressurized against the drillstring, minimizing the potential of experiencing a leak. The passive RCD system also comes as a single system. [18]

3.1.2 Active system

The active RCD system uses a hydrostatic system to seal the rubber against the drillpipe. This system is highly automated, and no action, besides closing and opening the packer is required by the operator.

3.2 Choke manifold

The choke manifold is, next to the RCD, the primary mean for controlling the BHP. By altering the choke position, one manipulates the back-pressure applied from surface, and is thereby able to keep the BHP within the limits decided by the operating margin. In the centre of Figure 7 there is an illustration of a typical choke manifold for off-shore MPD operations. It is made up of two redundant main chokes (AC-2 and AC-3 in the figure), and one auxiliary choke (AC-1). The two main chokes operate independent of one another, and normally only one of them are utilized at a time, leaving the other as a safety precaution in case the first one malfunctions. However, should there be use for a higher flow rate, both choke lines can be used in parallel. Before the choke system was automated, the auxiliary choke was used as a mean for avoiding pressure spikes that could occur during connections, when the pumps where either shut down, or put back on. These pressure spikes usually occurred because of a too fast ramp up/down of the flow rate. As the system have become more and more automatic, it has been possible to implement a step-wise ramping schedule, as is illustrated in Figure 9 which is an example of a ramp down of the flow rate.

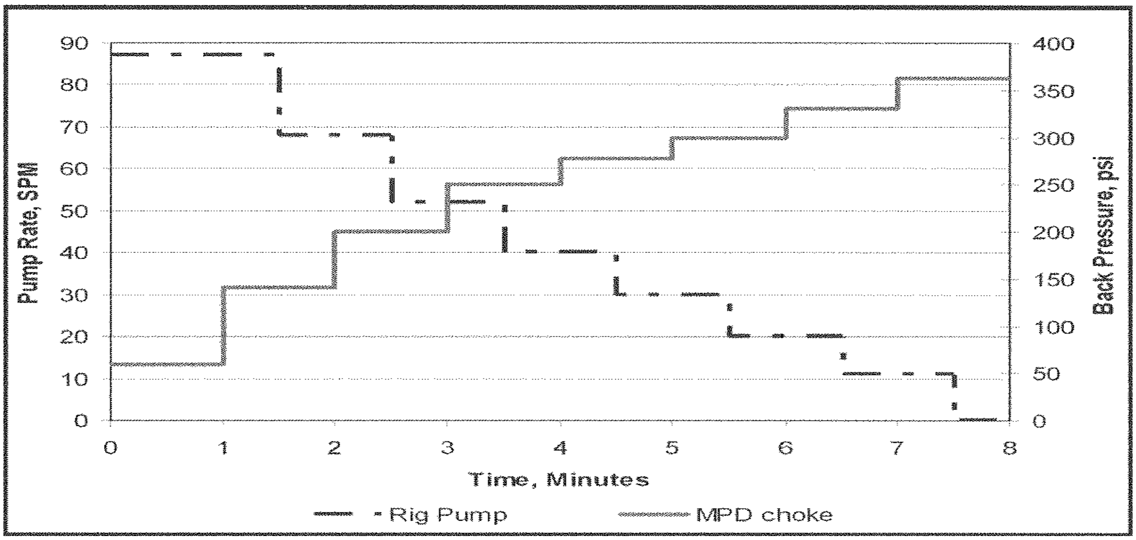

Figure 9 **Pump rate and back-pressure schedule to maintain the BHP. (Courtesy of Medley et al., 2008) [19]**

Here one can see that the choke opening is first reduced, to increase the back-pressure. When the desired back-pressure is achieved, the flow rate is ramped down one step. This process is repeated until the pumps are completely turned off. This automation means that the auxiliary choke no longer is needed to prevent the pressure spikes, and is now used either as a primary or back-up Pressure Relive Valve.

3.3 Back-Pressure Pump

When the flow rate is ramped down, the choke opening has to reduce to preserve the back-pressure, as could be seen in Figure 9. As the flow rate is shut down, the choke has to close completely to trap the remaining pressure. However the choke manifold has one big flaw. As the flow through the choke reduces, the choke becomes less and less reactive. During a controlled ramp down of the flow rate, it is possible to compensate for this flaw. However, should there arise an unforeseen situation that led to loss of circulation the choke has to react quickly to trap enough pressure to maintain control of the well, which could cause a serious problem, and in worst-case lead to loss of the well.

To resolve this problem, the choke manifold has been equipped with a dedicated back-pressure pump that provides extra flow trough the choke on demand. This pump is not only utilized in emergencies, but has become a part of the primary system, automatically delivering flow when the sensors detect that the primary flow is reaching a threshold level.

3.4 Automation

Both the choke manifold and the back-pressure pump have the possibility of being non-, partly- or fully automated. This automation is provided by a Programmable Logic Controller (PLC) which collect pressure measurements and feedback from the choke limit-switches, and monitor and adjusts the choke and back-pressure pump according to a dynamic hydraulic flow model. The PLC, when tuned, does not need any human interference to control the choke set points or back-pressure pump rate, which makes it capable of reacting quickly in case something were to happen. The hydraulic model uses real-time data from the well to calibrate itself. Down hole pressure measurements are usually transmitted to surface through mud pulse telemetry, which, depending on the length of the wellbore and pump rate, can cause a significant delay in the hydraulic models data input. This problem can be resolved by the use of wired pipe or similar technologies, though at a higher cost.

3.5 Non-return valves

When utilizing back-pressure down the annulus, a situation occurs when the Stand Pipe Pressure (SPP) drops below the back-pressure in which the mud actually can be pushed back up through the inside of the drill string. It is therefore important that there is a barrier that prevents this mud back-flow from occurring, as the mud could carry cuttings that plug the motor or MWD, or in worst case, blow out the drill string. This barrier is established by the use of drill pipe Non-Return Valves (NRV), also known as floats.

The most common design of these NRVs is the piston float, which is located just above the bit and utilizes a spring that is pushed back when flow enters down the drill string. When the flow stops, the spring, together with well-bore pressure force the valve closed. This barrier sytem has proven reliable, and failures are generally a result of poor maintenance or very high-volume pumping of an abrasive fluid.

3.6 Coriolis flowmeter

To obtain even better control of the down hole conditions, a Coriolis flowmeter has become an important part of MPD operations. The flowmeter is installed in the closed fluid loop, before the shale shakers or mud gas separators, enabling it to take direct measurement while cuttings and gas are still present in the mud. The flowmeter provides measurements of mass flow rate, volumetric flow rate, density of the mud and temperature. The flowmeter uses a U-tube as shown in Figure 10 to detect the Coriolis effect, which is used to determine the mass flow and density. From this, volume flow can be calculated as mass flow divided by density.

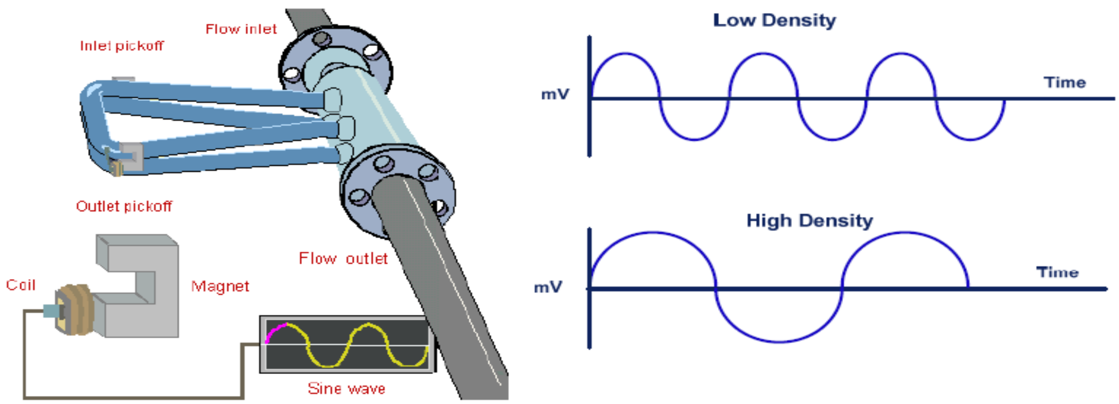

Figure 10 Coriolis flowmeter with oscillation period [16]

4 BHP

The sources for this chapter are [20] and [21] unless specified otherwise.

During drilling operations there are several parameters that influence the BHP. These parameters include fluid properties such as rheology, density and compressibility; flow rates, ROP, RPM, surface backpressure, drillstring configuration, hole geometry etc. The challenge in keeping a CBHP during MPD operations lay in the understanding of how the different parameters influence the wellbore pressure, and in what way the parameters interact with one another.

4.1 Fluid properties

The sources for this chapter are [22], [23] and [24] unless specified otherwise.

The wells drilled today become more extreme and the down hole conditions follow the same pattern, resulting in higher temperature and pressure regimes in which the drilling fluids has to endure. These large conditional differences from the surface to the reservoir can lead to changes in the drilling fluid properties that, if not accounted for, can lead to drilling problems such as risk of formation fluid influx, especially in narrow operating windows.

The properties of drilling fluids are probably the most important parameter for managing the wellbore pressure. By altering the properties of the drilling fluid one can, among others, manipulate the friction loss, alter the hydrostatic head, improve cuttings transportation etc. The drilling fluids used for offshore operations can generally be divided into three main categories, Water Based Mud (WBM), Oil Based Mud (OBM) and Synthetic Based Mud (SBM), dependent on their composition.

4.1.1 Rheology

Rhology is the study of the deformation and flow of matter, and provides a description of the relationship between the shear stress, τ , experienced by the fluid, and the share rate, γ , of the fluid.

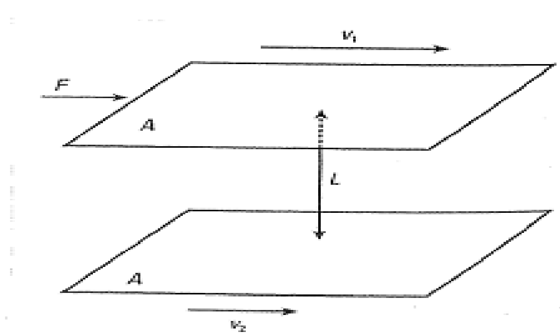

Figure 11 Shear flow described by two planes sliding parallel to each other. [23]

A fluid is divided into layers as shown in Figure 11, and the shear stress can be defined as a force per unit area between two layers that are sliding by each other, expressed as:

$$\tau = \frac{F}{A} \qquad \text{(Eq. 5)}$$

where F is the force and A is the area in contact with the fluid subjected to the force.

When two layers in the fluid passes each other, they are subjected to different velocities, and the change of velocity in the adjacent layer is known as the shear rate, defined by:

$$\gamma = \frac{V_a - V_b}{h} \qquad \text{(Eq. 6)}$$

where V_a = velocity at layer a, V_b = velocity at layer b and h = the distance between the layers a and b. In general, the relationship between the shear rate and shear stress determines how the fluid flows, or in what flow regime the fluid flow is. The different flow regimes are addressed later.

The most important properties of rheology are Plastic Viscosity (PV), Yield Piont (YP) and gel strength.

4.1.1.1 Plastic Viscosity

As the layers slide over one another they exert friction between themselves. Viscosity is a measurement of this friction, and express how much shear stress that develops as one layer slides over another. Viscosity is highly dependent on temperature and velocity of the fluid, and it is therefore difficult to provide an absolute or effective value for the viscosity of a fluid.

PV is however used as a indication of the viscosity of the fluid and is found by the use of a Fann V-G meter. It is defined as the value obtained by finding the slope of the curve from the 300 RPM reading from the 600 RPM reading. Figure 12 shows a typical flow curve of a drilling mud where the 300 and 600 RPM readings are marked. [25]

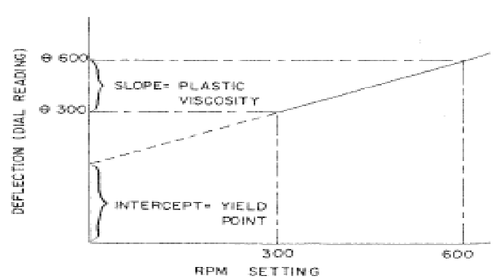

Figure 12 Typical flow curve of drilling mud using a direct-indicating viscometer. [25]

4.1.1.2 Yield Point

YP is the minimum amount of shear stress that has to be exerted to a fluid to obtain a shear rate. This implicates that as long as the shear stress is below this critical value, the fluid will act like a solid. Some fluids, such as Newtonian and Power-law fluids intersect the share stress axis at the point of origon, i.e. has an YP equal to zero. However, most drilling fluids are non-Newtonian, and consequently have a non-zero YP. The effect of YP is that there has to be exerted a certain pressure to the fluid before it becomes mobile, resulting in a sudden pressure jump, which is reversed when the fluid becomes stationary again. This effect is shown to the left in Figure 13. Historically the YP has been estimated by the use of the same Fann V-G meter as the PV, where the YP is found by subtracting the PV, from the 300 RPM viscosity reading, which can be seen in Figure 12.

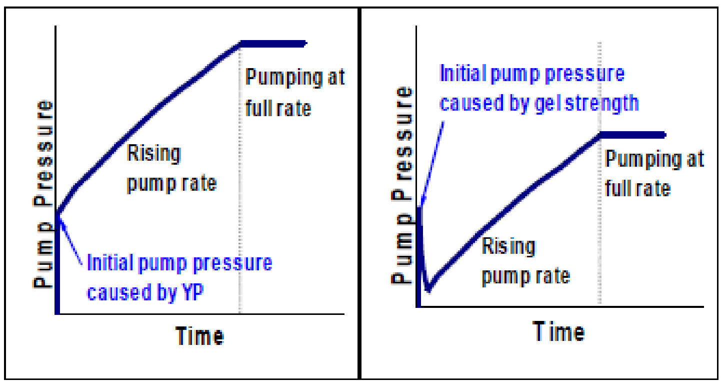

Figure 13 Effect of yield point on pump pressure [20]

The reason for of having a non-zero yield point is because that since the fluid will act as a solid whenever stationary, it will have the ability to keep cuttings in suspension, preventing them from sinking, and accumulating at the bottom of the hole.

During MPD operations, where the pressure margin is narrow, and especially if the hydrostatic head is underbalanced, it is important to take this effect into considerations whenever stopping for connections, tripping etc, due to the danger of formation fluid influx into the wellbore.

4.1.1.3 Gel strength

Drilling fluids also have a similar property called gel strength. Gel strength is a measure of the minimum shearing stress necessary to produce slip-wise movement of the drilling fluid. The major difference between YP and gel strength in terms of hydraulics can be seen to the right in Figure 13, where the gel strength disappears when the gel is broken.

4.1.1.4 Rheology models

In the later years, it has become generally accepted that the Herschel-Bulkley rheological model best represents drilling fluids, and this was also the model recommended in API 13D. The states that [26]:

$$\tau = \tau_y + \mu\gamma^n \qquad \text{(Eq. 7)}$$

where τ_y is YP, μ is the consistency index and n is the flow behavior index.

Figure 14 shows a representation of the Herschel-Bulkley model for a typical drilling fluid. As one can see form this model it does not consist of a linear line, but a curve that better represent the modern drilling fluids behavior.

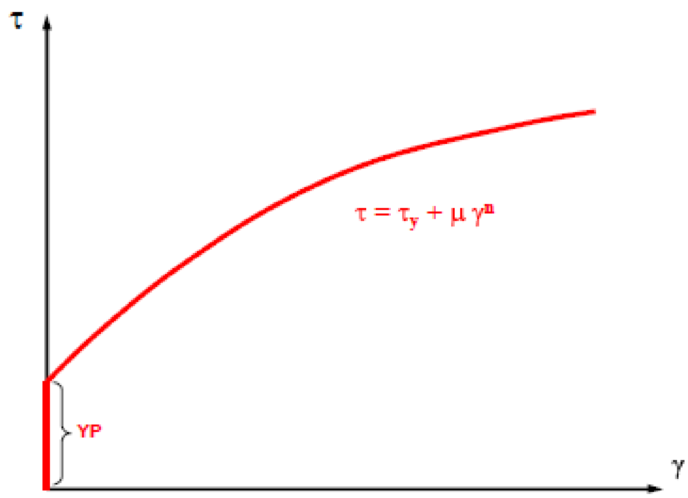

Figure 14 Herschel-Bulkley YP [20]

4.1.2 Compressibility

The source for this chapter is [27] unless stated otherwise.

The dimension of compressibility offers yet another parameter that has to be accounted for when trying to manage the wellbore pressure. All fluids are subjected to compressibility due to pressure and temperature changes. However, for some fluids, mainly pure liquids, the compressibility is considered to be negligible, as change in density with pressure is small when kept within reasonable ranges of temperature. This is the reason why WBM is considered to be an incompressible fluid, whereas OBM and SBM, that contain particles that are much more sensitive to pressure changes, are usually considered to be compressible.

The density of a fluid is, as mentioned above, dependent on both temperature and pressure, and the relationship between the variables of state can be expressed by the equation:

$$p = p(\rho, T) \qquad \text{(Eq. 8)}$$

where p is pressure, ρ is density of the fluid, and T is the temperature.

Normally the density in the equation above is replaced by specific volume, v, given by the relationship:

$$v = \frac{1}{\rho} \qquad \text{(Eq. 9)}$$

which gives the following equation of state:

$$p = p(v, T) \qquad \text{(Eq. 10)}$$

Since this equation of state is dependent on three parameters, it can be represented by a surface in the coordinate system v, T, p, as shown in Figure 15.

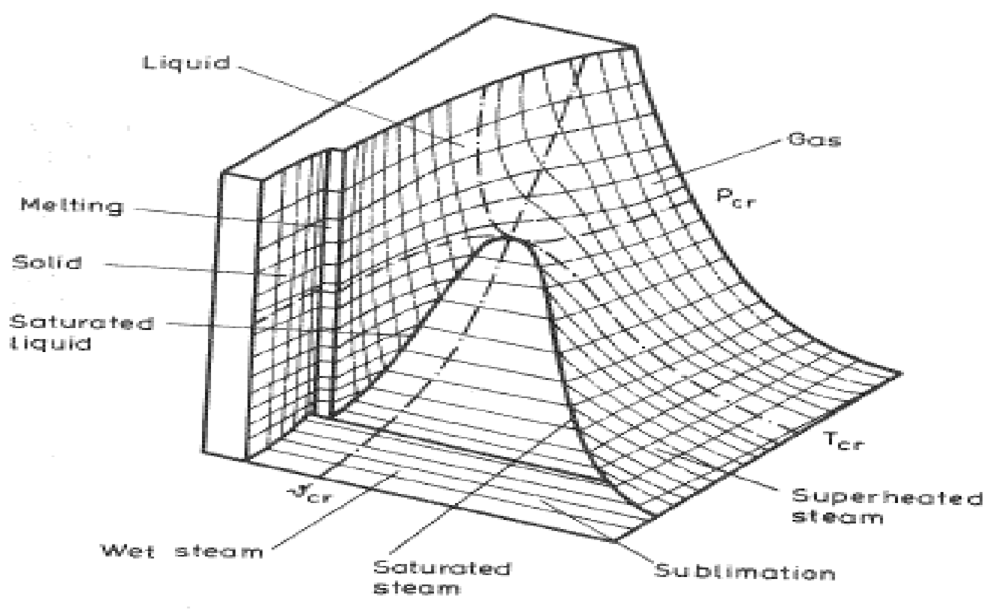

Figure 15 Surface of thermal state [27]

From Equation 4, it is possible to derive three partial derivatives to determine three important properties related to the compressibility of the fluid, the thermal expansion, the isothermal compressibility and the isochoric pressure coefficient.

The coefficient of thermal expansion, α, is defined by the equation:

$$\alpha = \frac{1}{v}\left(\frac{\delta v}{\delta T}\right)_p \qquad \text{(Eq. 11)}$$

The isothermal compressibility, β, is defined as:

$$\beta = -\frac{1}{v}\left(\frac{\delta v}{\delta p}\right)_T \qquad \text{(Eq. 12)}$$

Last, the isochoric pressure coefficient, π, is defined by the expression:

$$\pi = \frac{1}{p}\left(\frac{\delta p}{\delta T}\right)_v \qquad \text{(Eq. 13)}$$

For analyzing the compressibility of a drilling mud, the latter term is not of interest, as the density is not held constant during drilling conditions. The two first terms are however of significant importance to the mud properties when drilling a well. In Figure 16 and Figure 17 the effects of isothermal compressibility and thermal expansion of the well to be investigated in this thesis is plotted as specific gravity vs. pressure and temperature respectively.

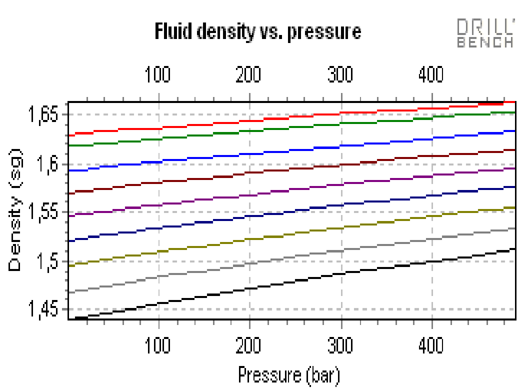

Figure 16 Isothermal compressibility effect

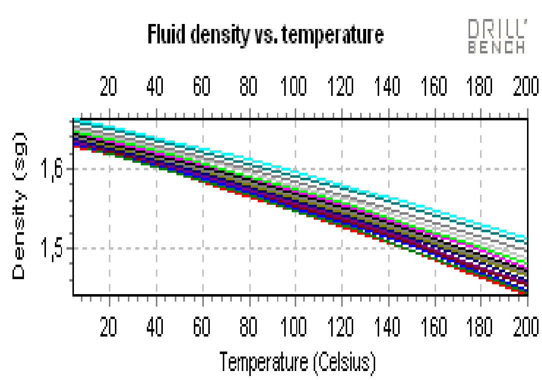

Figure 17 Thermal expansion effect

From the figures above it can be seen that the effects of α and β are given for specific temperatures and pressures, as these are held constant. Since there are given a sufficient amount of plots it is possible to obtain the value of either α or β for values in between these temperatures and pressures by the use of interpolation.

4.2 Flow rate

Figure 18 illustrates the effect that flow rate has on the BHP and hole cleaning, where the green line shows the BHP as a function of flow rate, and the blue line shows the concentration of cuttings as a function of flow rate. From the figure it can be seen that the dominating factor for BHP at low flow rates is the concentration of cuttings, which is shown by the parallel decrease of both cuttings concentration and BHP. As the flow rate increases, the hole cleaning capabilities improve, and the concentration of cuttings will decrease. At a certain rate, around 400 gpm for the example in the figure, the cuttings concentration approaches a level where it does not affect the BHP to the same extent, and the annular friction loss takes over as the dominating factor. If the ROP is zero, i.e. there are no cuttings involved; the BHP will increase at any flow rate, as the friction loss will be the only parameter present.

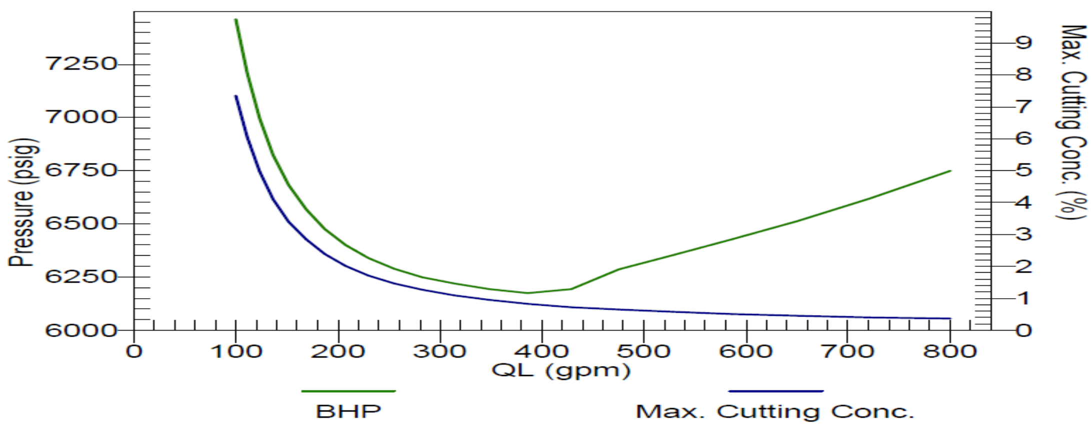

Figure 18 Effect of pump rate on BHP and cuttings concentration [20]

One of the main reasons for MPD operations is narrow or unknown pressure margins, which often demands for quick altering of the ECD. From conventional drilling, the most efficient method of lowering ECD during drilling is to lower the flow rate. This solution might cause a problem when operating in MPD mode, as one often operate closer to the pore pressure, and therefore might have a higher ROP. This combination of higher ROP and lower, or even insufficient flow rate can lead to accumulation of cuttings in the wellbore, which increases the chance of stuck pipe and twist-off situations. The circulation rate must therefore always be sufficiently high enough to ensure proper hole cleaning. [28]

4.2.1 Flow regimes

The behavior of the friction pressure loss is highly dependent to which flow regime that governs the flow throughout the well bore. The annular flow is commonly classified as being within one of the two flow regimes laminar or turbulent, or in a transition phase between the two. In Figure 18 the transition phase can be seen as the pressure jump occurring at 420 to 480 gpm. However, which flow regime that will dominate the annulus flow is rather difficult to estimate, as it is dependent on several parameters that are subjected to uncertainties, as for instance roughness of the formation, eccentricity of the drill string, true well bore diameter etc.

In 1883 Osbourne Reynolds demonstrated the difference between the two types of flow by injecting a fine threadlike stream of colored liquid having the same density as water into a tube in which water was flowing. When the velocity in the tube was small, thread of colored liquid followed a layer throughout the tube, which demonstrated that during laminar flow, the fluid are divided into different layers, sliding by each other with different velocities, and forms a velocity profile as shown in Figure 19.

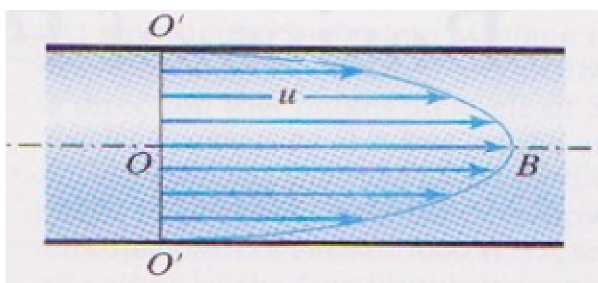

Figure 19 Typical velocity profile for a real fluid [29]

When Reynolds steadily increased the velocity in the tube, there was a reaction in the flow pattern when the velocity reached a critical value. The colored liquid started a wavy flow pattern, and as the velocity was further increased, the colored liquid broke into numerous vortices beyond which the color became uniformly diffuse so that no streamline could be distinguished. The flow had now entered the turbulent flow regime, which produces a more chaotic flow pattern, seen in Figure 20 and Figure 21. [29]

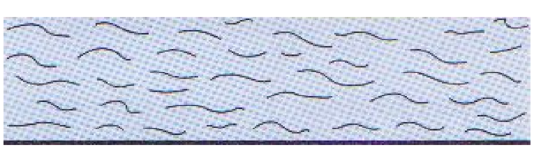

Figure 20 Turbulent flow [29]

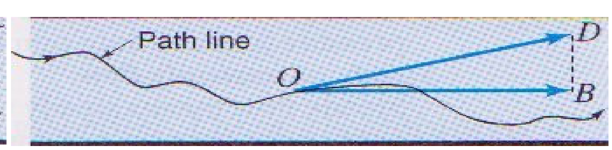

Figure 21 Path line in a turbulent flow [29]

4.2.1.1 Reynolds number

The source for this chapter is [29] unless stated otherwise.

The Reynolds number is thought to give an indication to what flow regime, laminar or turbulent, that the annulus flow will undertake. It expresses the ratio between the inertia forces and the viscous forces in the fluid.

$$R = \frac{F_i}{F_v} = \frac{L^2 V^2 \rho}{LV\mu} = \frac{LV\rho}{\mu} = \frac{LV}{\nu} \qquad \text{(Eq. 14)}$$

where L = any length that is significant to the flow pattern, V = mean fluid velocity, ρ = density of the fluid, μ = the dynamic viscosity of the fluid and ν = is the kinematic viscosity.

From Equation 14 it can be seen that the Reynolds number, and thereby the flow regime, is dependent on several factors, strengthening the fact that determining which flow regime is dominant is difficult.

Laminar flow occurs at low Reynolds number where the viscous forces are dominant, and is characterized by a smooth, constant fluid motion, as could be seen in Figure 19. For high Reynolds numbers, the flow regime tends to be turbulent, and is dominated by internal forces that tend to produce random eddies, vortices and other flow instabilities, causing a chaotic flow pattern.

4.3 RPM and eccentricity

The sources for this chapter are [25], [30] and [31].

The effect that rotation of the drillstring has on the BHP is not always straight forward. The rotation will usually have two opposing effects, one being that the rotation increases the absolute velocity of the circulating mud, resulting in increased friction loss, and a higher BHP. The other effect is that the increased velocity improves cuttings transportation, which leads to improved hole cleaning, which results in a lower BHP. Which one of these opposite effects are the dominating depends on the magnitude of RPM, ROP and cutting size, but usually it is the beneficial lowering of the BHP that dominates. Rotation of the drillstring also has other beneficial effects, as lowering the torque and drag.

The eccentricity of the drillstring, meaning how centered the drillstring is in the hole, will also have an effect on the BHP. If the drillstring is off center there will much likely be a difference in the hole cleaning between the “wide” and the “narrow” side, which might lead to different friction losses for the two sides. This can in the worst case result in differential sticking or wash out of formation on the “narrow” side.

4.3.1 Taylor-Couette flow

The Taylor-Couette flow has emerged from the basic Couette flow, which describes the behavior of laminar flow of a viscous fluid confined between two plates moving relative to one another. Taylor-Couette flow is the flow that appears when the viscous fluid is confined between two cylinders rotating relative to each other, which relates to the drilling of a well where the drill string rotates relative to the rigid borehole wall. Sir Geoffrey Ingram Taylor investigated the stability of Couette flow, and found that when rotation of the inner cylinder reached a certain threshold velocity, instability occurred in the flow, and a secondary steady state appeared, characterized by axisymmetric toroidal vortices, known as Taylor vortices which could cause pressure changes to the BHP.

The Taylor number, Ta, indicates if these Taylor vortices are present, or not. For Couette flow with $Ta_c > Ta$, instabilities in the flow are not present, and the flow is steady. The Taylor vortices will start to form when the Taylor number exceeds Ta_c, and instability will be present. However, the nature of this instability does not lead to turbulence in the flow, but as mentioned above, lead to a change of stabilities, and a new steady state appears.

4.4 Rate of Penatration

Drilling with a high ROP may result in such a large volume of cuttings that the cuttings cannot be circulated out of the wellbore in one circulation. If this is the case, it could lead to a build up of cuttings concentration in the drilling fluid. The consequence of undesirable solids accumulation in the fluid could be an altering of the fluid properties, depending on the size of the particles. As PV is a measure of friction between the layers in the fluid, it will increase due to the mechanical friction between the solid particles. YP and gel strength are dependent on the degree of attractive forces between particles, and will consequently increase as cutting particles pollutes the fluid. [23]

As the vertical depth increases, there will be an increase in bottom hole temperature dependent on the geothermal gradient, as well as the hydrostatic head of the drilling fluid column. These two factors will have an opposing effect on the ECD, where the increased temperature will lead to an expansion of the drilling fluid, resulting in a decrease of the ECD, whereas the increased pressure will compress the drilling fluid, leading to a increase of the ECD. These two opposing effects are often assumed to cancel each other out, which according to Harris et al. [32] might not always be the case. In their paper: “Evaluation of Equivalent Circulating Density of Drilling Fluids Under High-Pressure/High-Temperature Conditions” they conclude that the effects of high temperatures and pressures play an important role in the volumetric and rheological behavior of the drilling fluid, and therefore on the BHP.

4.5 Surface backpressure

The fastest way of altering the BHP while drilling in MPD mode is to apply backpressure from surface, which will have an immediate effect. Although this method allows for better control of the wellbore pressure, it is important to be aware of its limitations. When using backpressure to keep a CBHP, the pressure is only constant at a specific point in the well, illustrated as the intersection of the red and blue line in Figure 22. These two lines indicate that it is not possible to have an infinitely long open hole section. However, by being aware of this limitation, it is possible to enhance the open hole section by keeping a target pressure higher up in the well, as shown to the right in Figure 22.

A side effect when utilizing surface backpressure to keep a CBHP is that there will be some cyclic loading on the formation above and, if possible, below the point of constant BHP during drilling and connection. This cyclic loading might weaken the formation and lead to well stability issues.

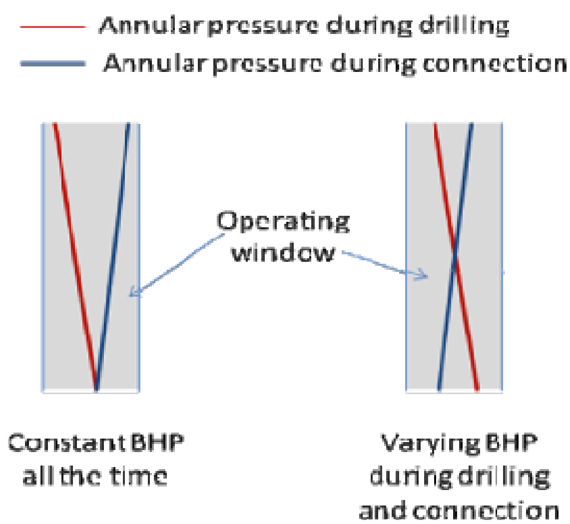

Figure 22 Point of constant pressure during drilling and connection [21]

Another issue of importance is that the pressure in a horizontal leg of a wellbore will approach a constant when static. Any backpressure applied to the well in this static condition will have the same effect over the whole interval. However, when circulating, the ECD will always be higher at the end of the horizontal interval, which has to be taken into consideration when the operating window is small. [21]

4.6 Pipe movement

Sources for this chapter are [33] and [34] unless specified otherwise.

Whenever the drill pipe is moved up or down in the annulus, it induces a velocity change to the drilling mud, which leads to changes in the annular friction loss, referred to as pressure surge when pipe movement increases the frictional pressure drop, and pressure swab when the movement reduces the frictional pressure drop. Pressure surge is commonly associated with running the pipe into the hole, as this forces the mud out of the well, inducing an upward flow that increases the BHP. Running the pipe out of the hole creates a void below the bit that has to be filled by the drilling mud, thereby inducing a downward flow, decreasing the BHP. The magnitude of these pressure fluctuations is dependent on several parameters.

4.6.1 Fluid properties

The pressure fluctuations are highly dependent on fluid behavior. High gel strength and viscosity will cause high fluctuations, as the fluid needs to be exerted to higher pressures both to be set, and kept in motion, than would be the case for a fluid of lower gel strength and viscosity.

Compressibility of the fluid dampens the pressure fluctuations, as the volume of fluid changes with pressure, leading to a lower fluid velocity, as illustrated in Figure 23 that show the BHP change over time for a compressible and an incompressible fluid caused by pipe movement. However, this effect has it counterpart in the inertia present in the fluid, which in some cases may cause a greater, but opposite effect compared to the compressibility. The fluid inertia is also the cause of the pressure fluctuations that often occur after the pipe has stopped moving.

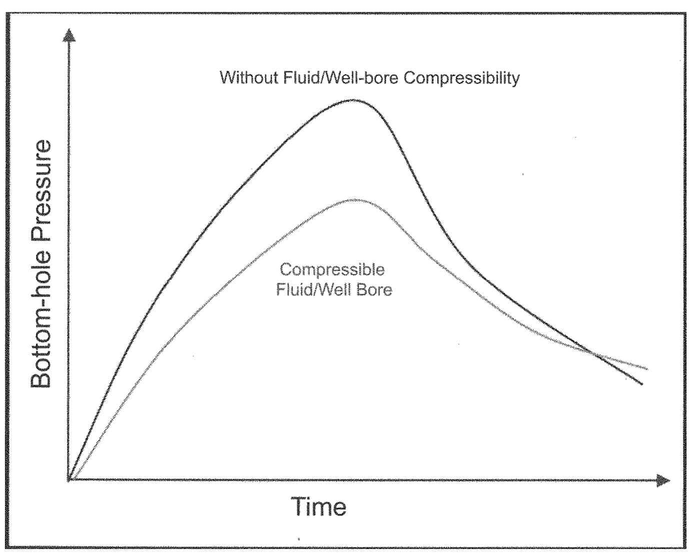

Figure 23 Compressibility of the drilling fluid and formation dampens the bottom-hole pressure change while moving the pipe. [33]

4.6.2 Pipe velocity and position

The velocity in which the pipe is moved determines the rate that the drilling fluid is displaced, which again determines the flow regime of the fluid. During laminar flow, the relationship between the pipe movement and pressure change is linear. However, when the flow becomes turbulent, the pressure changes increase rapidly with speed of pipe movement, as is illustrated in Figure 24.

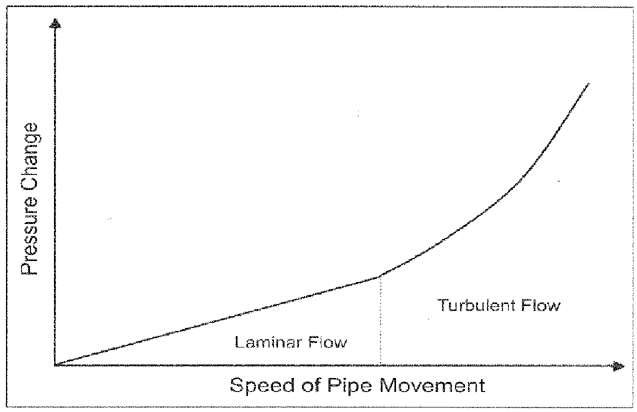

Figure 24 The pressure change in the annulus depends on the speed of the pipe movement and fluid flow pattern. [33]

Whether the pipe is off the bottom of the hole or not also plays an important to the magnitude of the pressure fluctuations. As Figure 25 illustrates, if the pipe is on the bottom of the hole, it will induce a higher pressure fluctuation compared to if the pipe had been located higher up in the well bore. This is because when located further down the well bore, there is more mud that has to be displaced, compared with higher up.

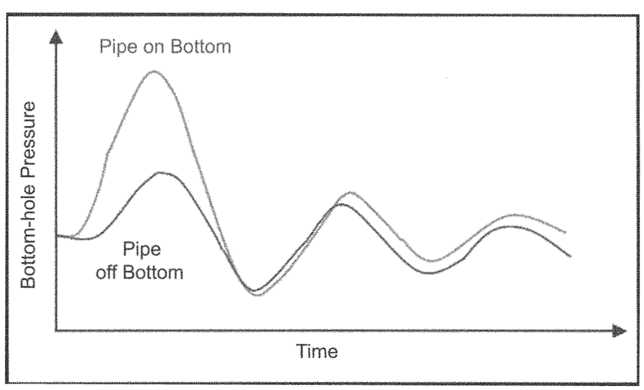

Figure 25 The effect of pipe movement with an off-bottom pipe. [33]

4.6.3 Geometry of the well

The geometry of the well and how the drill pipe is located in the well decides the flow passage in which the mud can travel. If there is a narrow flow passage, the mud will be exposed to a higher velocity, than if the flow passage was wide. This will again affect whether the flow regime is laminar or turbulent, and thereby the magnitude of the pressure fluctuations.

5 Probability

In this chapter, a short description of the probability theory needed for this thesis is provided. The sources for this chapter is [35], [36] and [37]

5.1 Student-t

The Student-t distribution (or the t-distribution) is used for statistical work where the standard deviation of the population is unknown, and has to be estimated; as is the case for most experiments. The distribution has a bell shaped form similar to that of the normal distribution; however it is lower at the top and wider at the ends, as can be seen in Figure 26.

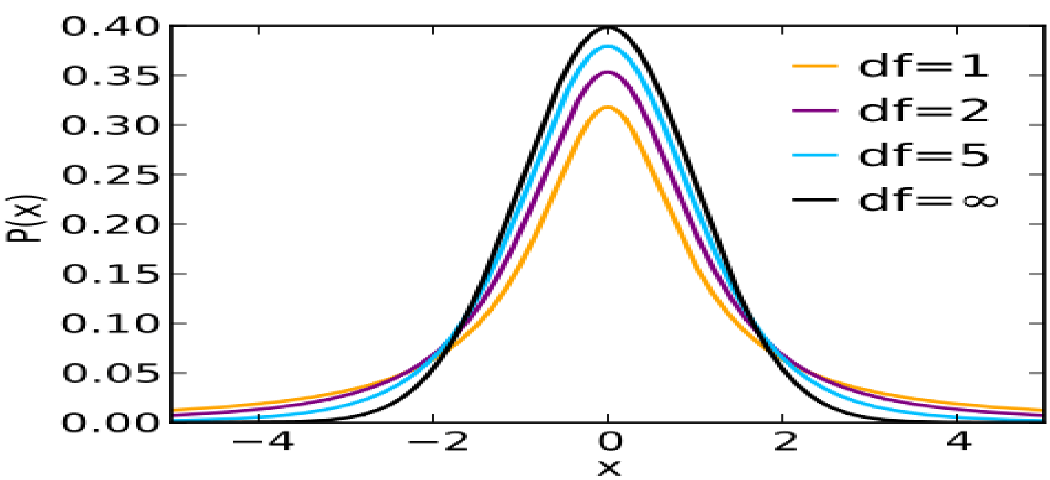

Figure 26. Student-t distribution for different degrees of freedom. [37]

It can also be seen from the figure that the t-distribution is dependent on the degrees of freedom in a given experiment, where lesser degrees of freedom provide a wider bell shaped distribution. This makes it more applicable when estimating the mean and variance in of smaller sample sizes, i.e. n < 30, than for the rigid normal distribution.

In the t-distribution the sample mean is defined as:

$$\overline{X} = \frac{(X_1 + \ldots + X_n)}{n} \qquad \text{(Eq. 15)}$$

and the sample variance as:

$$S_n^{\ 2} = \frac{1}{n-1}\sum_{i=1}^{n}\left(X_i - \overline{X}_n\right)^2 \qquad \text{(Eq. 16)}$$

5.2 Analysis of variance

To test whether there are statistical reason for concluding that samples collected from similar experiments does not originate from the same population, an Analysis of Variance (ANOVA) test is often used. For the ANOVA test, the data collected from an experiment is sorted into groups based on difference in testing parameters. The mean value and variance of these groups are found, and the variances among the mean values are analyzed to find if the difference can be explained by chance, or if there are statistical reason for concluding that the mean values actually differ.

5.2.1 H-test of Kurskal and Wallis

Since the data collected in this thesis cannot be assumed to be normally distributed, it is imperative to utilize a non-parametric test, i.e. a test that does not rely on the assumption that the data is drawn from a normal distribution. The H-test of Kurskal and Wallis is such a non-paramteric test, and is therefore chosen for analyzing the data in this thesis. The test does however assume an identically shaped and scaled distribution for each population.

The H-test of Kurskal and Wallis analysis the variance among mean values of populations by ranking all the n values obtained in the experiment from 1 to n based on their magnitude. If two values are tied, i.e. have the same value, they are assigned the average of the rank they would have received had they not been tied. The ranked values are then sorted back into their respective population. Let R_i be the sum of the ranks in the ith population, then the variance of the population rank sums R_i is given as $\overline{H}$:

$$\overline{H} = \left(\frac{12}{n(n+1)} \right) \sum_{i=1}^{k} \frac{R_i^{\;2}}{n_i} - 3(n+1) \qquad \text{(Eq. 17)}$$

Under the null hypothesis this test statistic has, for large numbers of n, a chi-squared distribution with k-1 degrees of freedom. Therefore, whenever n_i=> 5 and k=> 4, the null hypothesis H_0 is rejected when $\overline{H} > \chi^2_{k-1;\alpha}$. However, the approximation to the χ^2 distribution is fairly accurate even when one or more of the populations includes as few as three observations.

5.2.2 Welch's t-test

The Welch's t-test is a sub-category of the Student's t-test in which two sample means are tested against the null hypothesis of being a part of the same population. What differs the two tests is that the Welch's t-test is not based on a pooled variance estimate, meaning that the test is not dependent on the two sample means having an equal variance. The Welch's t-test defines the statistic t as:

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}}$$

(Eq. 18)

And the corresponding degrees of freedom as:

$$\nu = \frac{\left(\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}\right)^2}{\frac{s_1^4}{N_1^2\left(N_1 - 1\right)} + \frac{s_2^4}{N_2^2\left(N_2 - 1\right)}}$$

(Eq. 19)

The null hypothesis is rejected when t > $T_{\alpha;\nu}$.

6 Drillbench ©

The source for this chapter is [38] unless stated otherwise.

Drillbench © is an intuitive simulation tool delivered by Scanpower, containing a package of different modules related to different aspects of the drilling operation. Drillbench © is based on over 20 years of extensive research from Rogaland Research, leading to an advanced model where verifications against both laboratory and field data has been of importance. The software was in 1998 purchased by Petec Software & Service whom both commercialized it, and further developed it. The technology and personnel was in 2004 acquired by Scanpower Petroleum Technology, which have continued the work of achieving a model accurate enough to handle the narrow pressure margins experienced in the wells drilled today.

6.1 Pressmode ©

For this thesis the Pressmode © module was the one of interest, as it deals with the actual drilling of the well. Pressmode © is a coupled thermal and hydraulic flow model, where the two different models run in a parallel with as much integration as possible.

6.1.1 Hydraulic model

The hydraulic model is based on accurate fluid modelling, with pressure and temperature dependent rheology and density, accurate well geometry, with 3D well profile, drill string configuration and casing program. This enables the simulator to calculate the pressure loss due to circulation, rotation geometry and equipment.

The main flow model is based on the equation of conservation of mass, conservation of momentum and partial differential equations with regards to time and position.

6.1.2 Temperature model

The temperature model is based on conservation of energy, forced convection and natural convection. The basic generators of heat in the model are heat generated due to frictional pressure loss, mechanical energy, i.e. torque, and flow regime.

6.1.3 Back pressure mode

The Pressmode © module has a dedicated function to simulate wells being drilled with a RCD, i.e. in MPD mode. This function does however contain a flaw in regards to this thesis, where it cannot handle a steady low flow rate of approximately 100 lpm or lower. The reason for this is probably that at this low rate there is not enough flow over the choke to create the desired back pressure, which causes the model to malfunction. This is one of the reasons why all the simulations carried out in this thesis is simulated as conventional drilling operations, without the use of surface back pressure.

Another reason for carrying out the simulations in a conventional drilling mode is that since the aim of the thesis is to relate the changes in drilling parameters to actual physical phenomenon seen in the well, the use of surface back pressure offers yet another uncertainty factor to the calculations performed by the simulator. By eliminating this factor, the uncertainty of the values obtained by the simulation is lowered.

6.1.4 Batch mode

Another choice offered by the Pressmode © function is the choice between interactive mode, where interactive actions can be made at any time, and batch mode, where a dedicated drilling schedule is programmed into the simulator via a batch configuration. For the simulations carried out in this thesis, the latter mode was chosen, as it provided identical scenario for each simulation, allowing for controlled alteration of different drilling parameters between runs.

6.1.5 Base Cases

There was created three base cases based on real time data collected from Well A, where the settings for flow rate and rotational velocity is given in Table 1.

Base Case	Flow Rate	RPM
Low/low	1475 lpm	30 RPM
Medium/medium	1600 lpm	60 RPM
High/high	2000 lpm	120 RPM

Table 1 Settings for the base cases.

When comparing the results obtained from the simulation of these base cases it was found that the simulator had a tendency of underestimating the effect that the drillstring rotation had on the BHP. However, the underestimation was found to be approximately the same for all the cases. It was therefore decided to not alter the settings of the simulator, as it is not the absolute value of pressure change caused by the drilling parameters, but the trend when altering the parameters that were to be investigated.

By altering the parameters of flow rate and RPM in the base cases, there were performed nine simulations for three different depths to provide a basis for comparing the simulation results against the observations drawn from the real time data. The three different depths were at the casing shoe, at the point of the lowest measurement obtained from real time data, and at the lowest point of the 8" MPD section.

There was also performed a set of nine simulations with a different configuration to the BHA for the shallowest depth.

The reason for not altering the RPM parameter that occurred before any flow was present is because there could not be seen any effect of this rotation to the BHP neither before the low flow rate was established, nor when turning off the rotation after the low flow was established.

For results, see Appendix C.

6.1.6 Limitations

As mentioned earlier, there are some limitations to the simulator, as there is to all simulators. One being the mentioned problems with establishing a low flow rate when drilling in MPD mode. Another limitation affecting this thesis is the ignorance of the effect from cuttings concentration. As described in chapter 4, the presence of cuttings can have significant effects to the ECD and the behaviour of pressure change during rotation. There is also a limitation to the location of the drillstring in the wellbore. As the simulator is programmed to always be drilling, it will ignore any open hole section below the bit. This made it impossible to simulate the difference in effects from the drilling parameters when being on or off bottom.

Being that the simulator has its limitations, the output, as well as the input, has to be handled with care. A simulator will always provide an output value that is dependent on the input value. If crap is fed to the simulator, then crap will come out the other end, and consequently the results have to be evaluated with some scepticism.

7 Case Study

The uncertainty related to the interaction between parameters become most severe during operations where the flow rate is shut down and the mud pulse telemetry is off line, as is the case, for example, during connections. This means that for a period of time where several of the drilling parameters are in a transition phase, the BHP control relies entirely on the calculations performed by the hydraulic model that, for this time span, does not have the ability to calibrate itself up against real time data from the well. There are also other problems related to the transition from a static to a dynamic state, and visa versa, such as mud YP and gel strength, which can cause sudden pressure fluctuations when broken. These factors make the transition phase an area of importance, and are the basis for this study.

7.1 Background information

This thesis relies mainly on a case study of a well that was drilled on the Gullfaks field in the North Sea. Du to confidentiality reasons, the well name, along with actual depths and pressures has to be masked. All the depths in this thesis are therefore measured from a reference depth of where the MPD section started. The BHP is reported as absolute pressure changes from the start of each run.

The well was drilled as a sidetrack from a previous well that is located on the southwest side of the Gullfaks C field. The well in question was the fourth well drilled on Gullfaks C with the use of a MPD system. It was however the first well to utilize a fully automated MPD system.

7.2 Gullfaks field

The sources for this chapter is [39] and [40] unless specified otherwise.

The Gullfaks field was first discovered in 1978 and it was the first license run by a fully Norwegian joint venture corporation. It has been produced since 1986. [41] In the later years a problem has evolved, in which has led to severe problems when drilling wells, especially on Gullfaks C. In the time period of 1998-2002 a lateral distribution of abnormal pore pressure was detected in the upper part of the Shetland group. In the following years, the frequency of problem wells, showing unexpected high pressures in this area increased, leading to an investigation of the phenomenon. The reason was found to originate from the water injection used for enhancing oil recovery from the old wells. The water had been injected into the reservoir sands at rates and pressures that had exceeded the initial formation strength of both the reservoir and the cap rock. Further fracturing of the Shetland group, rejuvenation of faults and liquid movement behind poorly cemented intervals was found to be the most probable conduits for the high pressure to migrate from the reservoir to the upper parts of the Shetland formation. The reason for the pressure to accumulate here is that there is considered to be a mechanical anisotropy terminating the propagation of fractures. There is also a limestone stringer separating the Lista formation from the Shetland group thought to enhance this effect, as limestone stringers are known to possess more formation strength than claystones and shales. The probable reason for the relatively wide lateral extent of the problem area is that pressures and reservoir fluids have spread through the semi-permeable lower zone of the limestone cap.

The suspicion that the pressure build up is caused by the water injection is further enhanced when plotting the wells drilled in the time period of 1998-2003 into a map along with the injection wells, as done in Figure 27.

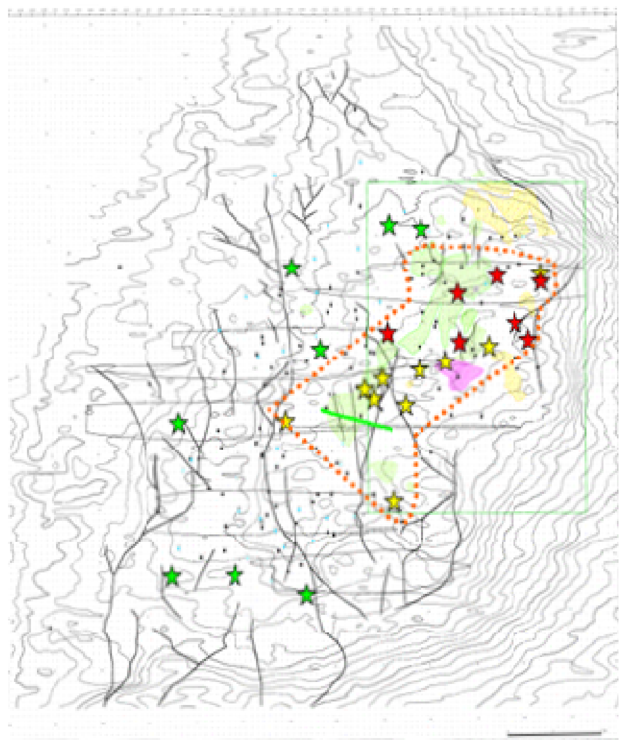

Figure 27 Depth structure map of the top of the Shetland Group with an overview of problem and injection wells. [40]

Here the problem wells are marked as yellow starts, the injection wells with red starts, and the wells drilled without problems are marked with green stars. The figure seems to show a clear connection between the injectors and the problem wells, and the dotted red line indicates the area that has to be considered as a high-risk area with regards to encountering abnormal high pressures in the Shetland group.

The effect of this pressure build up can be seen in Figure 28 showing the pressure gradients for the Gullfaks C area, where there is a clear spike in the pore pressure as one enters the Shetland group, causing a very narrow operating window.

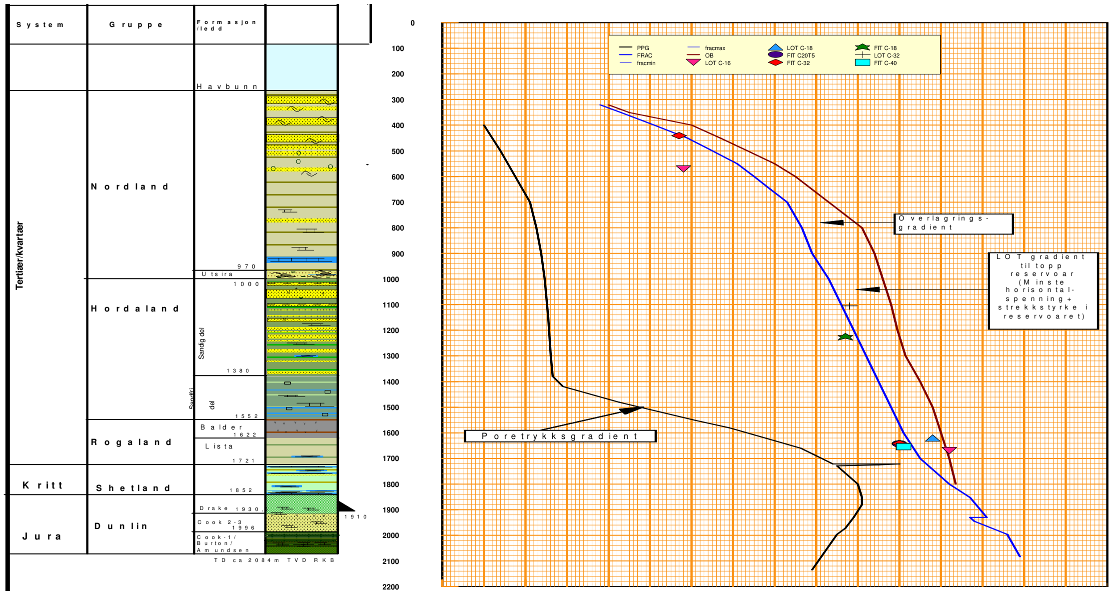

Figure 28 Pore pressure distribution map of the top of the Shetland Group [40]

To resolve the problem of drilling through this narrow operating window, several techniques was suggested, with Through Tubing Rotary Drilling and, as it was know as at the time, UBD as the ones of greatest interest. After much consideration UBD, or MPD, was chosen, which has proven to be a successful technique, leading to five successfully drilled wells through the trouble zone. At the time of writing this thesis, the sixth MPD well was drilled down to Target Depth, however there was encountered some problems afterwards, not directly related to the drilling operation.

7.2.1 Drilling conditions

The source for this chapter is [42] unless stated otherwise.

Figure 29 shows the well schematics planned for the well, where the MPD sections of 8 ½ " and 6 " are circled in red. However, due to the MPD technique, this well was drilled to TD with 8 ½ " assembly.

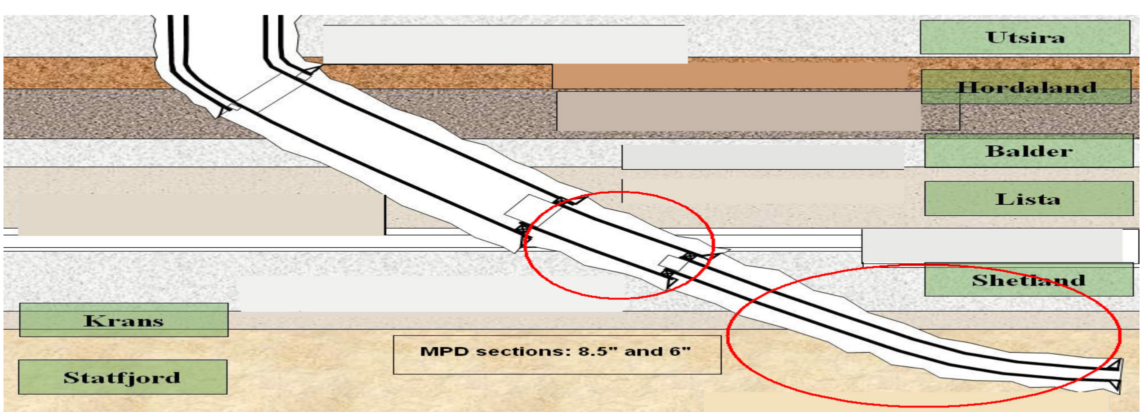

Figure 29 Well schematics for Well A [40]

Due to the mitigation of the injected water pressure mentioned above, the 8 ½” reservoir section had to be drilled through over-pressurized formation, leading to an operating window estimated to be only 7 bars. In reality this meant that the BHP had to be held within $\pm$ 2.5 bars because of uncertainties in pressure estimation.

The small operating window made it impossible to drill the well with the use of conventional methods. The well was therefore drilled in MPD mode utilizing automatically controlled choke and backpressure pump aided by an advanced flow and temperature model provided by SINTEF and operated by Halliburton. This hydraulic model calculated the choke set point, and thereby the backpressure applied based on variable input data regarding flow, bit depth, RPM, torque, mud temperature and density, and rigid input data regarding drillstring configuration, survey, wellbore and formation temperature.

Several tests and tuning processes were performed to ensure that the system could maintain a constant BHP within 5 bars throughout the operation. In [43] “Performance and Reliability for MPD Control System Ensured by Extensive Testing” Godhavn and Knudsen describes how the system was tested and tuned before it was sent offshore, and in the paper [44] “Use of Real Time Dynamic Flow Modelling to Control a Very Challenging Managed Pressure Drilling Operation in the North Sea” Bjørkevoll et al. describes the problems that were encountered, and how they were resolved, when the system was tested and tuned on the rig before the actual operation was carried out. Before the operation, it was decided that the target ECD of 1.83 should be held constant 40 meters below the lowest casing shoe, which was assumed to be where the most critical zone would be encountered.

The mud used for the operation was a Versatec OBM, with a Mud Weight (MW) of 1.63sg. The MW was initially planned to be 1.58sg, but the pre-job simulations showed that an increase of MW to 1.63sg provided more flexibility to maintain a constant BHP with regards to the limits of applied surface backpressure.

After just eight days of drilling, a problem associated with exceeding the pressure limits of the narrow operating window was encountered, leading to loss of pressure control. The well was therefore temporarily abandoned.

When re-entering the hole after two months, a pressure test showed that the operating window between the leak-off and pore pressure was greater than first assumed. The drilling was therefore resumed, and the MPD section was carried out without further losses or incidents.

7.3 Challenges

One of the challenges that Bjørkevoll et al. [44] mentions in their paper, which also has been mentioned earlier in this text, is the problem related to the loss of real time data transmitted through mud signals when the flow rate drops below a threshold level of approximately 1000 lpm. However, a MWD tool, which is a battery driven down hole tool, still records measurements during this period, and these memory data can be obtained after tripping out of the well. The objective of this study is to use these memory data obtained from the MWD tool to eliminate each frictional pressure contributor to the BHP. Unfortunately, after extensive investigation, it turned out that there had not been any batteries in the MWD tool during the run in which that the longest MPD section was drilled, limiting the available data. However, there was recovered enough data from the earlier runs for this study to be carried out; although the reliability of the conclusions drawn from this thesis is somewhat less than if all the data had been available.

The reason for performing this study is that whenever the target pressure does not match the actual pressure recorded in the well, the hydraulic model compensates by adjusting the surface backpressure by a fractional factor. This fractional factor is not linked to one specific source, but merely a compensating factor that matches the specific situation. By analyzing the different drilling parameters, and eliminate how each and one of them affect the BHP; one might be able to link the adjustment factor to a specific source, thereby reducing some of the uncertainty encountered when drilling.

7.4 Use memory data to understand how the BHP is affected by each drilling parameter

As mentioned earlier, the uncertainty about how the BHP is affected by each drilling parameter become most severe whenever the flow rate is below a threshold level, where the mud pulse telemetry become unavailable. This study therefore focuses on those areas where the well status is in transaction from drilling to static conditions, and visa versa. During these phases there are relatively high uncertainties in the BHP calculations done by the hydraulic model du to simultaneous alteration of several drilling parameters.

7.4.1 BHP measurements

The MWD collects measurements every tenth second, which proved to be sufficiently accurate for analyzing the problem in hand. However, as the well is a MPD well, where the aim is to keep a constant BHP, the memory data of the BHP collected from the MWD tool show the BHP as a straight line with some minor deviations, regardless of how the drilling parameters change. This can be seen in Figure 30 where the reported BHP from the MWD is plotted together with flow rate.

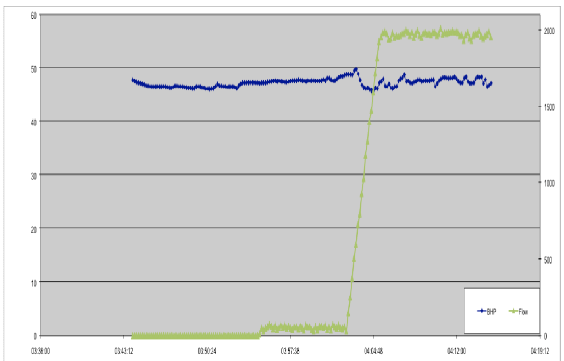

Figure 30 BHP and Flow Rate reported from MWD plotted against time.

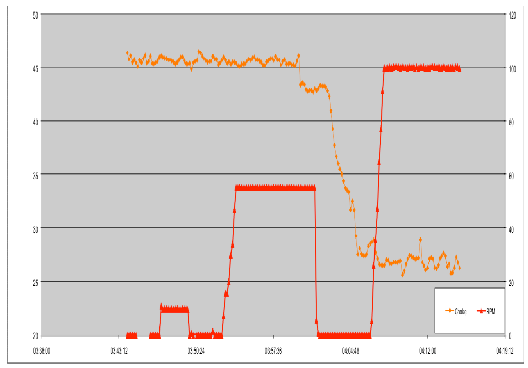

Figure 31 Surface choke pressure and RPM plotted against time.

The reason for this is of course the backpressure applied from surface, which is plotted in for the same period along with RPM in Figure 31 to the right. Equations 3 and 4 show that by subtracting the surface backpressure, one will in theory obtain the natural BHP. There is however some issues that will lead to uncertainties when subtracting the backpressure directly from the reported BHP to obtain measurements of how the BHP is affected by the drilling parameters.

The first issue is the compressibility of the drilling fluid. Since the drilling fluid is a compressible fluid, pressure applied to the fluid will probably not have a ratio of 1:1 in pressure exerted at the surface and pressure seen at the bottom of the hole. By assuming this 1:1 ratio, as is done in this thesis, one probably underestimates the effect of the surface back pressure somewhat. Assuming no change in other parameters than the back pressure applied, the extra pressure will compress the fluid, allowing for more fluid to be present in the well, and thereby increasing the hydrostatic pressure component of the ECD. The extent to how much the fluid is compressed depends on the compressibility of the fluid, which for the mud used when drilling the well in question is given in Figure 16 and Figure 17 on page 31.

However, there will probably be other factors affected by this phenomenon, for example temperature, and the investigation of this is beyond the scope of this thesis. The ratio to the back pressure applied, and the pressure seen at the bottom of the hole is therefore assumed to be 1:1 in this thesis.

The second issue is also related to the compressibility of the fluid. As the fluid is compressible, pressure applied to the surface will travel as a wave through the fluid, down to the bottom of the hole at a speed of approximately 1400-1500 m/s for the drilling fluid used [45]. This wave imposes a time delay from when the pressure is applied till it reaches the bottom of the well, which for deep wells could be significant. However, the depth of the well in question was not considered to be of significant magnitude, and a time delay of approximately 3 seconds was therefore not implemented in the ten second real time data.

The same period of time that was plotted in Figure 30 and Figure 31 are now plotted together in Figure 32 with the choke pressure subtracted from the corresponding measured BHP. Here one can see that the calculated BHP is reacting to changes in the drilling parameters, and for the remainder of the study, it is this value that will be meant when referring to BHP, unless specified otherwise.

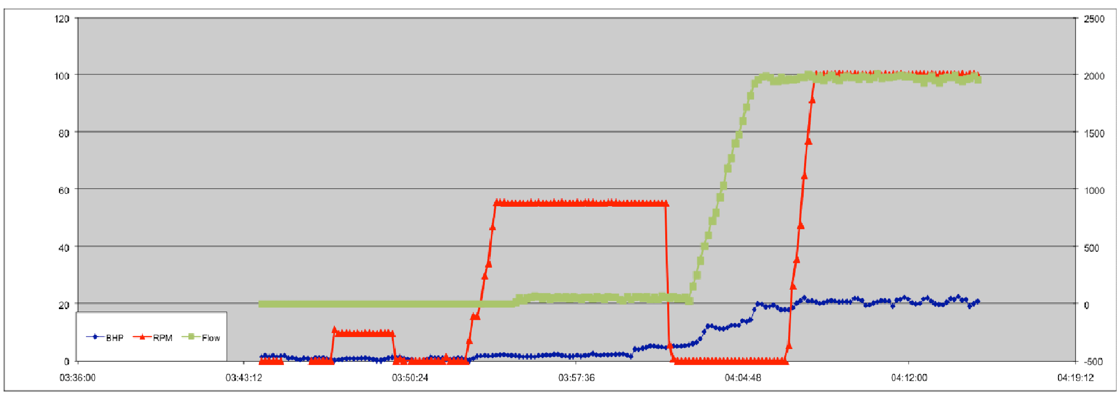

Figure 32 BHP, RPM and Flow Rate plotted against time.

7.4.2 Start up/shut down procedure

When drilling an MPD well it is important to minimize the potential of experiencing sudden pressure fluctuations. One potential source for causing fluctuations is the yield pressure and/or gel strength of the drilling fluid. To cope with this problem there has been developed a dedicated start-up and shutdown procedure for MPD wells on the Gullfaks field, which is as follows:

7.4.2.1 Start-up procedure

1) Switch to drill mode.
2) Rotate drillstring.
3) Ramp up flow rate to 75 lpm.
4) Stop rotation.
5) Ramp up to desired flow rate.
6) Start rotation.

An example of this start-up procedure can be seen in Figure 33 where RPM and flow rate is plotted vs. time.

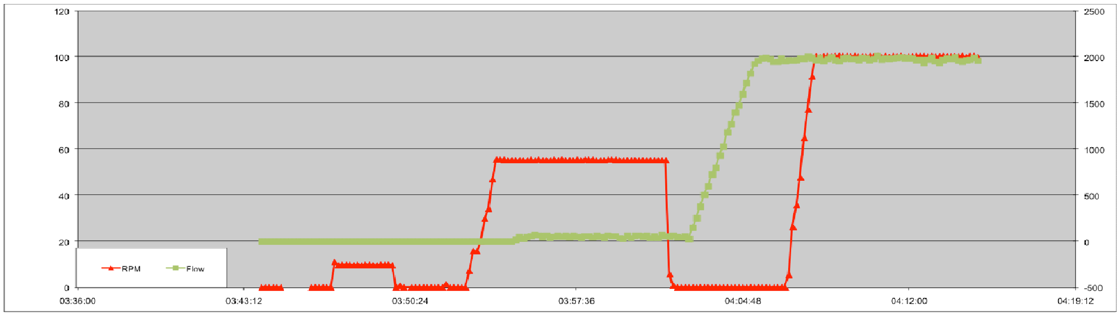

Figure 33 Typical start up procedure.

7.4.2.2 Break-up procedure

1) Stop rotation.
2) Ramp down flow rate to 100 lpm.
3) Wait for stable BHP readings.
4) Turn off flow rate.
5) Switch to connection mode.

This break-up procedure is illustrated in Figure 34 where RPM and flow rate is shown for a typical run.

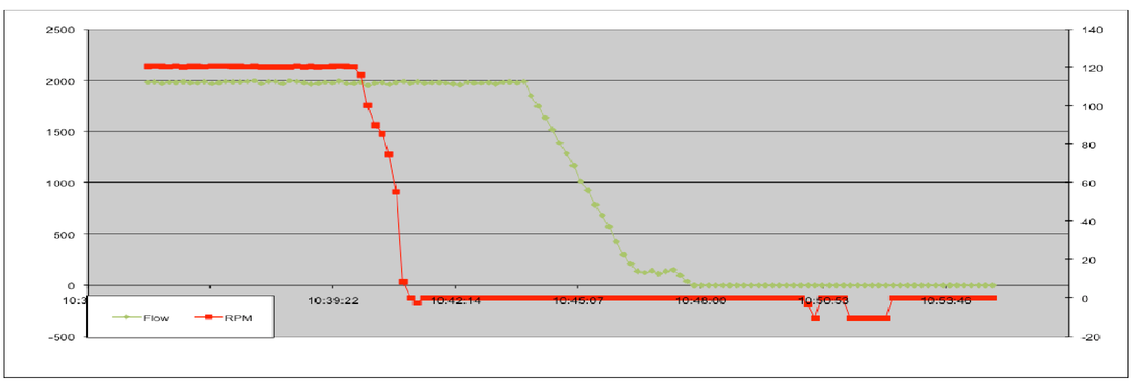

Figure 34 Typical break up procedure.

7.5 Analyzing the data/Results

7.5.1 Procedure

The following procedure was used to relate resolve the task of relating the changes in the BHP to the different drilling parameters:

1) Memory data from the MWD tool was used to understand how the drilling parameters affect the BHP, and thereby relate the changes in pressure to specific drilling parameters.
2) Simulation with the simulating tool Drillbench © was used to identify and verify BHP variations caused by changes in drilling parameters.
3) Based on the two above, calculate an average percentage factor of the total pressure change due to each drilling parameter.

There were found approximately 20 useable runs for analyzing both for the start-up and the shutdown procedure. To analyze the influence of drilling parameters on BHP, the collected data was plotted as illustrated in Figure 32. For plots from all the runs, see Appendix A. From studying these plots, the changes in BHP were related to the changes in the different drilling parameters. However, as the absolute magnitude of the changes to the BHP caused by the different drilling parameters increases with depth, it is imperative to use an analyzing method that allows for comparison between the runs. The method that was used to resolve this was that instead of relating the changes in absolute pressure change to each drilling parameter, where for example ramping up flow rate caused a 5 bar increase in the BHP and starting rotation caused a 2 bar change in the BHP, the changes in pressure by each drilling parameter was given as a fraction of the total pressure change for a given run. Therefore, when referring to percentage pressure change, or percentage effect caused by the different drilling parameters, it is the percentage of the total pressure change that is meant for the remainder of this thesis, unless specified otherwise.

The results are found in Appendix B, for both the start-up and break-up cases.

7.5.2 Start-up cases

From Figure 33 it could be seen that the start-up procedure consists of five different elements with regards to changes in the drilling parameters. Table 2 shows the results obtained for how much each of the drilling parameter affect the BHP after all the start-up runs were evaluated, along with the corresponding variance and Standard Deviation (SD). An explanation to the following parameters presented in Table 2 follows:

- Main Flow; meaning the ramping up of the main flow rate from approximately 75 lpm up to desired flow rate, had a mean value of 62.5 %.
- RPM; meaning starting of drillstring rotation after the main flow has been established, had a mean value of 12.2 % with a corresponding 3.4 % SD.
- Low Flow; meaning the establishing of low flow rate, had a mean value of 15.6 % with a corresponding 3.1 % SD.
- RPM 1; meaning starting rotation of the drillstring before any flow is present, had a mean value of 3.4 % with a corresponding 4.0 % SD.
- RPM 2; meaning stopping rotation of the drillstring before ramping up the main flow, had a mean value of 6.1 % with a corresponding 2.4 % SD.

Drilling Parameter	Mean	Variance	Standard Deviation
Flow	0,6251	0,0041	0,0642
RPM	0,1222	0,0012	0,0341
Low Flow	0,1560	0,0010	0,0313
RPM on	0,0341	0,0016	0,0395
RPM off	0,0610	0,0006	0,0240

Table 2 Mean value, Variance and Standard Deviation of the percentage effect of the different drilling parameters for the start up procedures.

The results found in Table 2 show that the SD for the different factors are rather large. The SD indicates that the percentage effect vary somewhat amongst the different runs. It is therefore apparent that the different runs be evaluated to see if there are any parameters that dominate the distribution of the percentage effects of the different drilling parameters. To do this the percentage effect were plotted against the magnitude of the different drilling parameters to get an indication of which parameters that might dominate the distribution of the percentage effect between the parameters.

7.5.2.1 Flow Rate

The changes in BHP caused by flow rate is highly related to whether or not there are cuttings present in the wellbore. In general for the start up runs, the cuttings concentration is thought to be low, as the cuttings present when drilling is transported quite far up the annulus before a connection is made. It is also, prior to connections, common to verify that hole cleaning is near perfect by taking the weight on the string up and down. This, along with the fact that any problematics regarding YP or gel strength of the mud hopefully has been resolved by the aid of the dedicated start up procedure, indicates that the friction loss due to flow rate is the only parameter present when considering the effect that up ramping of the flow has on the BHP. The magnitude of the friction loss is however decided by which flow regime the flow undertakes in its path up the annulus. When analysing the runs, it was found that the inlet temperature of the drilling mud was approxematly the same as the outlet temperature, and as the flow regime is highly dependent on temperature, or temperature is highly dependent on flow regime, the flow regime in the main part was assumed to be laminar for all the runs, and it is therefore expected that the velocity of the flow rate is the governing parameter to the magnitude of the BHP change.

The absoulte pressure change caused by ramping up the flow rate is also expected to increase with depth as the friction loss is dependent on the length of which it is in contact with the borehole wall. The percentage effect from the flow rate was also thought to increase with depth, as the friction loss caused by the flow was thought to increas the most with depth relative to the friction loss exerted by the other drilling paramters, such as RPM and low flow rate.

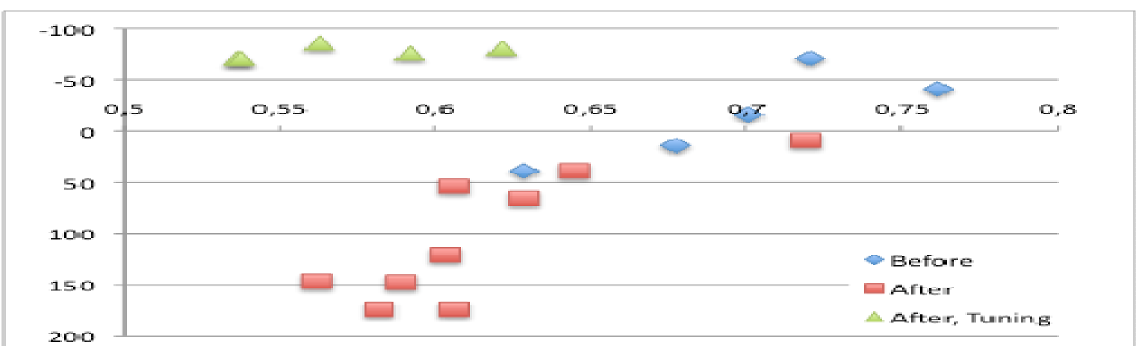

Figure 35. Percentage effect caused by flow rate plotted against depth.

However, when plotting the percentage effect of flow against depth, as is done in Figure 35 where the percentage effect of the total BHP build up caused by flow rate is divided into three groups of before temporary abandonment, after temporary abandonment and tuning session after temporary abandonment and plotted vs. depth, it seems as if the percentage of BHP build-up caused by ramping up the flow rate decreases with depth when excluding five of the runs that are taken from when the MPD system was tuned.

The simulations done in Drillbench © do however not support this trend. Figure 36 shows an identical scenario with regards to the magnitude of flow rate and RPM for three different depths. From this figure it can be seen that the percentage effect on pressure loss caused by ramping up the flow rate should have a slight increase with depth, as was expected in beforehand.

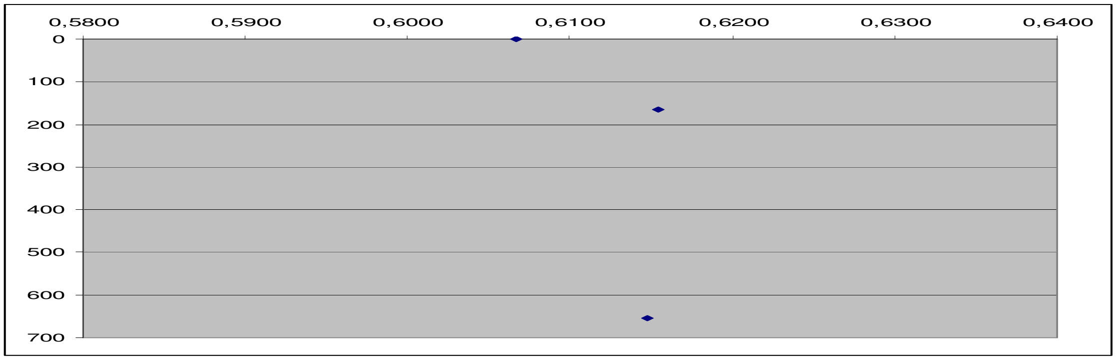

Figure 36 Simulation results obtained in Drillbench © when simulating identical scenarios with regards to the magnitude of Flow Rate and RPM for three different depths.

The two contradicting observations made from real life and simulated data arose the question if the decrease of percentage effect from the flow rate with depth can be explained by other factors.

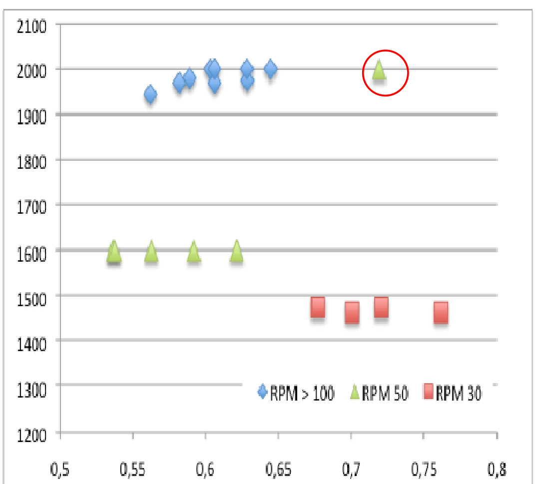

Figure 37 Percentage effect caused by flow rate plotted against magnitude of flow rate.

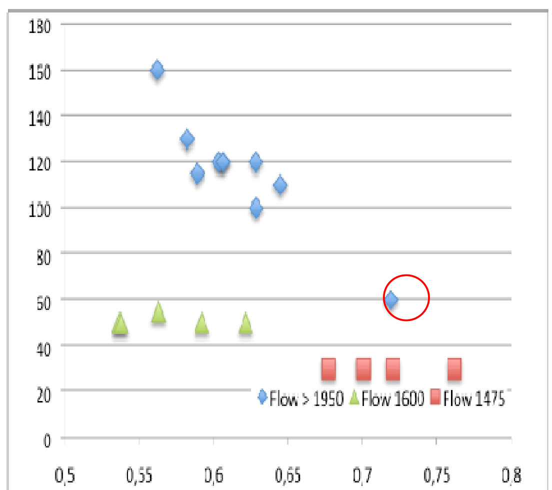

Figure 38 Percentage effect caused by flow rate plotted against magnitude of RPM.

Figure 37 shows the values obtained for the percentage effect of main flow grouped by the magnitude of RPM, and plotted against flow rate. While Figure 38 show the same values, now grouped after magnitude of flow rate, and plotted against RPM.

By evaluating these two figures is seems that Figure 37 show a clear connection between the flow rate and the fractional effect of flow, which is to be expected as a higher flow rate provides a higher friction loss in the annulus. It also seems that Figure 38 gives an indication that there is a connection between the velocity at which the drillstring is rotated, and the percent effect of flow. This would also be to expect as the friction exerted from the rotational effects increases with increasing levels of RPM, where a higher RPM at the same flow rate provides a decrease in the percentage effect caused by flow rate.

Although, what is not expected is that the cases with the lowest flow rate gives the highest averages for the fractional effect caused by main flow. Some of this could be explained with the fact that the RPM values for these cases are low as can be seen in Figure 38. However, the cases with low flow rate and low RPM seems to give just as high a value for the weighted flow average as the one case where there were a high flow rate and a low RPM value circled in red in the two figures Figure 37 and Figure 38. This could of course also be a consequence of human error caused by difficulty in evaluating the pressure plots, as it is only a single incident.

7.5.2.1.1 Alteration in rigid drilling parameters

After investigating the problem of why the cases with low rate and RPM gave the same result as the one case consisting of a high rate and kow RPM, another explanation arose. It was found that the cases taken from the time span before the temporarily abandonment of the well was drilled with a different configuration to the BHA, and a different mud weight, which might have an effect on the percentage distribution to how the parameters affect the BHP.

The difference in mud weight would probably be of miner importance, as the back pressure applied should assure a constant BHP, and thereby what is gained in hydrostatic pressure, is lost in surface back pressure, ideally not changing the BHP. Also, when simulating the two different mud weight scenarios in Drillbench © without the use of back pressure, there was only a small alteration in the percentage effect caused by main flow rate, where a higher MW induces a higher percentage effect of the main flow rate, seen in Figure 39 where the percentage effect of the total BHP build up caused by flow rate is plotted against magnitude of RPM for three different scenarios with regards to MW, flow rate and RPM.

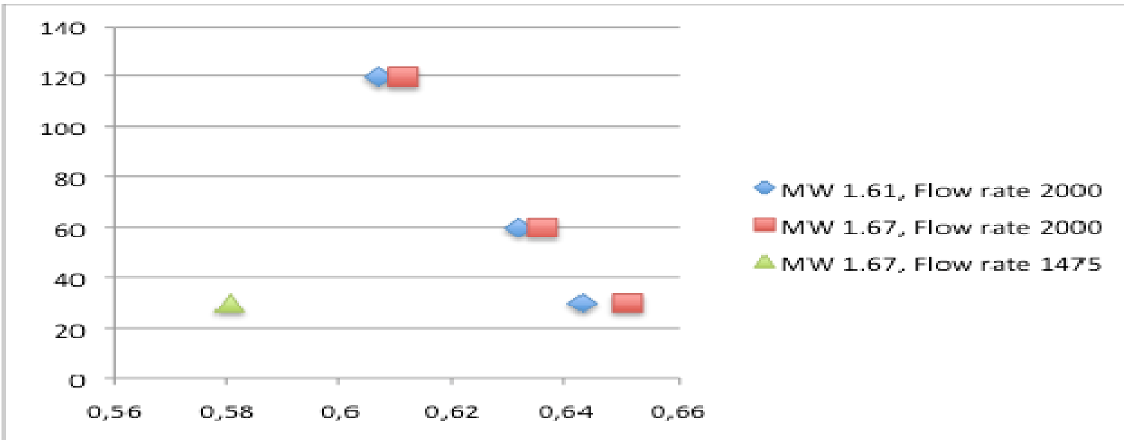

Figure 39 The percentage effect of main flow rate plotted against magnitude of RPM for three different scenarios.

The difference in BHA configuration is more likely to have an effect on how the well behaves with regards to the different drilling parameters. When comparing the two BHAs there was found two differences that might impose a difference to the friction loss. These are listed in Table 3 together with the likely effect, and the reason for these effects.

Difference in BHA configuration	Effect on friction loss	Cause
Longer BHA.	Higher percentage on friction loss caused by flow.	Longer area in which the velocity of the flow is higher.
Longer BHA.	Higher percentage on friction loss caused by RPM.	Longer area where the shear rate becomes higher when rotating.
Longer BHA.	Lesser percentage of friction loss caused by RPM.	Lesser space for Taylor vortices to from in the narrow area between BHA and wall.

Table 3 The effect that the difference in BHA will have on the percentage effect of the total pressure build up caused by flow rate and RPM.

It is difficult to conclude which one of these factors that will dominate from the few data available. Together with the fact that Drillbench © simulations showed the opposite effect for the different BHAs, it was decided that there could not be derived any conclusion to how the different BHAs affected the friction loss, and the runs collected before and after the alteration of the BHA was treated as equal runs.

7.5.2.1.2 H-test

To verify that the differences seen in the two figures Figure 37 and Figure 38 could be due to actual differences in the mean value, and not only explained by chance, there was performed a hypotheses test according to the H-test with a 0.05 level of significance for the three groups outlined in Figure 37 to test:

H0: The mean values of all the populations are the same

H1: The mean values of all the populations are the same

The results are given in Table 4, for calculations see Appendix D.

H-value	10.548
Degrees of freedom	2
$\chi_{2;0.05}$	5.991

Table 4 Results from H-test

From the results presented in Table 4 the null hypothesis can be rejected with a 95 percent probability, indicating that the populations have different mean values, as the H-value (10.548) obtained is larger than the value for $\chi_{2;0.05}$ (5.991). The result found in this test is consistent with the earlier conclusion that the percentage of friction loss due to flow rate is governed by the ratio of flow rate and RPM of the drillstring.

7.5.2.2 RPM

The prediction of what effect the rotation of the drill string would have on the BHP is, as mentioned earlier, rather difficult. When starting to rotate the drillstring, the absolute velocity of the drilling mud is increased, causing an increase in friction loss in the annulus. The rotation, depending on its velocity, could also create Taylor vortices in the fluid flow, causing even further increase in friction loss. If there were cuttings present, the rotation would likely ease the transportation of these, causing a lower the BHP. However, as it was mentioned in the introduction in the previous sub-chapter, the cuttings concentration for the start-up cases is thought to be low, or even non-present for all of these runs, providing the conclusion that the rotation will result in a higher BHP. All the runs collected for he start up cases verified this, see Appendix A. It was also thought that the pressure change seen at the bottom of the hole is a function of the velocity of the rotation, where a higher rotation velocity will educe a higher pressure change.

The effect that the rotation has on the BHP is not expected to increase significantly with depth, at least not compared relative to the increase of effect that the flow rate would have on the BHP with depth. The simulations done in Drillbench © verify this expectation to some extent as the effect of RPM seems first to decrease with depth, but then it increases slightly for the deepest point, as shown in Figure 40 where the results of the RPM effect obtained in the simulations is plotted against depth. However again this does not correlate to the data collected from real life, where it in Figure 41 can be seen that the percentage effect of the total pressure build up caused by rotation slightly increases with depth.

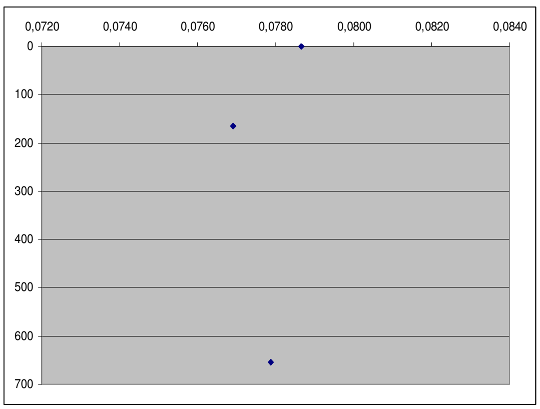

Figure 40 Simulation results of RPM effect plotted vs. depth.

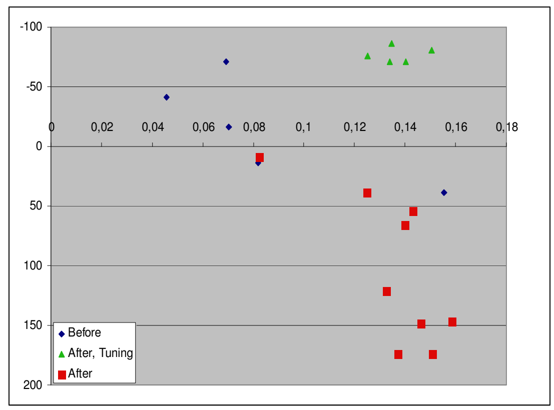

Figure 41 Results obtained from real time data of RPM effect vs. depth.

A reason for this increase with depth relative to the effect caused by the flow rate could be that the eccentricity of the drillstring is a function of depth, causing a higher friction loss due to rotation as the drillstring becomes longer. This increase in eccentricity with depth could be explained by the fact that there is a slight angle of inclination in the well of approximately 45 degrees. However, this angle is not considered to be of too large influence when considering eccentricity as it is relatively small. The reason for the increasing percentage effect due to rotation with depth is therefore thought to be caused by other factors.

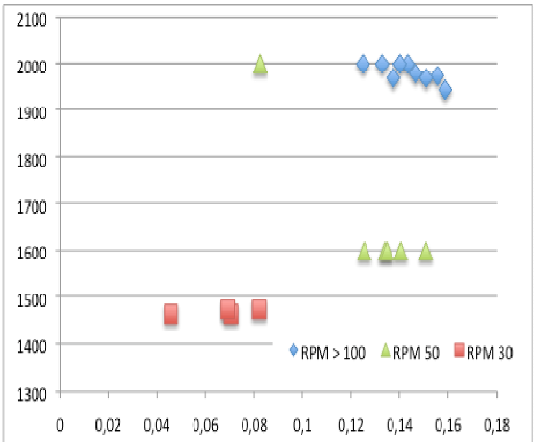

Figure 42 Percentage effect of the total BHP build up caused by rotation plotted against magnitude of flow rate.

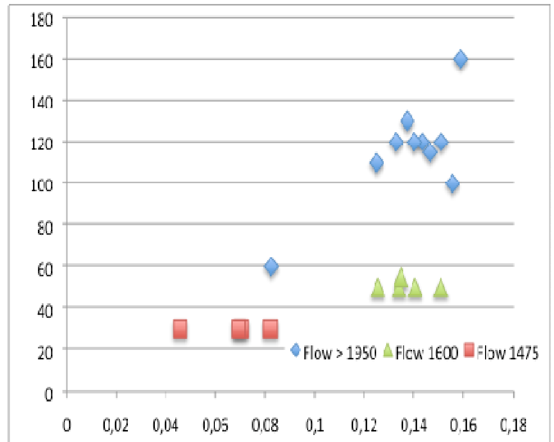

Figure 43 Percentage effect of the total BHP build up caused by rotation plotted against magnitude of RPM.

In Figure 42 the fractional effect obtained for RPM is grouped by the magnitude of RPM and plotted against flow rate. While in Figure 43 the same values are grouped by flow rate, and plotted against magnitude of RPM.

From Figure 42 it can be seen that for the cases collected after the well was resumed seems to be unaffected by the flow rate, with the exception of one run. The reason for the run that deviates can be found in Figure 43, where it is apparent that the magnitude of RPM has an effect, given the same flow rate, where a lower RPM provides a lower percentage value of the effect of RMP. This is also the expected result, as a lower velocity of the drillstring rotation will result in a lower friction exerted to the mud in contact resulting in a reduced absolute velocity of the mud, resulting in a lower friction loss.

However, as pointed out earlier, the different configuration of the BHAs were concluded to not have a significant effect on the friction loss, and that it is more likely that it is the ratio between the flow rate and the RPM that governs the distribution of the effects.

7.5.2.2.1 H-test

From the H-test performed below it can be concluded with a 95 percent probability that there is a statistical reason for rejecting the null hypothesis of: "the mean values of all the populations are the same". This gives reason to believe that the fraction of total BHP build up caused by the rotation of the drillstring is governed by the magnitude of RPM and flow rate as the H-value obtained is greater than the relevant value for $\chi_{2;0.05}$ when testing the three groups distinguished in Figure 43 at a 0.05 level of significance. The results are given in Table 5, for calculations see Appendix D.

H-value	9.456
Degrees of freedom	2
$\chi_{2;0.05}$	5.991

Table 5 Results from H-test.

7.5.2.3 Before the main flow

This conclusion is the same as made for the percentage effect of flow, which also was governed by the magnitude of RPM and flow rate. Since the two are weighted averages of the same incident, it would be expected that if one is influenced by a drilling parameter, then the other one, had it been the only other fraction, would be expected to have an opposite reaction to the same drilling parameter. However, these situations consist of one to three more factors that make up the whole pressure build up. The percentage effect of these the last drilling parameters show no clear relation to either of the other two earlier drilling parameters, RPM and flow rate as will be shown in the following. Actually, common for the three last factors investigated for the "on cases" are that the variation in the effects obtained for these factors does not seem to relate highly to any of the specific drilling parameters.

7.5.2.3.1 Low Flow

The reason for establishing a low flow rate before ramping up to the desired flow rate is, as mentioned, due to the pressure fluctuations experienced when breaking the YP. It is therefore expected that the pressure needed for breaking the YP govern the magnitude in pressure change seen when establishing this low flow. The magnitude of the BHP change is also thought to be affected by the friction caused by the movement of flow. It is therefore expected that the pressure change will increase with depth, as the flow path becomes longer, leading to a longer interval in which the drilling mud is in contact with the borehole wall. However, the percentage pressure change caused by establishing this low flow is not expected to increase with depth, as the absolute pressure change caused by this parameter is thought to increase less with depth relative to the increase imposed by the other parameters, such as Main Flow and RPM. This is also verified by the simulations done in Drillbench ©, which in Figure 44, where the results of the effect of main flow obtained from the simulations is plotted against depth, show that the percentage effect decreases with depth.

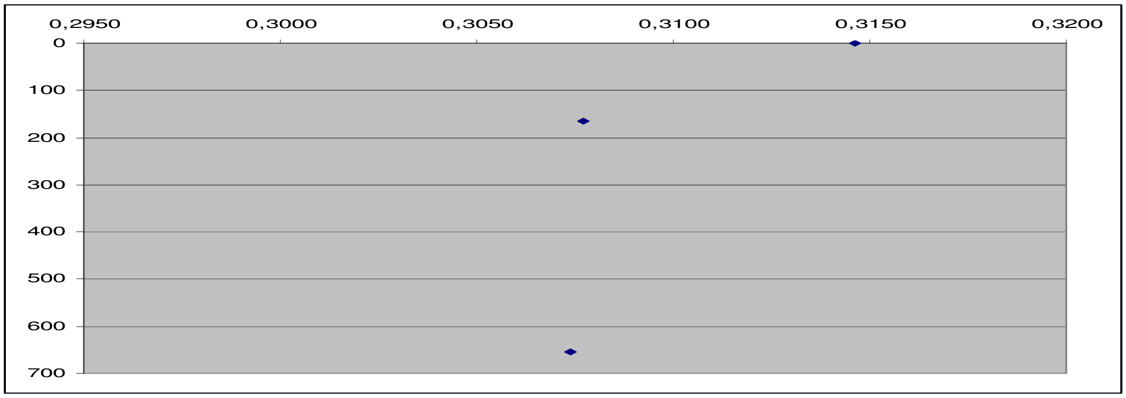

Figure 44 Simulation results of percentage effect of low flow rate vs. depth.

The friction pressure loss caused by establishing the low flow rate was found to make up approximately 15 percent of the total pressure loss, which is the second highest contributor to the total friction loss. It is also the one of the three most influential parameters showing the lowest SD. The reason for this, along with the fact that it seems to be unaffected by the magnitude of the other drilling parameters, could be due to the fact that it is the contact with open hole that governs the magnitude of the friction loss, rather than the magnitude of the other drilling parameters, for such low flow rates resulting in a relative stable percentage effect throughout the drilling operation.

7.5.2.3.2 Starting rotation before flow

Starting the rotation of the drillstring before there is any flow rate present is thought to have little effect on the BHP, as the motion of the drillstring would probably not be sufficient enough for breaking the YP. This expectation is further enhanced by the assumption that the cuttings concentration is relatively low for all the start up cases.

When investigating the data from real life, the difficulty in estimating the effect of rotation of drillstring seems especially true for the rotation that occurs before there is any flow present. The effect of drillstring rotation of the same magnitude seems to differ from causing the pressure to drop by 1.5 bars, to increasing the BHP by 1.5 bars, to having no apparent effect at all, seen in Figure 45, Figure 47 and Figure 49 respectively, where the BHP has been plotted together with RPM vs. time.

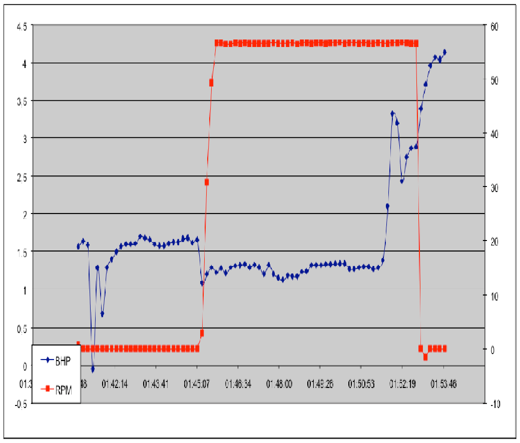

Figure 45 BHP and RPM plotted against time.

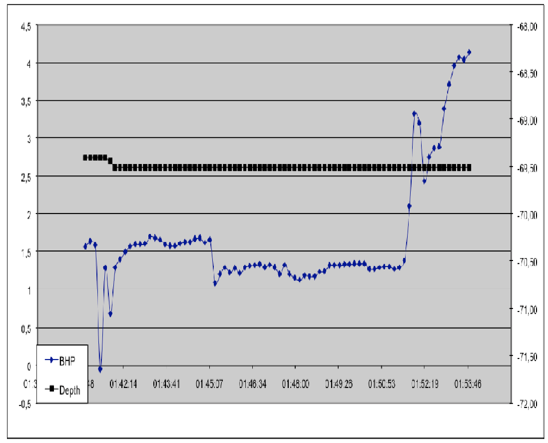

Figure 46 BHP and depth of drillstring plotted against time.

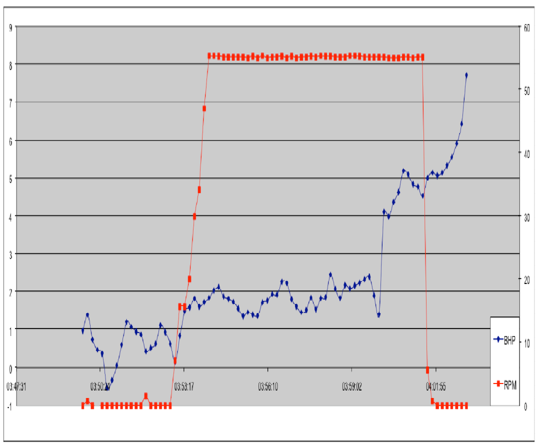

Figure 47 BHP and RPM plotted against time.

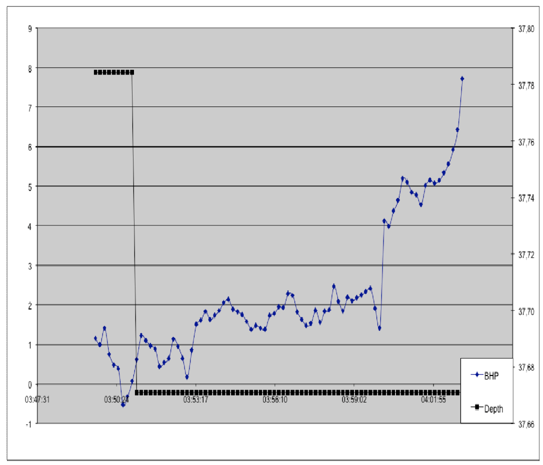

Figure 48 BHP and depth of drillstring plotted against time.

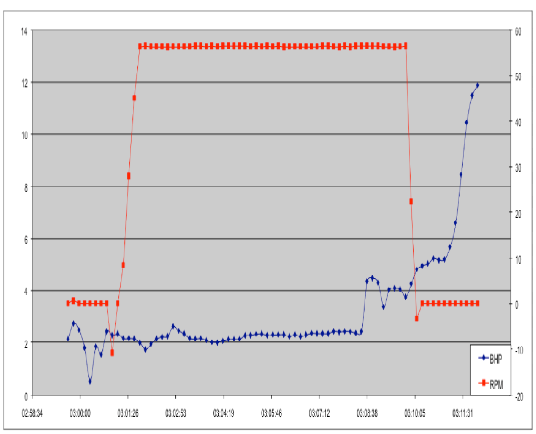

Figure 49 BHP and RPM plotted against time.

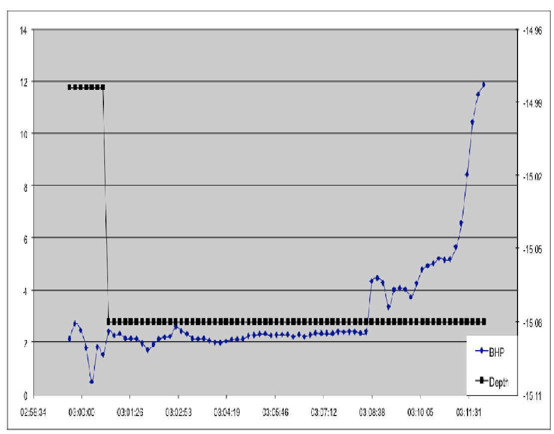

Figure 50 BHP and depth of drillstring plotted against time.

Common for all the runs, not limited to these three, is that there is some drillstring movement prior to the rotation, seen in figures Figure 46, Figure 48 and Figure 50, where the BHP has been plotted together with bit depth vs. time. There was however not found any correlation between the magnitude of the drillstring movement, and the magnitude of the pressure fluctuation seemingly caused by the drillstring rotation. Neither was there found any correlation to whether the drillstring was located on or off the bottom of the wellbore, or if there was any cuttings present, i.e. during drilling, except the fact that all the cases in which the rotation led to a pressure decrease came from runs where the drillstring was located off bottom, as seen in Figure 51 where the weighted values caused by starting the rotation is divided by whether the drillstring was located on the bottom or not.

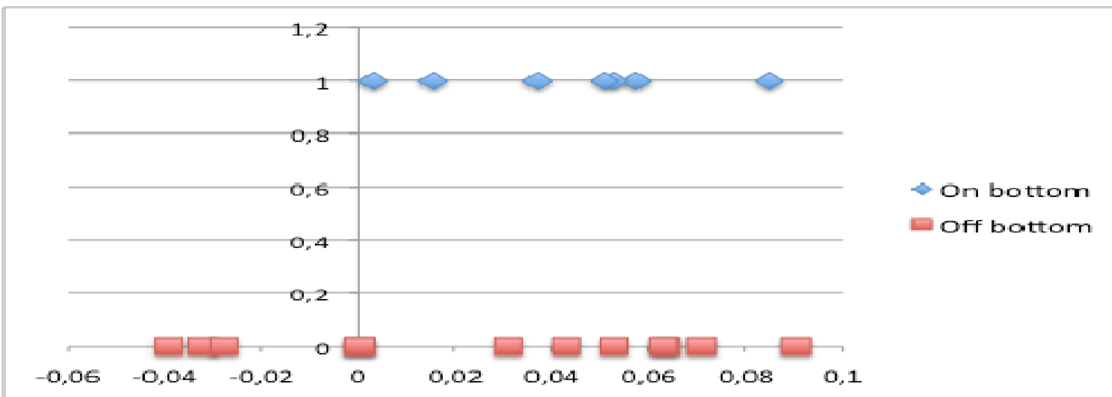

Figure 51 The percentage effects of the total BHP build up caused by drillstring rotation before any flow is present divided by whether the drillstring is located on or off bottom.

Some explanations to what could cause these different effects, in which is impossible to observe with the given data, are eccentricity of the drillstring, flow regime present around the BHA during movement, and the formation of Taylor vortices during the rotation.

7.5.2.3.3 Stopping the rotation during low flow

When stopping the rotation of the drillstring after the low flow rate had been established was thought to have a decreasing effect on the BHP for the same reasons as the rotation after the flow was ramped up to desired rate would cause a increase in the BHP, i.e. it would cause a decrease in the total velocity of the drilling fluid.

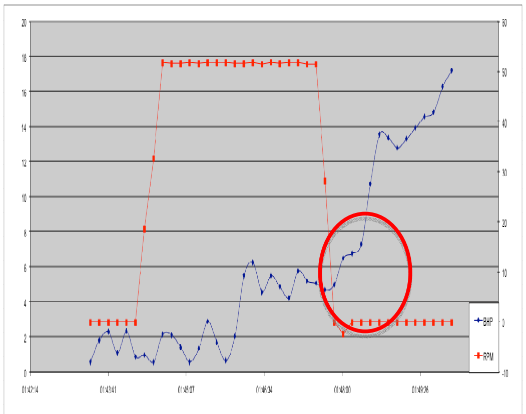

Figure 52 BHP and RPM plotted against time.

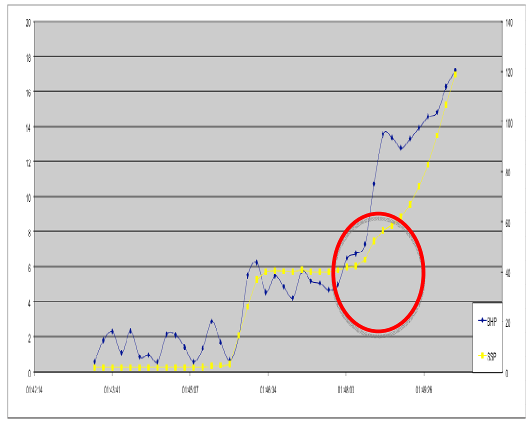

Figure 53 BHP and SPP plotted against time.

However, when looking at the circled part in Figure 52 that shows the change in BHP as the rotation is stopped after the low flow rate has been established, a rather unexpected observation was made. The stopping of rotation seemed to increase the friction pressure loss, and thereby the BHP. This effect could be due to the fact that the stopping of rotation creates instability in the wellbore. It could also be due to inertia effects exerted from the drilling mud, i.e. the mud tries to resist changes. One last explanation could be that the BHP increase is not caused by the changes in rotation, but rather that the pump rate is increased slightly to prepare for increasing the flow rate to the desired level. From Figure 53, one can see that the difference in Stand Pipe Pressure (SPP) matches the difference in BHP for the same incident that is shown in Figure 52, which could indicate that this is the case. After further investigation, the latter explanation seem more likely, as it was found that when having return after breaking circulation the SPP has to be at least as high as the back pressure applied, and that this increase in BHP therefore is a compensation made by the hydraulic model. [45]

7.5.2.3.4 One combined factor?

In the values obtained for the low flow there is one case that differ significantly from the rest, marked with a red circle in Figure 54, which show a plot of all the values obtained for the low flow. This high value can be explained by the fact that the start-up procedure for this specific run differs from the rest in the way that there was no rotation of the drillstring during the low flow. This run is therefore excluded in the mean value of the percentage effect for the three factors that occur before the main flow as it was important to compare similar cases when obtaining a mean value. However, the fact that this run does not differ significantly when looking at the effects of main flow and RPM earlier could indicate that the sum of the effects of the three drilling factors occurring before the main flow is ramped up would add up to approximately the same percentage as for the one special case mentioned above. This strengthens the suspicion that the pressure build up seemingly caused by stopping the rotation before ramping up the main flow is caused by an increase in pump pressure, rather than the rotation stop. Further investigation to whether this is actually the case is beyond the scope of this thesis, but is an observation that might be worth looking into when obtaining more data form new wells.

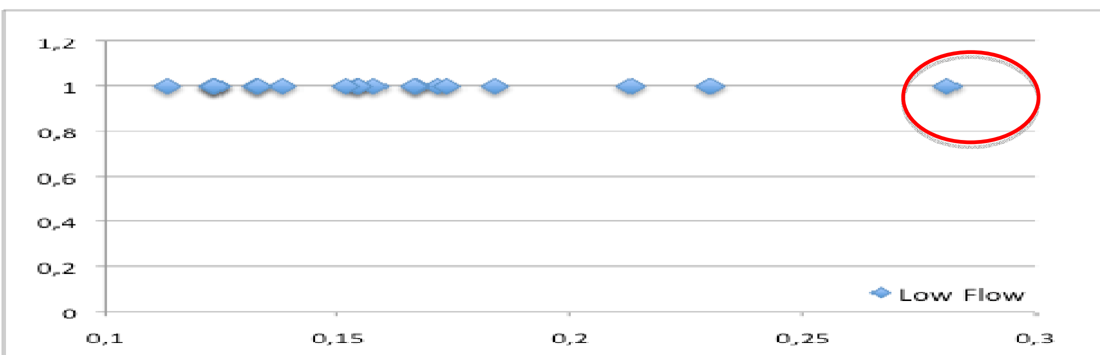

Figure 54 The percentage effect of the total BHP build up caused by establishing a low flow rate.

7.5.3 Break-up cases

The total BHP change in the break-up cases is divided into three parts, each part related to a significant change in a drilling parameter. Figure 55 shows the decrease in BHP related to the same case as was plotted in Figure 34 on page 53, which shows the changes in the drilling parameters, and display a typical break-up case.

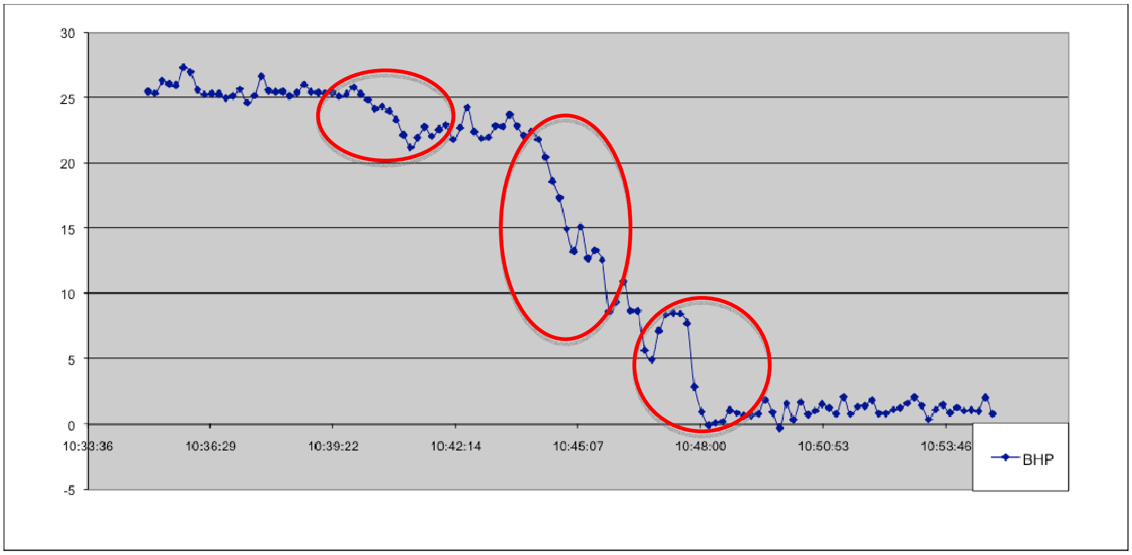

Figure 55 BHP plotted against time for a typical break up procedure.

The first part is related to stopping rotation of the drillstring, referred to as RPM. Reducing the flow rate till approximately 100 lpm causes the second part, which is referred to as Main Flow. The last one, referred to as Low Flow, is related to breaking circulation completely. The reason why they practiced this particular break-up procedure is, as for the start-up cases, to reduce the pressure fluctuations caused by YP and gel strength of the drilling mud. However, this break-up procedure was first practiced after part of the section had been drilled, due to observation of larger BHP fluctuations than expected when breaking circulation. Despite of this, it is to be shown that the effect of RPM and the total flow rate ramp-down has approximately the same distribution, and that it is the magnitude of the RPM and flow rate that seems to be the governing factors regardless to whether a low flow rat is established or not. For the low flow rate ramp-down, it seems as the time length in which the flow rate is kept constant at this low level before ramping down might have an effect on the magnitude of the BHP change.

The values obtained from evaluating the different drilling parameters for the different runs are given in Appendix B. By evaluating this table the mean percentage effect for the different parameters are found, along with the corresponding variance and SD. The results are given in Table 6.

Drilling Parameter	Mean value	Variance	Standard Deviation
Main Flow 1	0,9287	0,0013	0,0363
Main Flow 2	0,6378	0,0034	0,0587
Low Flow	0,2456	0,0043	0,0652
RPM	0,0972	0,0014	0,0377
Combined Flow	0,9028	0,0014	0,0377

Table 6 Mean value, Variance and Standard Deviation of the percentage effect of the different drilling parameters for the break up procedures.

From the table it can be seen that the Main Flow is divided into two factors, one from the cases where a low flow was established (Main Flow 2), giving a mean value of 63.8 %, and one form the cases without this low flow (Main Flow 1) giving 92.9 % with the corresponding SD of 5.9 and 3.6 % respectively.

The mean percentage factor for breaking the Low Flow was found to be 24.6 % with a corresponding SD of 6.5 %.

For the RPM the mean percentage was found to be 9.7 % when comparing all the cases, with a SD of 3.8 %.

The last factor in Table 6, Combined Flow, refers to the mean value obtained when combining the effects form the two different flows giving a mean value of 90.3 % and a SD of 3.8 %.

7.5.3.1 Rotation

The effect that the stopping of rotation would have on the BHP is thought to be governed by the same factors as for the starting of rotation for the start up runs, however in the opposite direction, causing a decrease in BHP as the rotation is stopped. There is however a significant difference that has to be accounted for when estimating the effect of the rotation stops in the break-up cases compared to the start up cases, and that is the presence of cuttings. When stopping the rotation in these cases, the time period from when the drilling commenced to the changes in drilling parameters is less than for the start up cases, and the assumption of the cuttings concentration being low cannot be made for the ramp down cases. The magnitude of the BHP change was therefore expected to be higher for the runs in which a ROP was reported before the rotation was turned off, as the rotation provides an increase in the transportation property of the drilling mud. However, when analyzing the data obtained from the well, there seemed to be no correlation between ROP and a lower percentage effect of the rotation to the total BHP change, as seen in Figure 56 where the runs have been divided into two groups, one with the runs that has a reported ROP, and one without ROP.

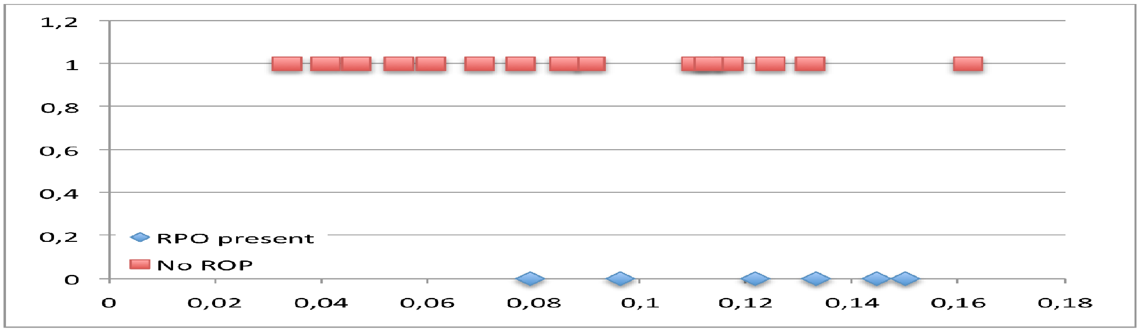

Figure 56 Effect of ROP on the percentage effect of RPM.

The reason why the percentage effect that the RPM had on the BHP change seemed to be unaffected by the presence of cuttings is most likely due to the fact that the cuttings concentration affect the whole friction loss picture, i.e. also having an effect on the flow factor.

7.5.3.1.1 RPM 1 vs. RPM 2

As mentioned above, there are two scenarios for the break-up cases, one where low flow rate is established before breaking circulation completely, and one where the practice of this low flow rate is not followed. When plotting the values obtained for the percentage effect of rotation, there seems to be a difference in the fraction of the total BHP decrease caused by stopping the rotation obtained from the two scenarios. This can be seen in Figure 57, where RPM 1 relates to the cases where the low flow is not practiced, and RPM 2 relates to where there is a stable low flow rate before break up.

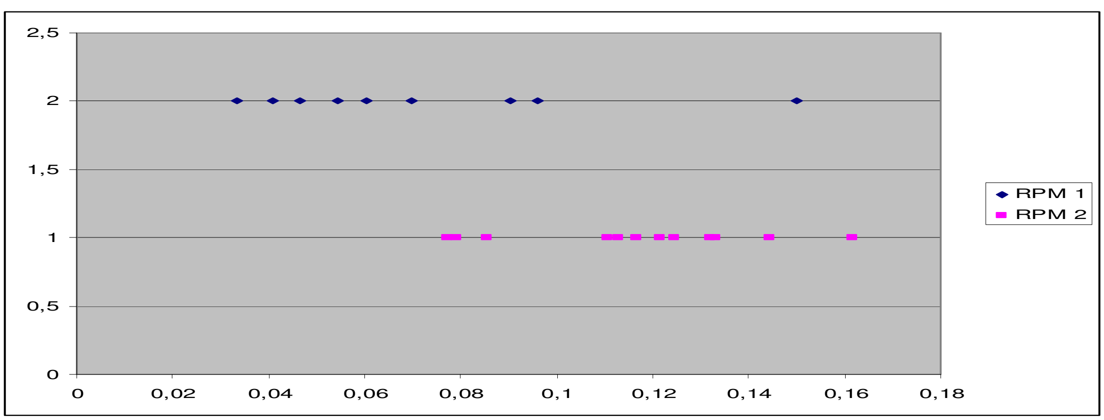

Figure 57 The percentage effect of the total BHP drop caused by stopping the rotation of the drillstring, divided by whether there was established a low flow rate or not.

7.5.3.1.2 Welch's t-test

For testing whether these two sample means are a part of the same population, the Welch's t-test is selected to test the null hypothesis of the mean values being part of the same population with a 0.05 level of significance, for calculations see Appendix D.

t-value	3.185
Degrees of freedom	14
$T_{14;0.05}$	1.761

Table 7 Results from the Welch's t-test.

The results given in Table 7 show that, since $t > T_{14;0.05}$ it can with a 95 percent probability be concluded that the null hypothesis of: "The mean values of the two populations are the same" can be rejected. This strongly indicates that the two mean values do not originate from the same population, which is in accordance with the suspicion above.

7.5.3.1.3 RPM vs. flow rate and rotation velocity

However, when investigating the cases more closely, it was discovered that the magnitude of the frictional pressure drop caused by RPM probably was governed by the combination of the velocity at which the string was rotating prior to stopping, and the flow rate present in the wellbore before break-up. From Figure 58 it can be seen that by dividing the percentage effect caused by stopping the rotation into groups dependent on the flow rate, and plotting these against the magnitude of RPM, there seems to be a relationship between the flow rate and velocity of the rotation, which seems to gather into four distinct groups.

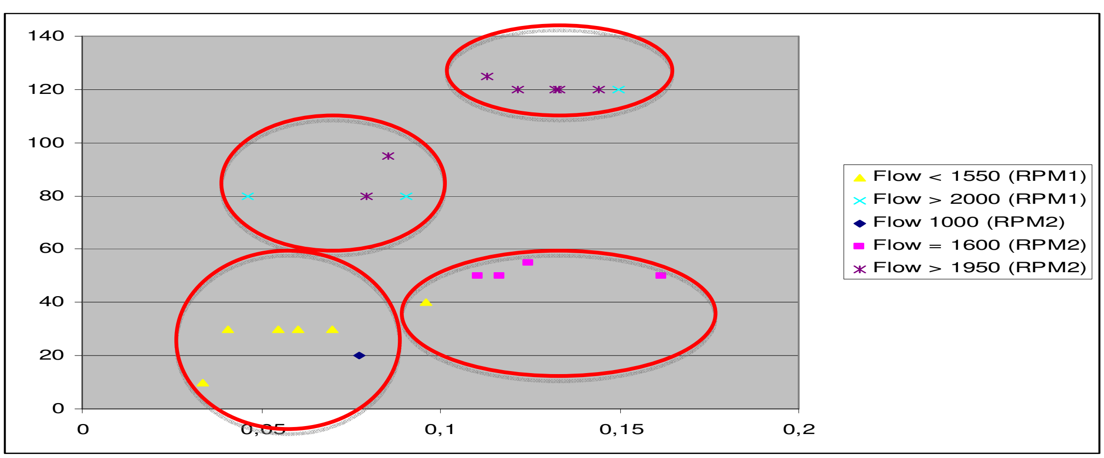

Figure 58 The percentage effect of the total BHP drop caused by stopping the rotation of the drillstring grouped by the magnitude of flow rate, and plotted against time.

7.5.3.1.4 H-test

In Table 8 below, the results of the H-test performed on the four groups defined in Figure 58 is found. The null hypotheses of: "The mean values of all the populations are the same" was tested at a 0.05 significance level. From the results it can be concluded with a 95 percent probability that this null hypothesis be rejected, and that the samples most likely do not originate from the same population, i.e. they are not unaffected by the drilling parameters, as the H-value obtained is greater than the value obtained for $\chi_{3;0.05}$. For calculations see Appendix D.

H-value	16.035
Degrees of freedom	3
$\chi_{3;0.05}$	7.815

Table 8 Results from H-test.

7.5.3.2 Flow

As for the stopping of rotation for the break up cases, the ramp down of flow rate will probably be governed by the same factors as for the ramp up of flow for the start up cases, with the exception of the assumption of low cuttings concentration. However, as for the rotation, the percentage effect of ramping down the flow seems to be unaffected to whether there are cuttings present or not, which can be seen in Figure 59 where the runs with a reported ROP is grouped apart from the runs where no ROP was reported.

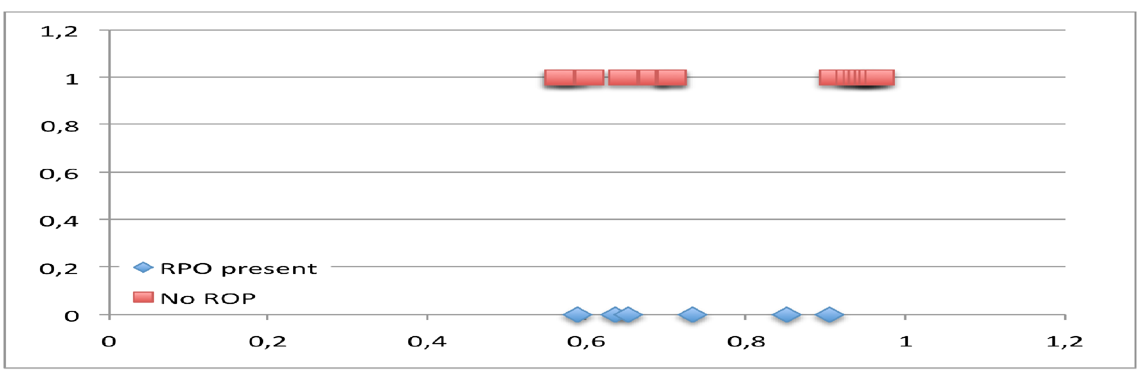

Figure 59 Effect of ROP on the percentage effect of Main Flow.

The fact that the percentage effect that the flow ramp down has on the total BHP change seems to be uncorrelated to the presence of cuttings indicates that all the runs can be analyzed together. However, as mentioned earlier, the dedicated ramp down procedure suggested for the MPD operation was not implemented until a while into the operation, providing two different scenarios for the ramp down cases.

7.5.3.2.1 Main flow vs. Low flow

As the percentage effect that RPM has on the BHP decrease during break-up runs seems to be unaffected by whether the flow rate is reduced in one or two steps, it would be expected that the total effect from the ramping down of flow rate also where unaffected by this, as they are weighted averages of the same total effect. To illustrate that this in fact is the case, the two scenarios are plotted apart in Figure 60, where Flow 1 refers to the percentage effect of the flow where the flow rate is ramped down in one step, and Flow 2 refers to the effect of the main flow ramp down in the scenarios where the flow is ramped down in two steps.

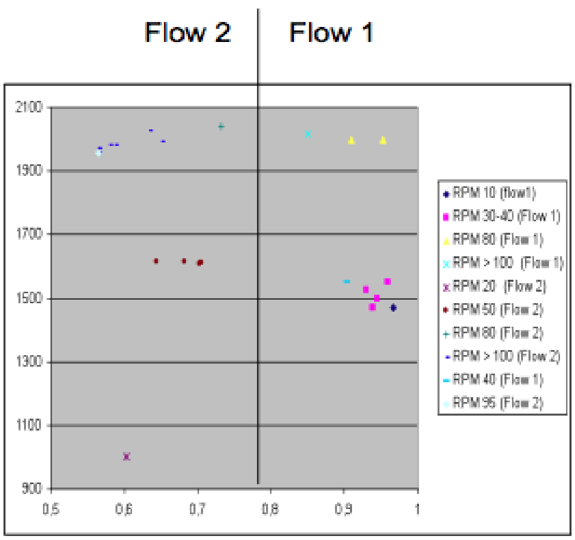

Figure 60 The percentage effect of the total BHP drop caused by breaking up the main flow rate, grouped by the magnitude of RPM, and plotted against magnitude of flow rate.

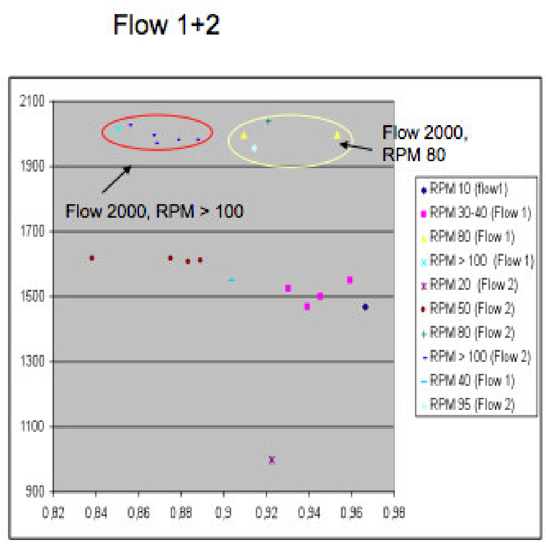

Figure 61 The percentage effect of the total BHP drop caused by breaking up the total flow rate, grouped by the magnitude of RPM, and plotted against magnitude of flow rate.

When combining the weighted averages of Flow 2 with the corresponding weighted averages for the low flow, as done in Figure 61, one can see that this combined value, referred to as Flow 1+2, groups together with the cases of Flow 1 having approximately the same pair of flow rate and RPM values.

The fact that neither the cuttings concentration, nor the two different ramp down scenarios seemed to govern the percentage effect that the total ramp down of the flow had on the BHP change makes it possible to analyze all the runs together.

The governing factors for how the fractional effect of ramping down the flow rate would therefore be the same as for the RPM as these are the two only drilling parameters present. The percentage effect of the total flow rate is therefore governed by the magnitude of the drilling parameters flow rate and RPM.

7.5.3.3 Low Flow

Even though the earlier analysis showed that by combining the percentage effect caused by the low flow rate and the high flow rate, for the runs where the low flow rate was present, one would obtain approximately the same total percentage effect as when there was no low rate present, an analysis of the runs where the low flow rate was present was found to be important, as it is this procedure that is thought to be followed when in future MPD operations.

Deciding the BHP changes caused by breaking up the low flow rate was rather difficult, as stopping the flow rate at approximately 100 lpm caused a fluctuation in the BHP, which can be seen in Figure 62 where the BHP has been plotted in a case where a low flow rate was established. This difficulty is also mirrored in the SD found for the mean value of the effect of breaking the low flow rate, which is the highest SD obtained in this study.

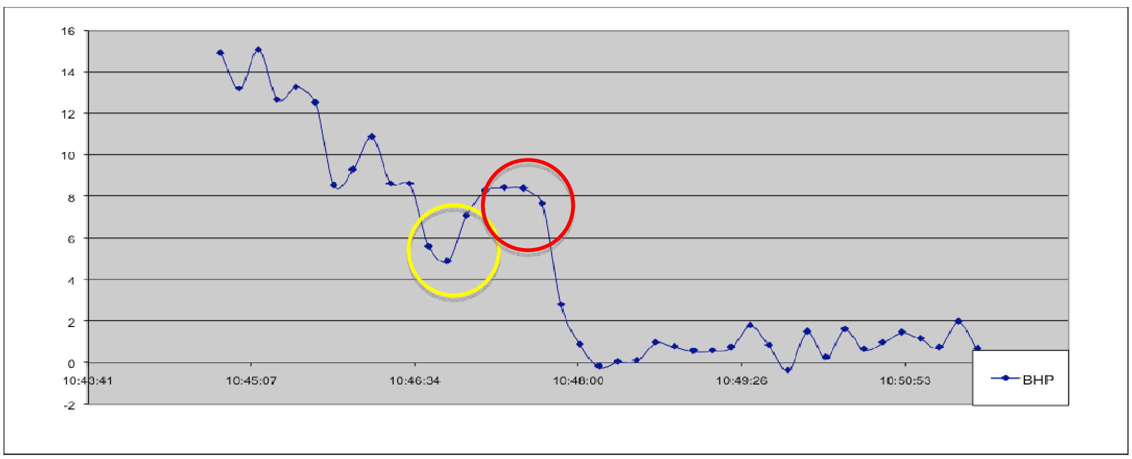

Figure 62 BHP plotted against time for a run where a low flow rate is established.

The dilemma was whether to take the reading from the lowest point, circled in yellow in Figure 62, which would give the ramp down of the main flow a greater emphasis, or start the measurement from the point where the BHP had stabilized, just before turning off the last 100 lpm, circled in red. It was decided to follow the latter option, giving greater emphasis to the low flow. This however, caused some difficulties as the low flow rate for some cases was hold for quite a short time span, not giving the BHP time to stabilize completely. There seems also to be a correlation between the magnitude of the changes in BHP and the time in which the low flow rate is held, plotted in Figure 63.

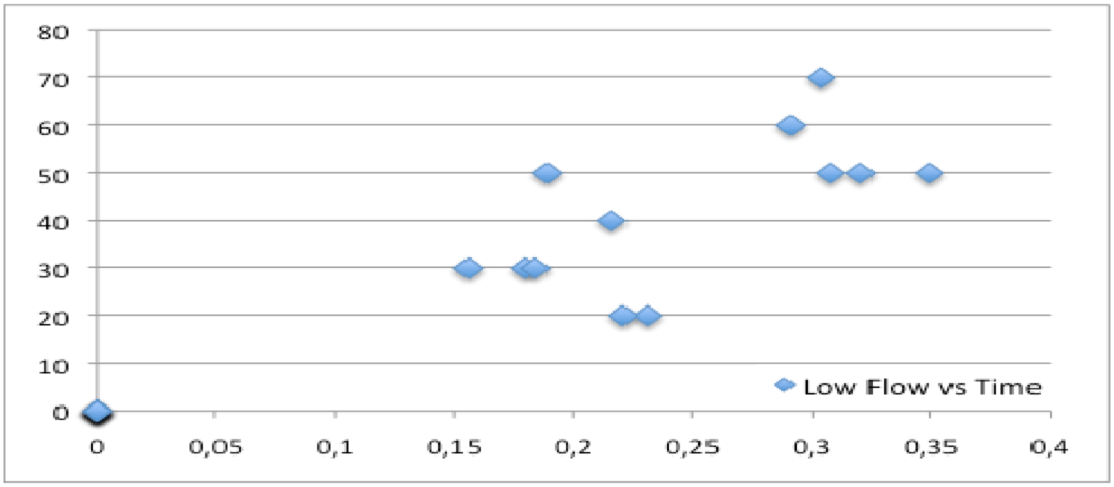

Figure 63 The effect of time on the percentage effect of the total BHP drop caused by breaking up the low flow rate.

However, as there are not sufficiently enough cases in which there is a low flow rate present, it is difficult to conclude anything about which parameter that affect the magnitude of the BHP decrease in relationship to the low flow rate. By comparing four of the runs, on can see from Table 9 below that there are quite a few parameters that change for each case, which make it impossible to conclude which factors that governs the magnitude of the BHP decrease for the low flow. There are therefore not made any distinction between the low flow effect in the different runs. However, as more data become available from new wells, this should be looked into.

Parameter	Run: 06/07 03:15	Run: 08/07 04:10	Run: 08/07 06:00	Run: 08/07 10:35
Operation	MPD Tuning	Drilling	Drilling	Drilling
Max gas in wellbore	?	2.9 %	5.2 %	1.8 %
Depth	- 76m MD	89m MD	119m MD	174m MD
Delta BHP	3.2 bar	4.6 bar	5.2 bar	7.1 bar
% of total pressure drop	18.4 %	21.6 %	22.1 %	29.1 %
Time length	20-30 sec	40 sec	10-20 sec	60 sec

Table 9 Parameters that may have an effect on the magnitude of the percentage effect of the total pressure drop of the BHP caused by breaking up the low flow rate.

8 Summary and Conclusion

A study of real time data from the MPD operation performed on Well A drilled on the Gullfaks field in 2009 was performed to obtain a percentage distribution to how much each drilling parameter contributed to the total BHP change during start-up and break-up procedures. Simulations performed in Drillbench © was thereby used to aid the work of deciding which parameters that governed the distribution.

8.1 Start-up cases:

From analyzing the real time data the mean value for the percentage effect of the drilling parameters was found to be 0.6251 for Main Flow, 0.1222 for RPM, 0.1560 for Low Flow, 0.0341 and 0.0610 for the two RPM changes, RPM on and RPM off, occurring before the main flow was ramped up.

When analyzing which factors that might govern the percentage effects found for the different drilling parameters, it was found that the percentage effect of the total BHP build up caused by ramping up the main flow rate and the RPM seem to be mainly affected by the ratio of the magnitude of the flow rate and RPM.

The percentage effect of the total BHP build up caused by establishing the low flow rate seem to be unaffected by the magnitude of the other drilling parameters, as where also the case for both the starting and stopping of drillstring rotation before ramping up the main flow.

The percentage effect of the BHP build up of all the drilling parameters seemed to be rather unaffected by depth, at least within the section, which indicates that it would be possible to establish the percentage factors of the drilling parameters for new wells high up in the section to be drilled, providing early input to the hydraulic model.

8.2 Break-up cases:

When analyzing the real time data from the break-up cases, it was found that there were two different scenarios, as the break-up procedure of establishing a low flow rate before breaking circulation completely was not implemented until a while into the operation. It was therefore found two different percentage factors for ramping down the main flow, one for the cases where there was no low flow rate present, proving to be 0.9287. For the cases where there was established a low flow rate the effect on the BHP decrease caused by the Main Flow was found to be 0.6378.

For the cases where there was a low flow rate, the percentage effect for the low flow was found to be 0.2456.

The difference in the mean value of the percentage effect of the total BHP decrease caused by RPM in the cases of where a low flow was established and where it was not established was found to significantly differ according to the t-test performed. However, a more likely explanation to the difference was found when investigating the percentage effect of RPM against the magnitude of flow rate and the velocity at which the drillstring was rotation prior to stopping. The effect of the RPM then seemed unaffected by the presence of whether a low flow rate was established or not, and the mean percentage effect of RPM change was therefore found to be 0.0972 for all the cases.

When combining the effects from the ramp down of the main flow rate and the low flow rate, at cases where this low flow rate was present, it was found that this combined value seemed to gather with the percentage effect for the ramp down of flow where there was not established a low flow rate, when grouping the cases into groups based on the magnitude of RPM and main flow rate. This indicates that the effect on the BHP decrease caused by the total ramp down is unaffected by whether a low flow rate is established or not.

There were not enough cases in which there was established a low flow rate to conclude which factors that governed the distribution of the percentage effect caused by ramping down the low flow rate.

The percentage effect of all the drilling parameters seemed to be rather unaffected by depth, as was the case for the start up runs.

It seemed that the presence of cuttings did not have any apparent effect to the distribution of which drilling parameter that contributed the most.

8.3 Recommendations

As the percentage distribution to which drilling parameters that affect the BHP probably would be dependent on relative rigid drilling factors, such as for example well bore geometry, inclination, formation temperature etc. the percentage factors would have to be established for new wells.

Since it was found in this thesis that the percentage effect of the drilling parameters were found likely not to be affected significantly by depth, it would for new wells be possible to establish these factors at an early stage. However, as the magnitude of the RPM and flow rate seemed to be the most influencing parameters to how the percentage effect would distribute between the drilling parameters, new distributions would have to be established every time these parameters are altered.

8.3.1 Further work

When data from new wells become available, these should be analyzed to see if the changes in rigid drilling parameters, like wellbore geometry, temperature etc., would result in a significantly different distribution to which of the drilling parameters that affect the BHP changes.

When obtaining new data it should also be performed a study to investigate which factors that govern the magnitude of the effect caused by breaking the low circulation rate, as there was an insufficient amount of cases in which there was established a low flow rate in the break-up cases available at the time of writing this thesis.

The conclusions drawn from this thesis are to be tested in a pilot test at Ullrig in the near future. The results from this test should then be evaluated and compared to the conclusions here to see if there is a consistency in the results obtained.

Abbreviations

ANOVA	Analysis Of Variance
BHP	Bottom Hole Pressure
CBHP	Constant Bottom Hole Pressure
ECD	Equivalent Circulating Density
gpm	Gallons per Minute
HPHT	High Pressure High Temperature
HSE	Health Safety and Security
IADC	The International Association of Drilling Contractors
lpm	Liters per Minute
MPD	Managed Pressure Drilling
MW	Mud Weight
MWD	Measurement While Drilling
NPT	Non-Productive Time
NRV	Non-Return Valve
OBM	Oil Based Mud
PLC	Programmable Logic Controller
PV	Plastic Viscosity
RCD	Rotating Controller Device
ROP	Rate Of Penetration
RPM	Revelations Per Minute
SBM	Synthetic Based Mud
SD	Standard Deviation
SPP	Stand Pipe Pressure
UBD	UnderBalanced Drilling
UBO	UnderBalanced Operation
WBM	Water Based Mud
YP	Yield Point

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Appendix A

Start-up runs

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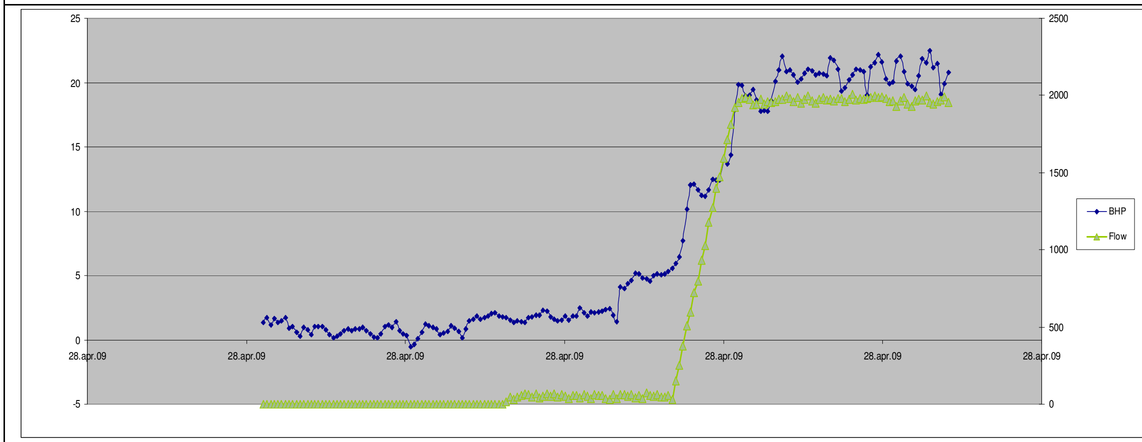

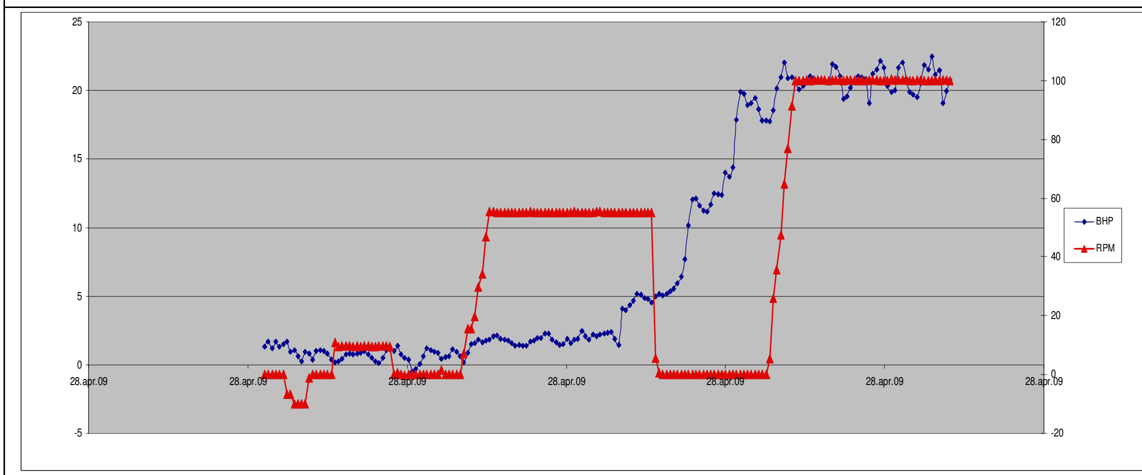

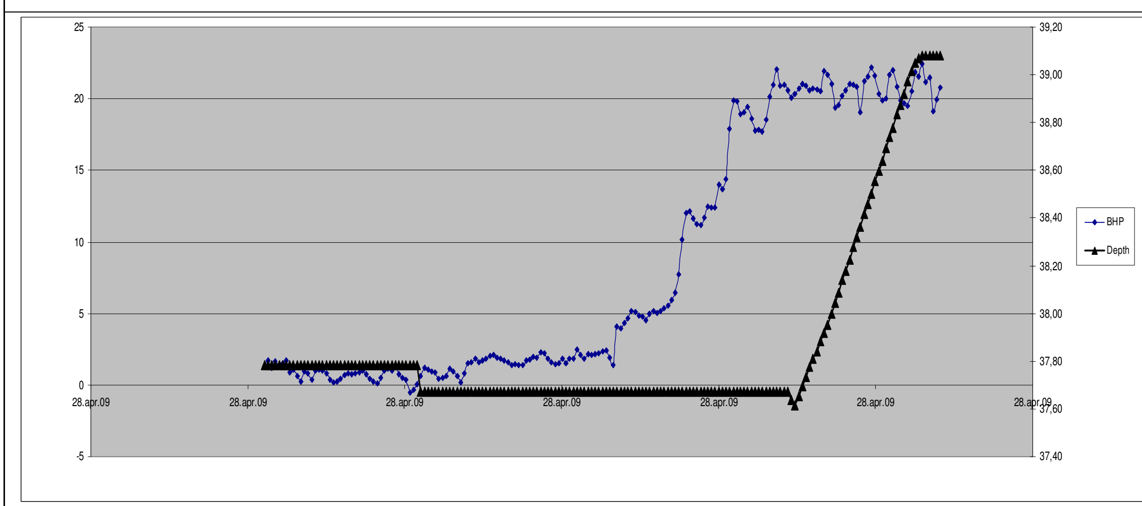

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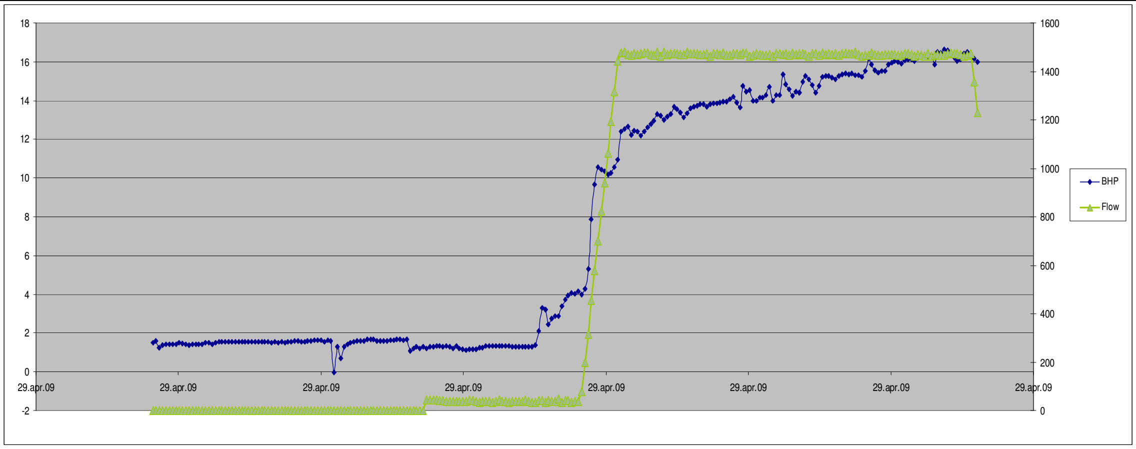

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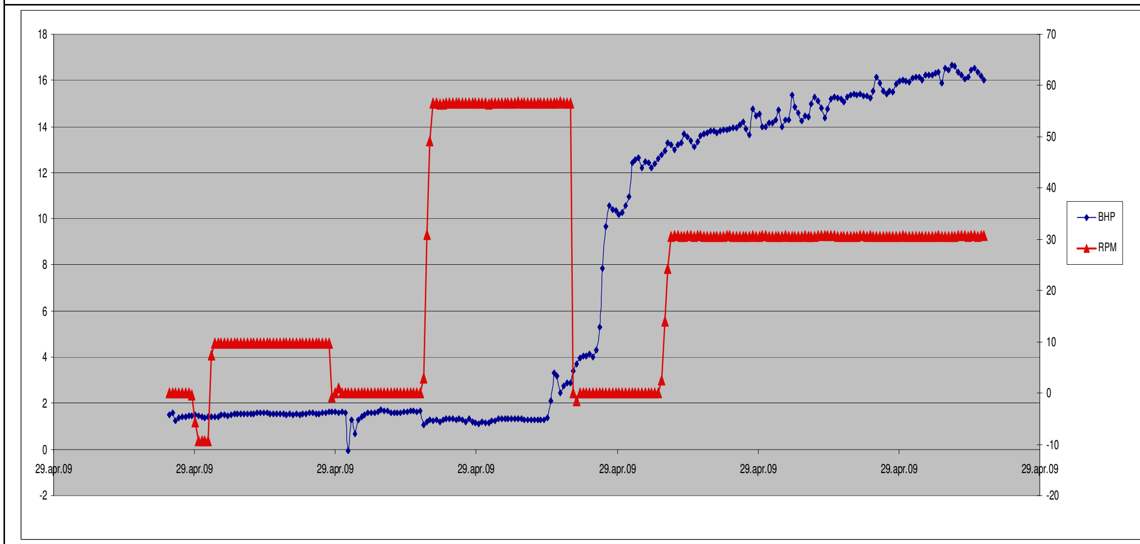

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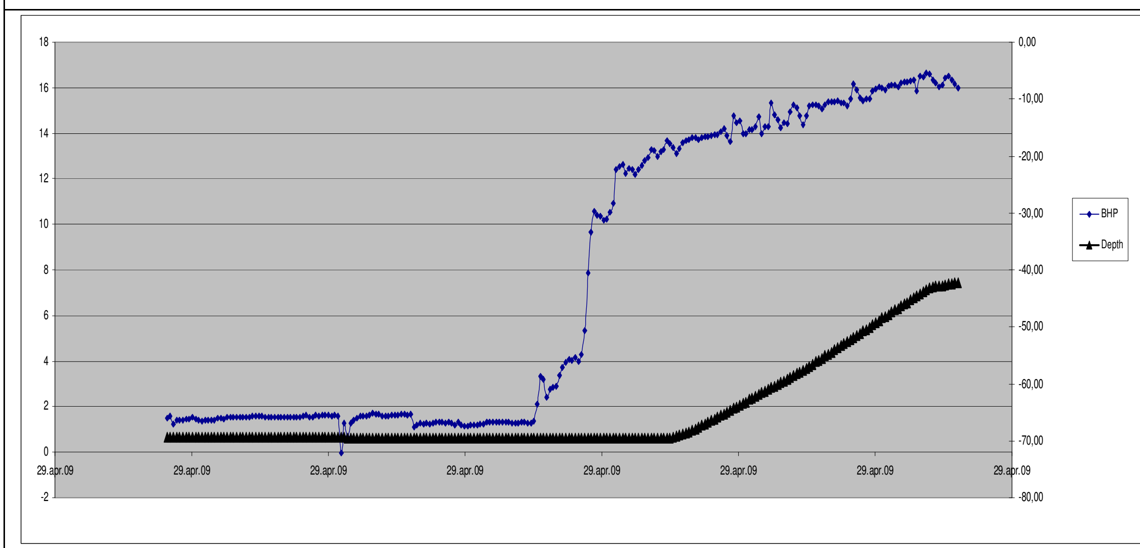

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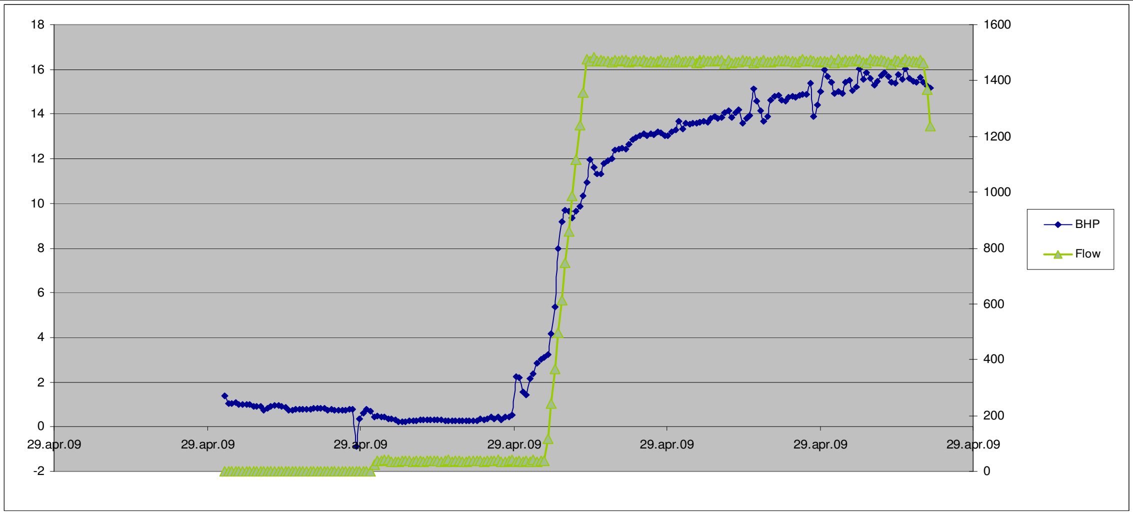
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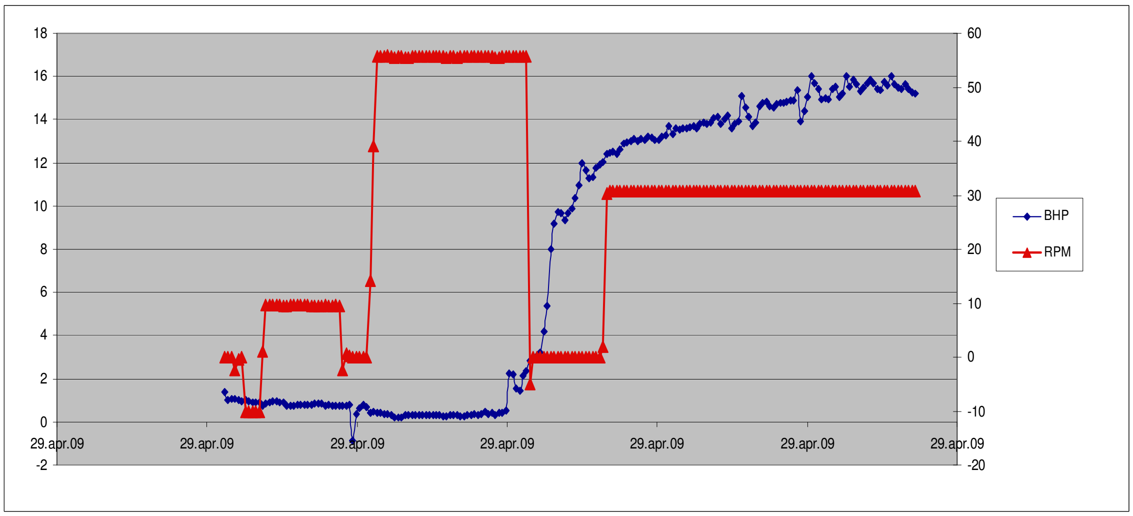
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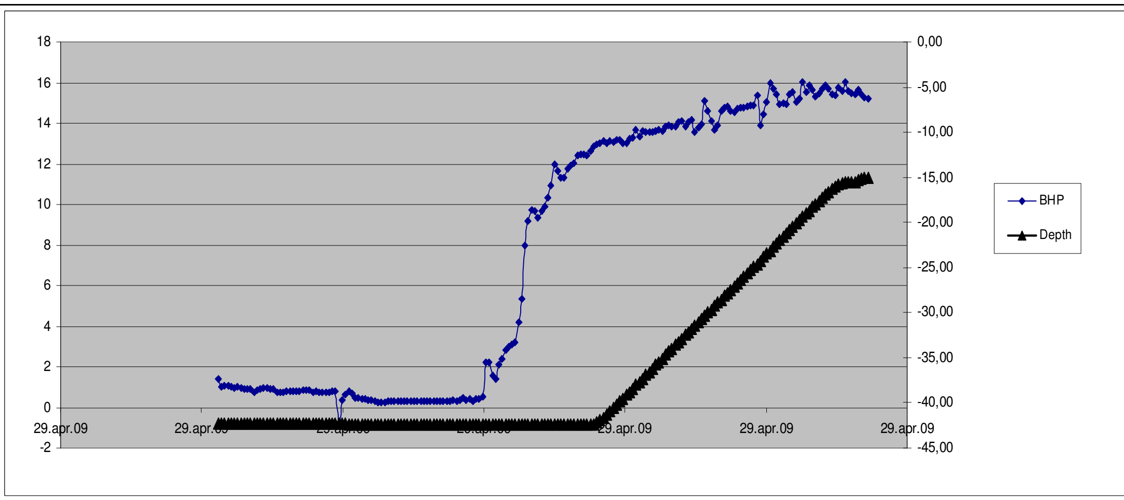
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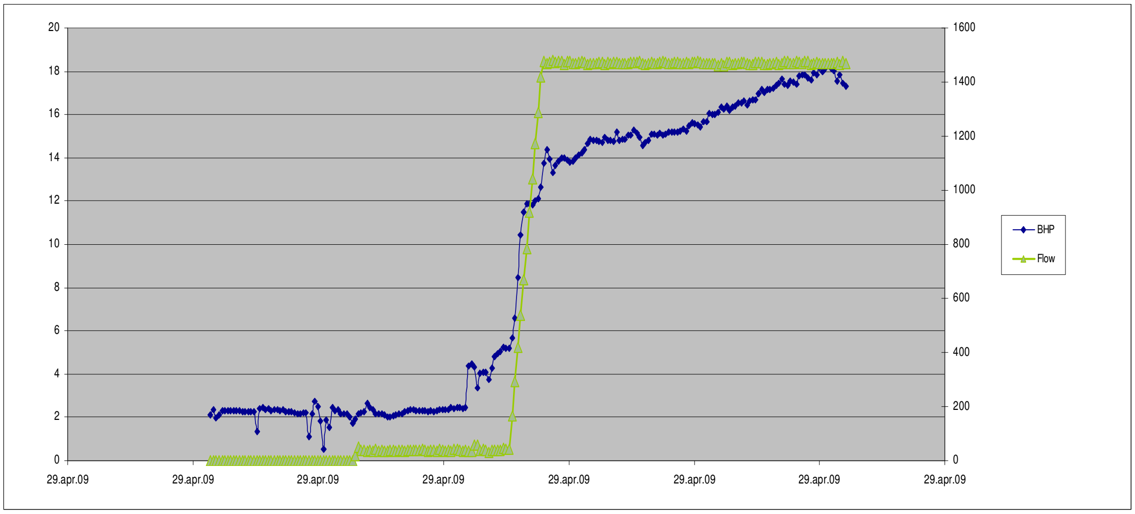

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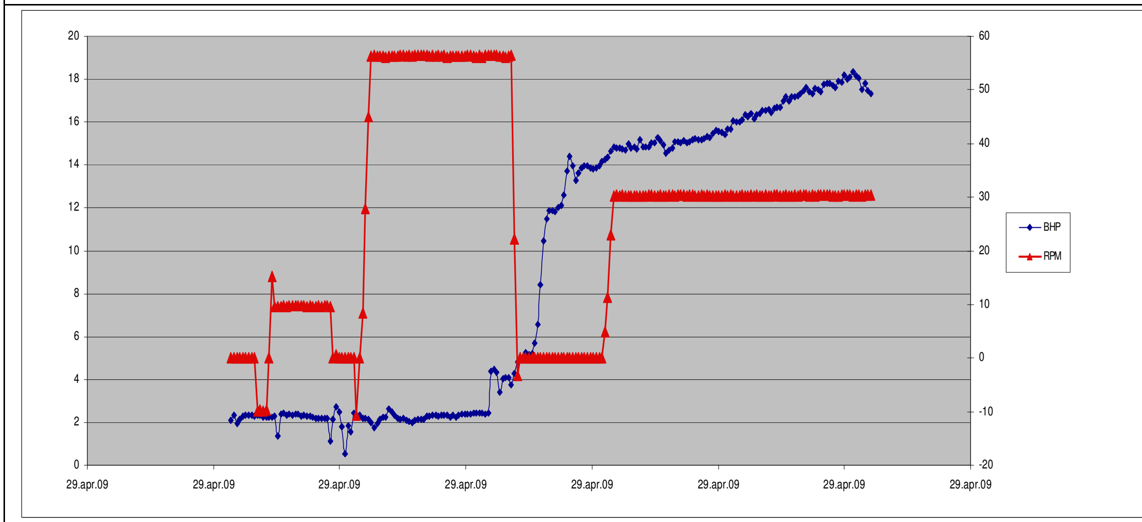

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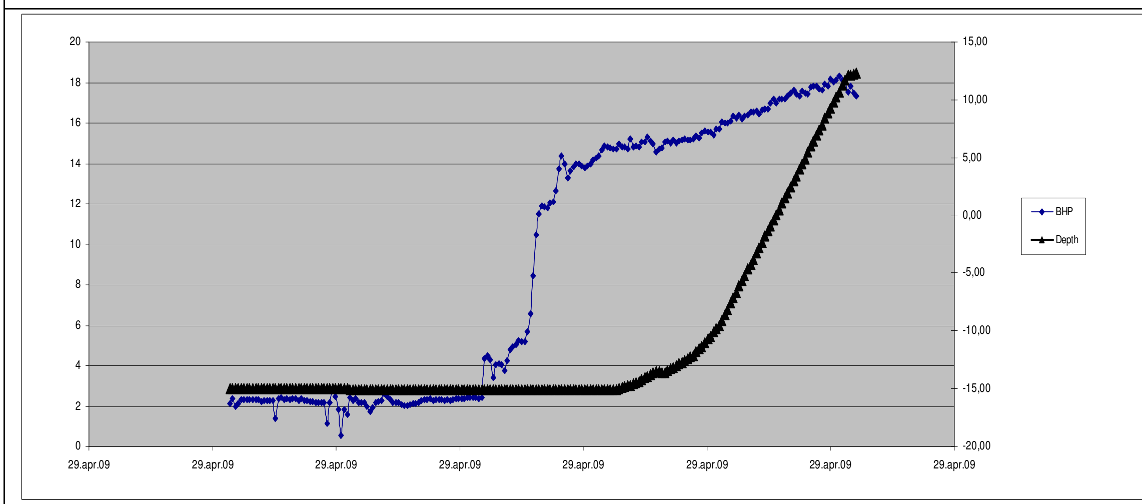

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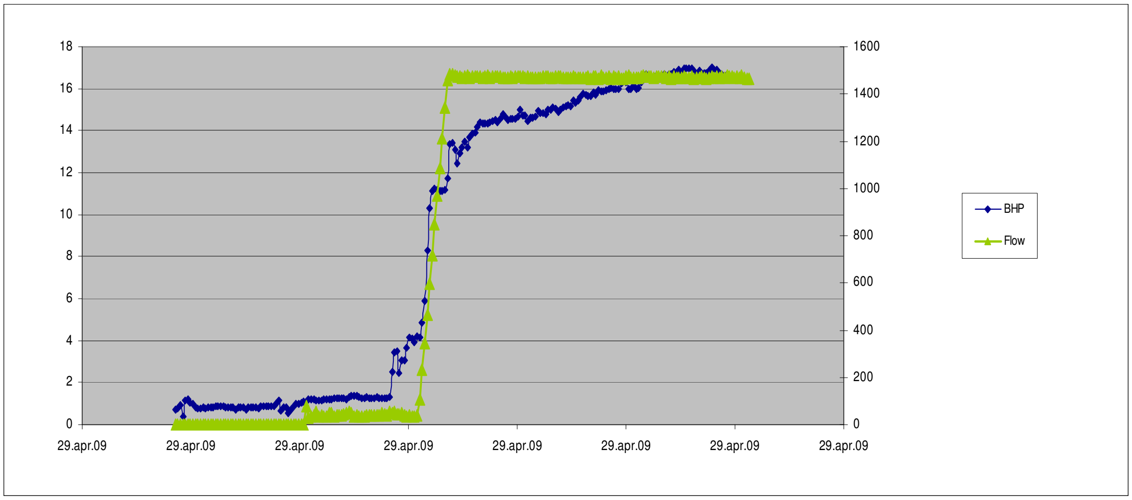

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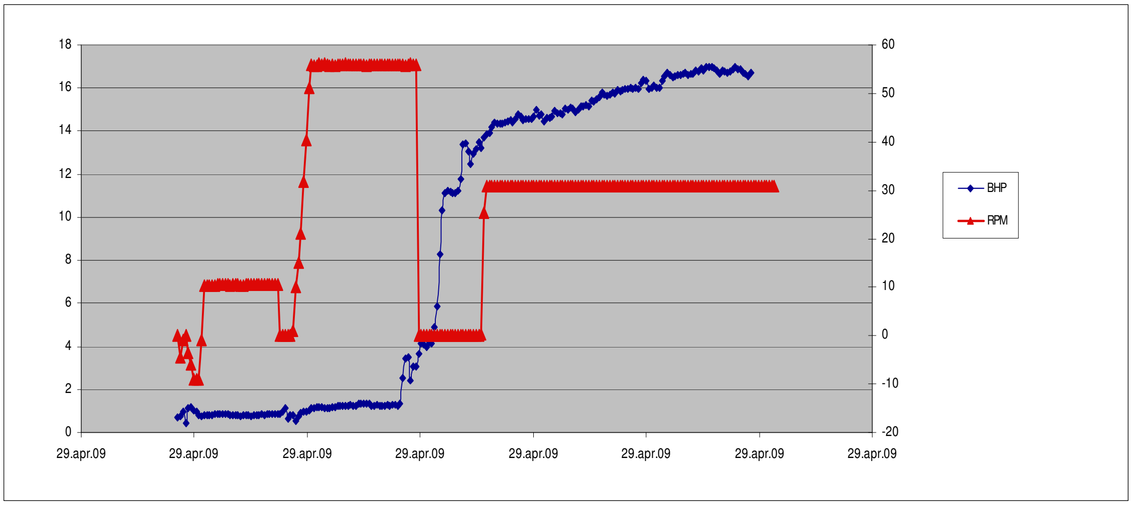

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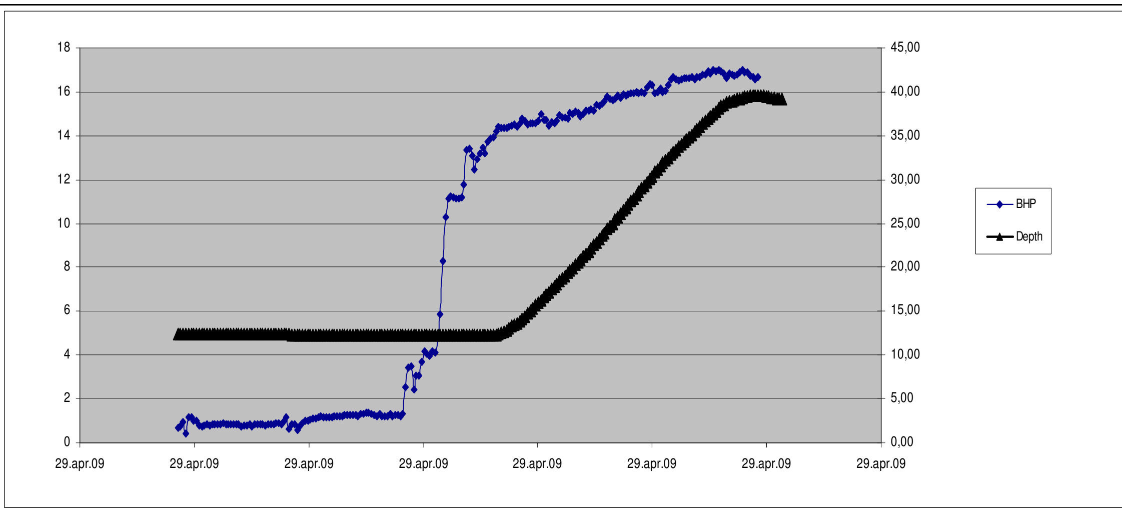

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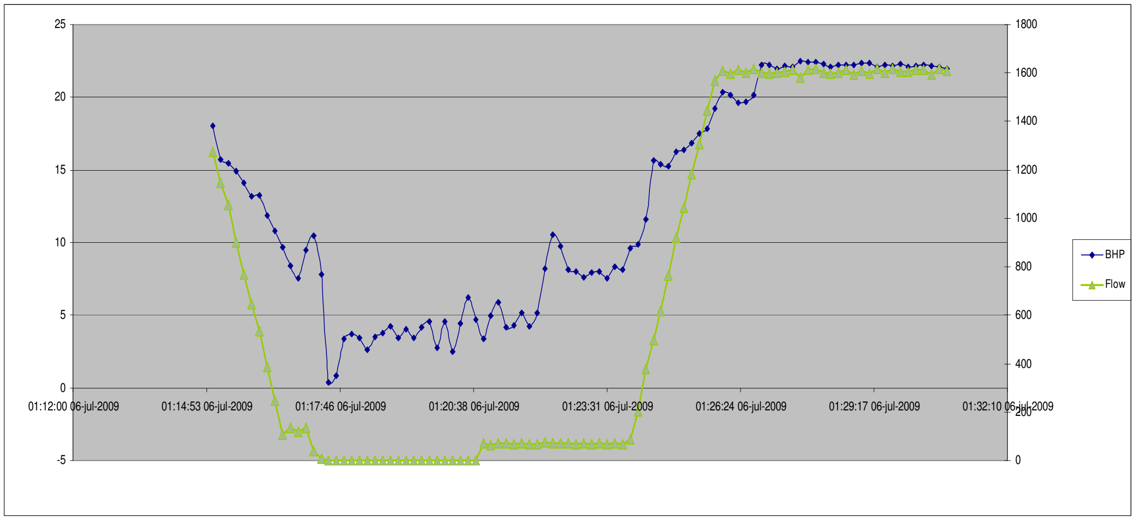

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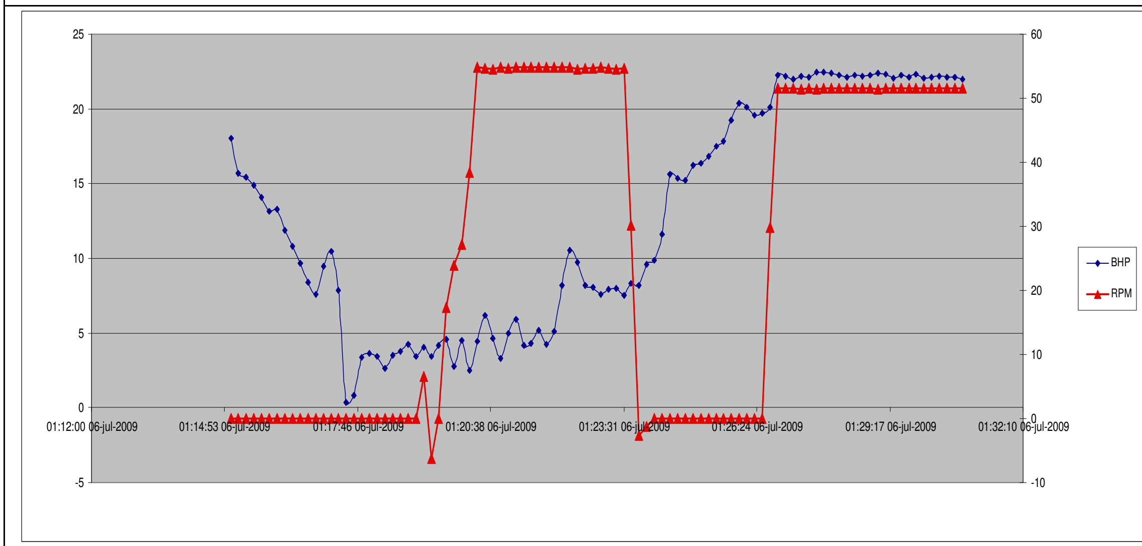

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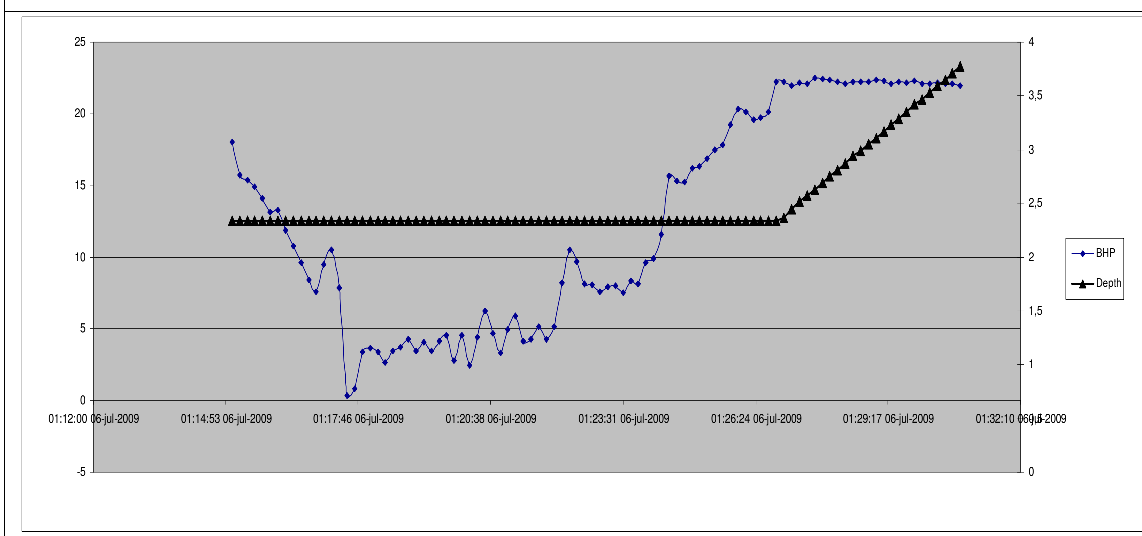

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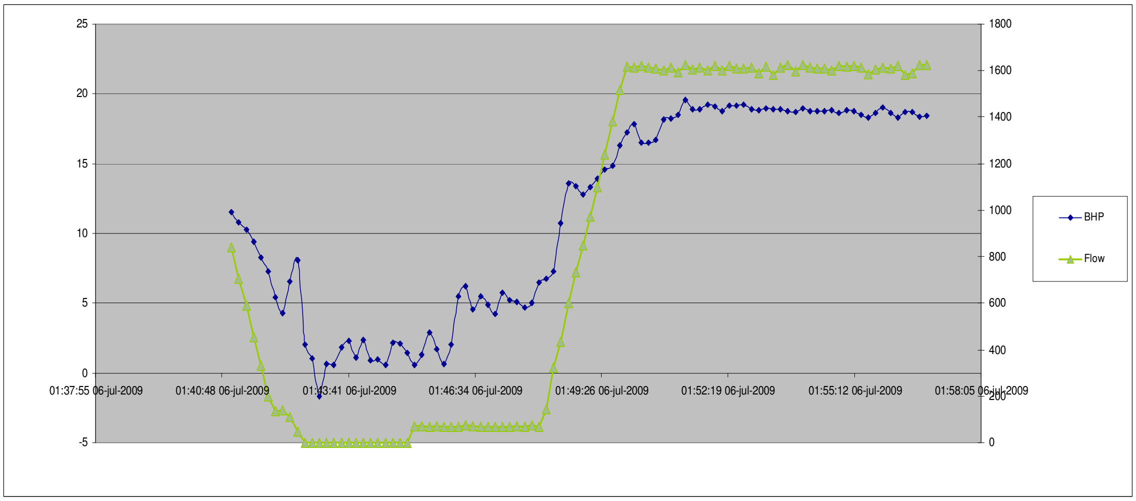

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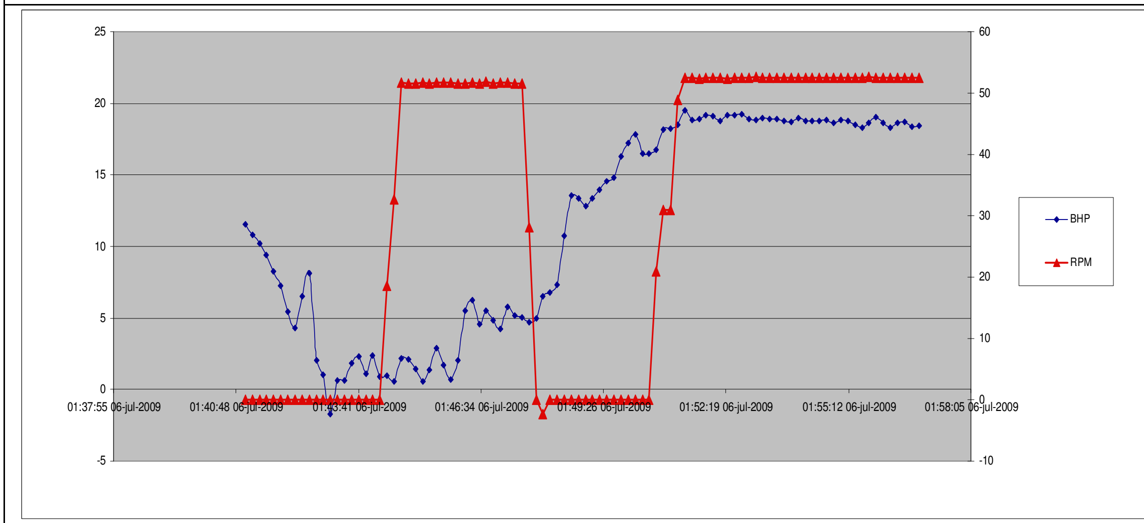

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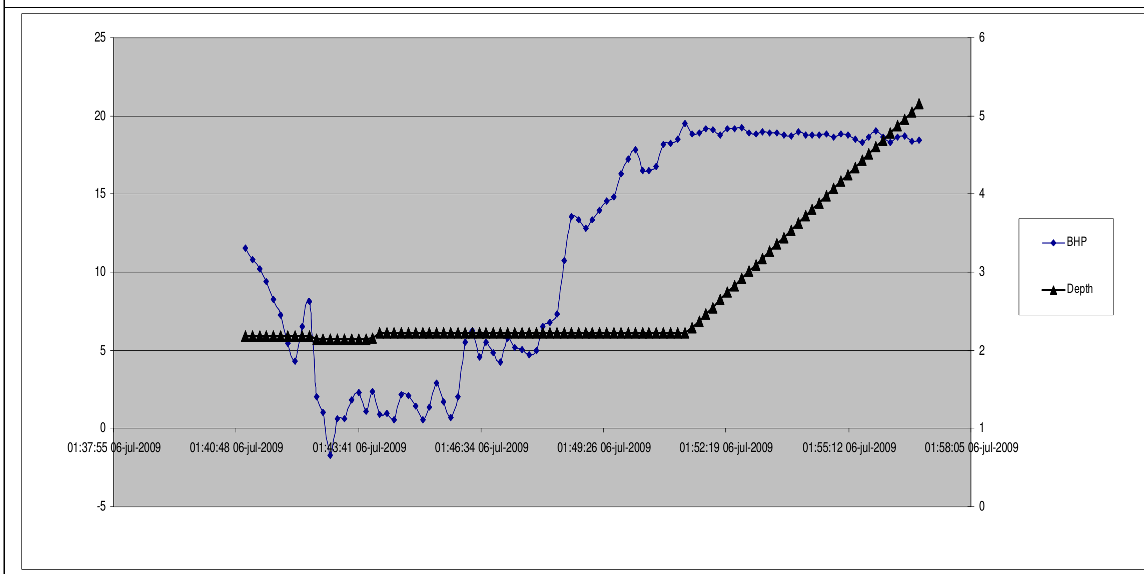

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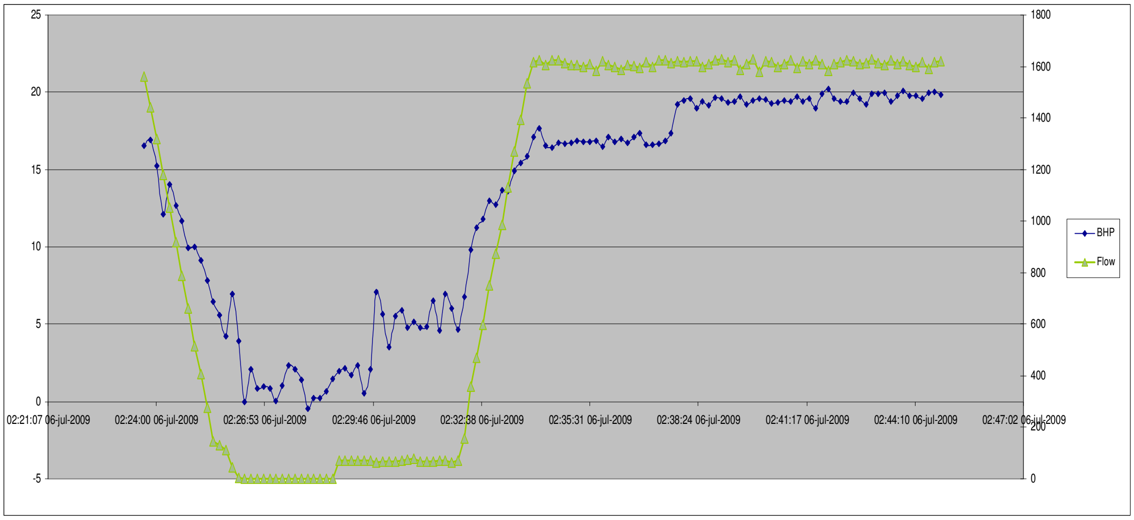

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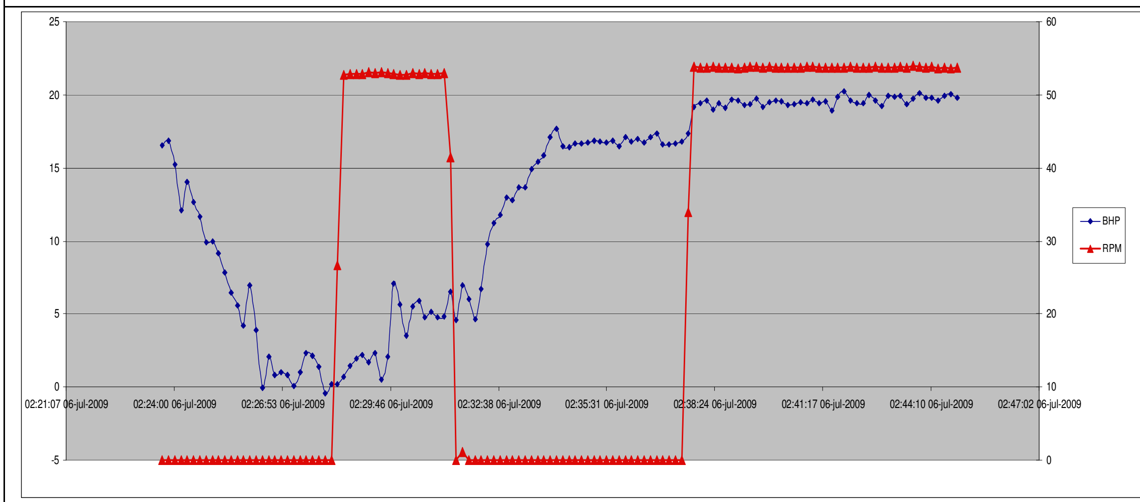

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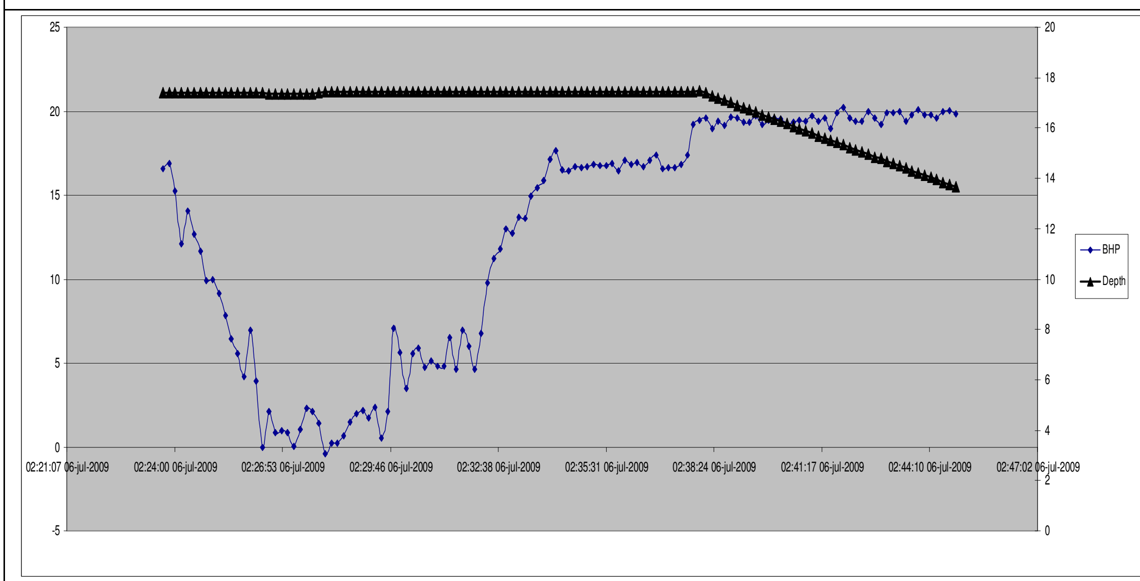

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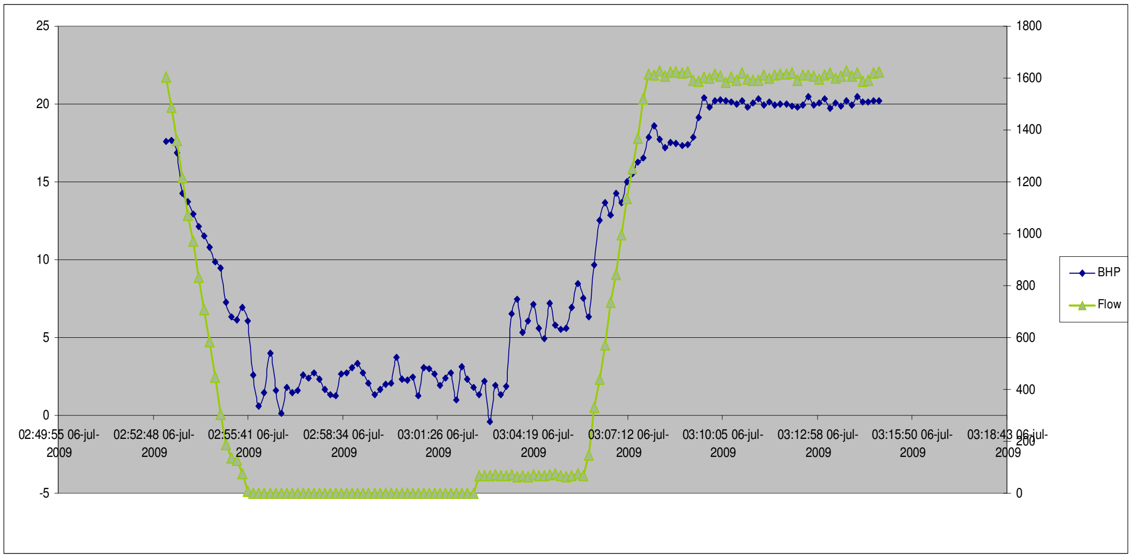

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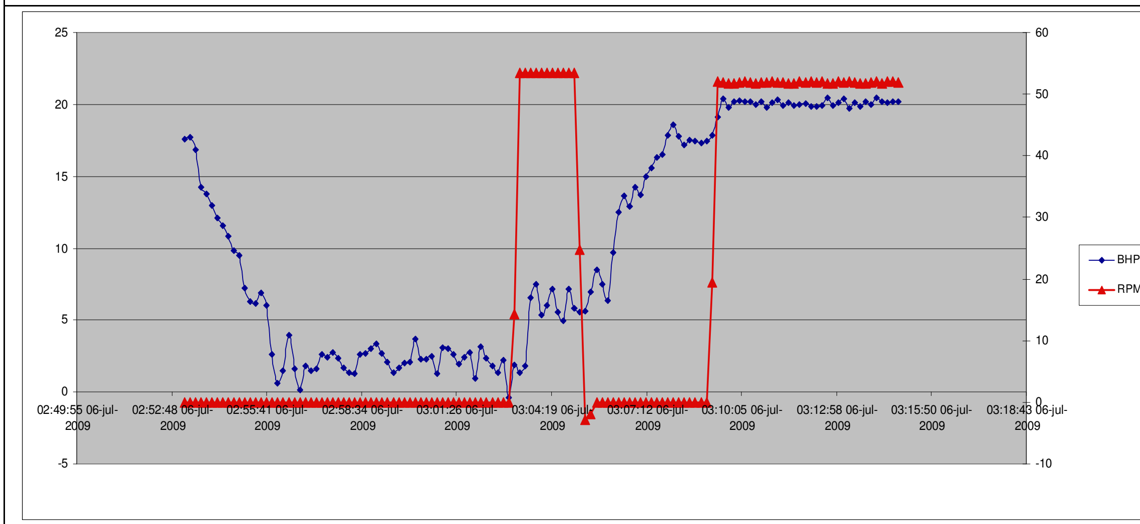

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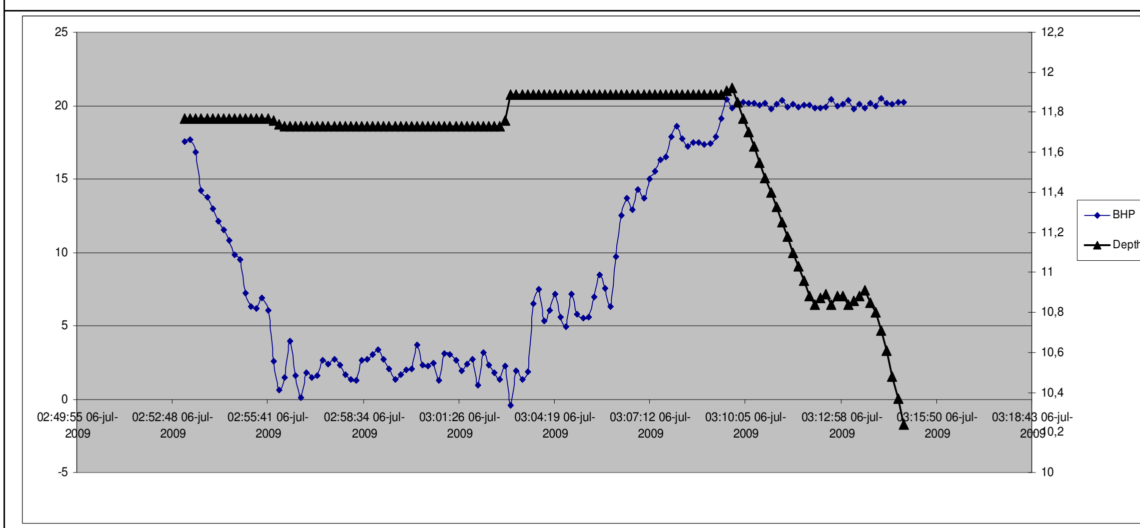

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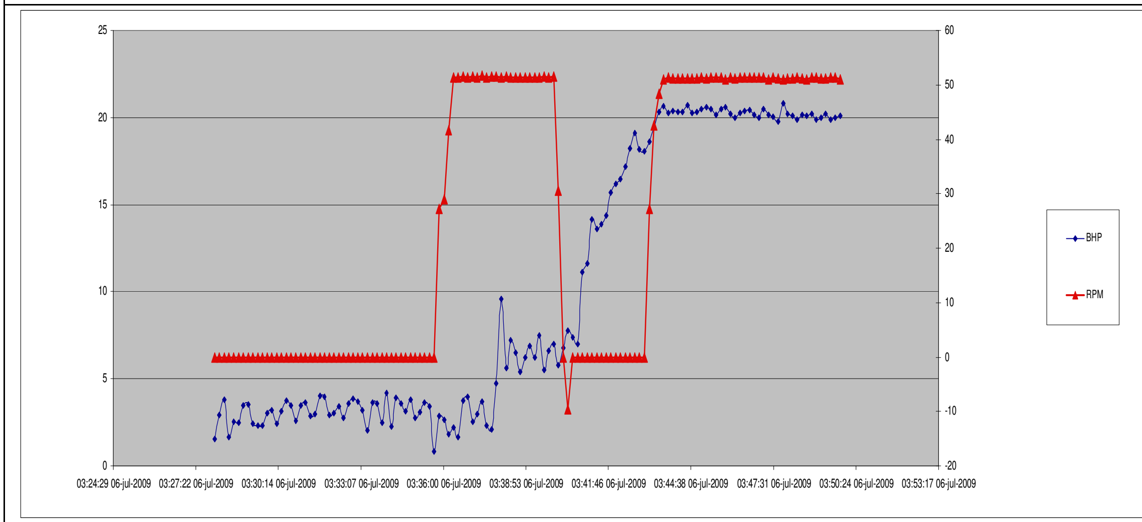
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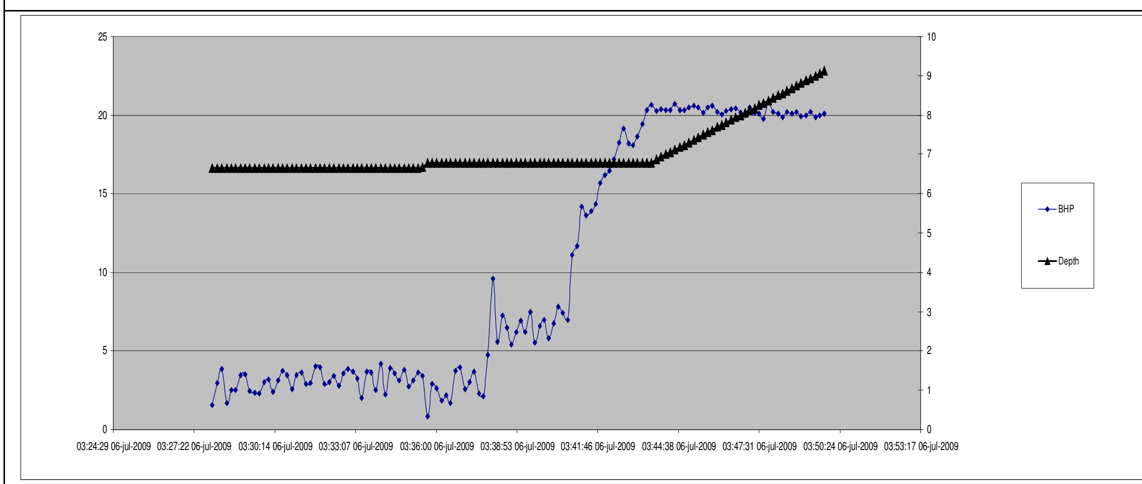
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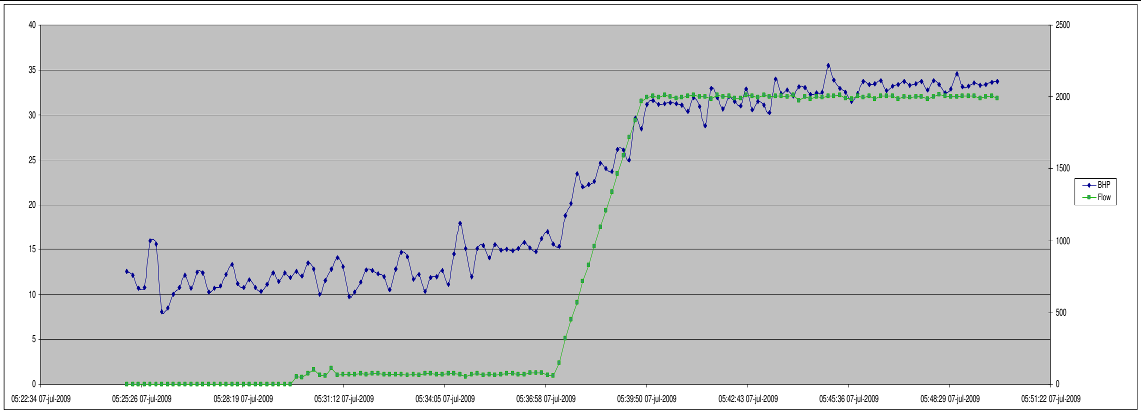
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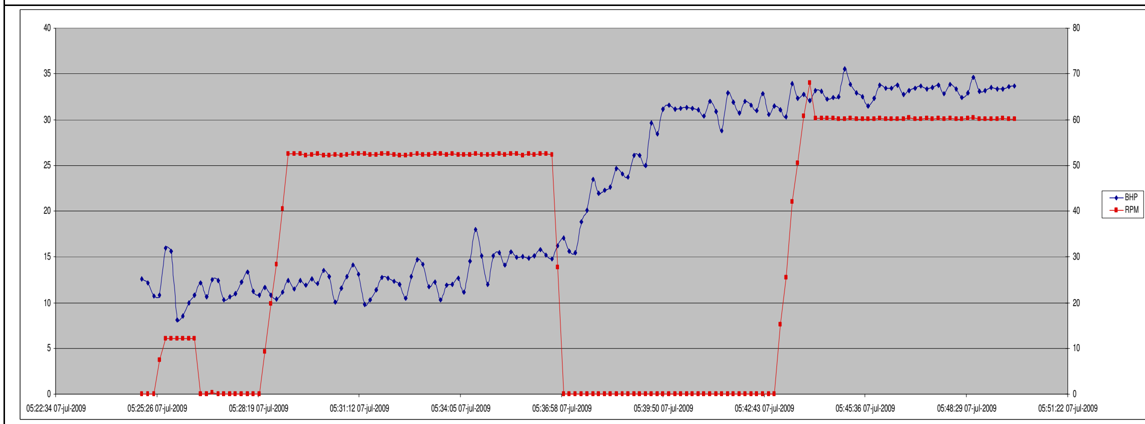
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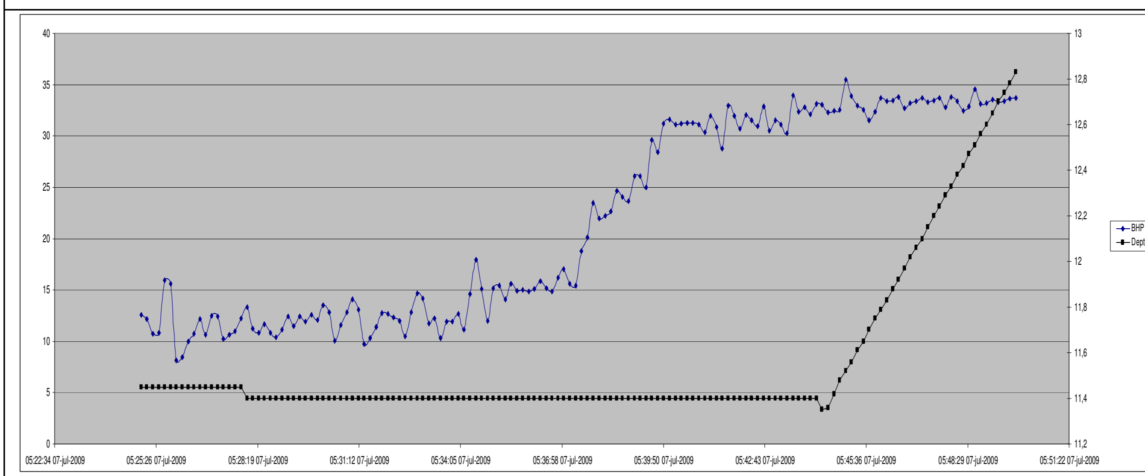
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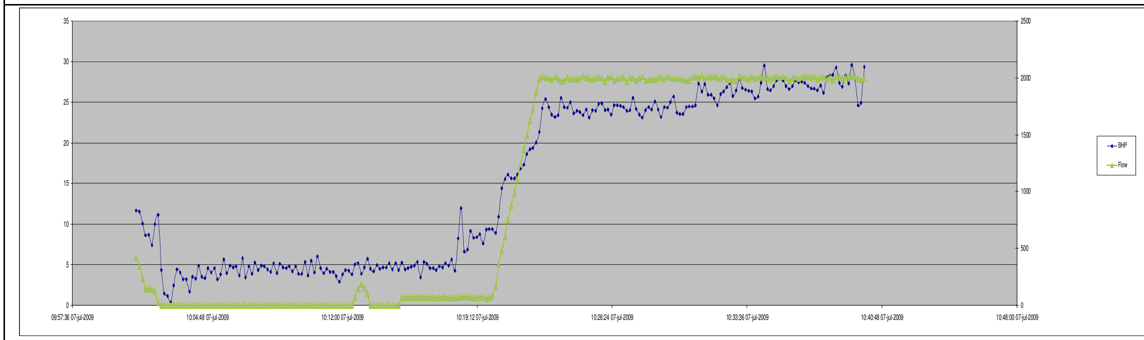

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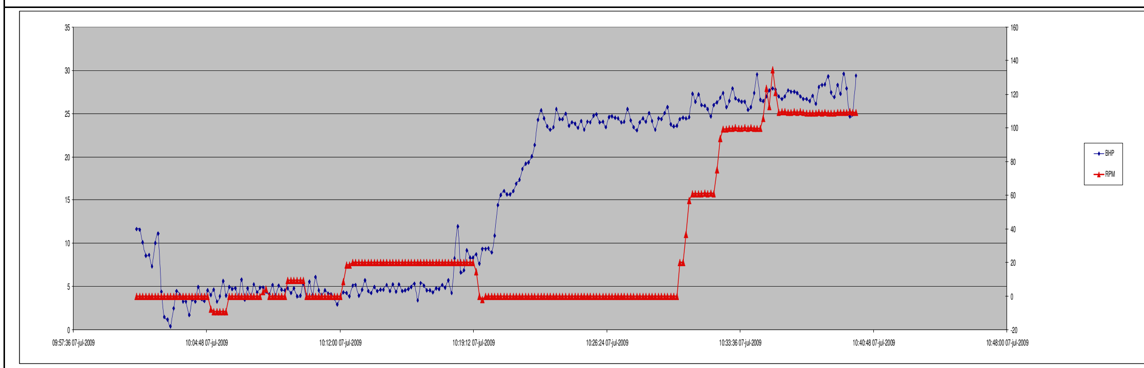

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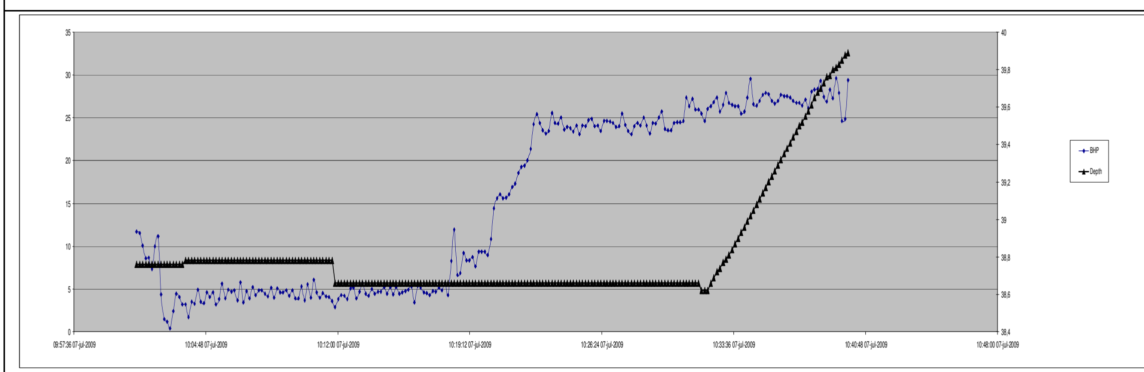

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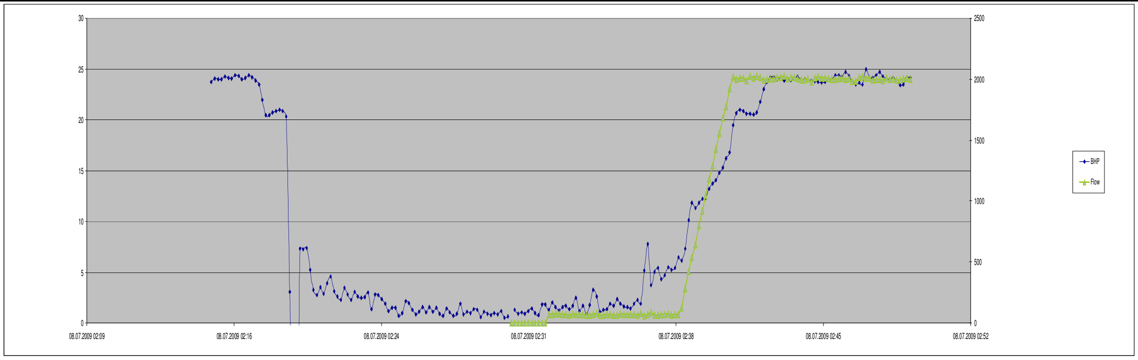

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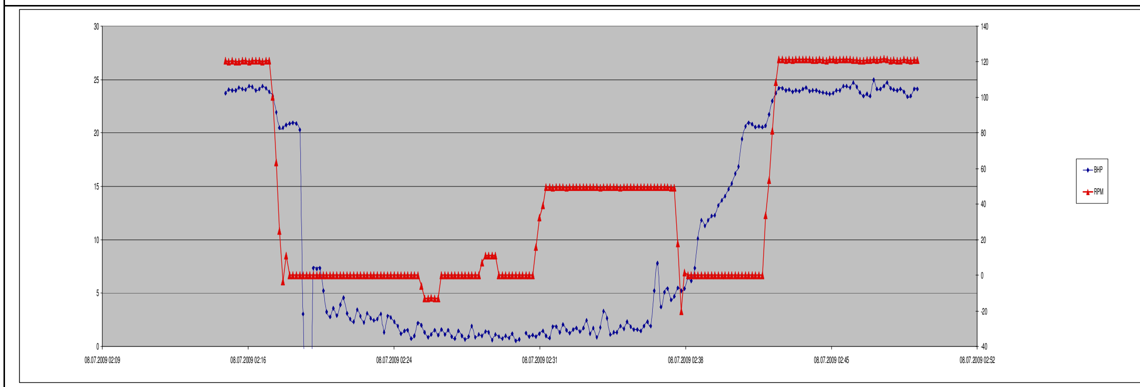

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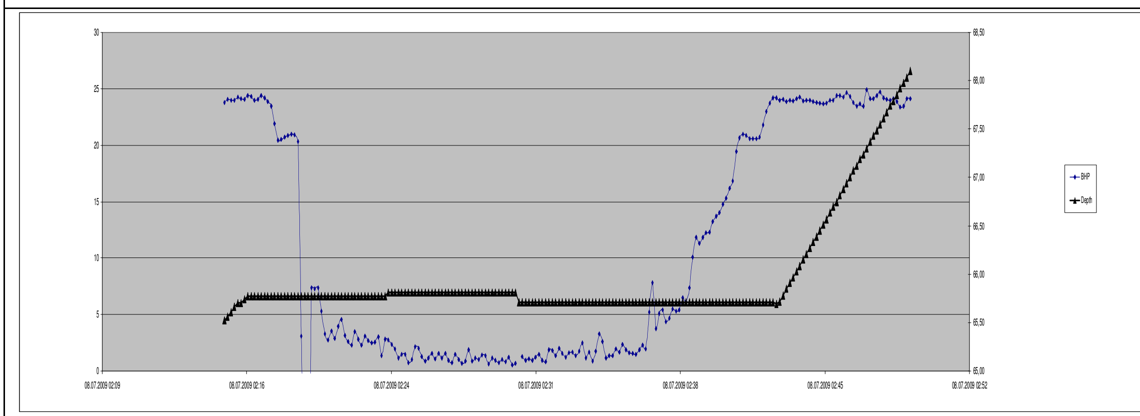

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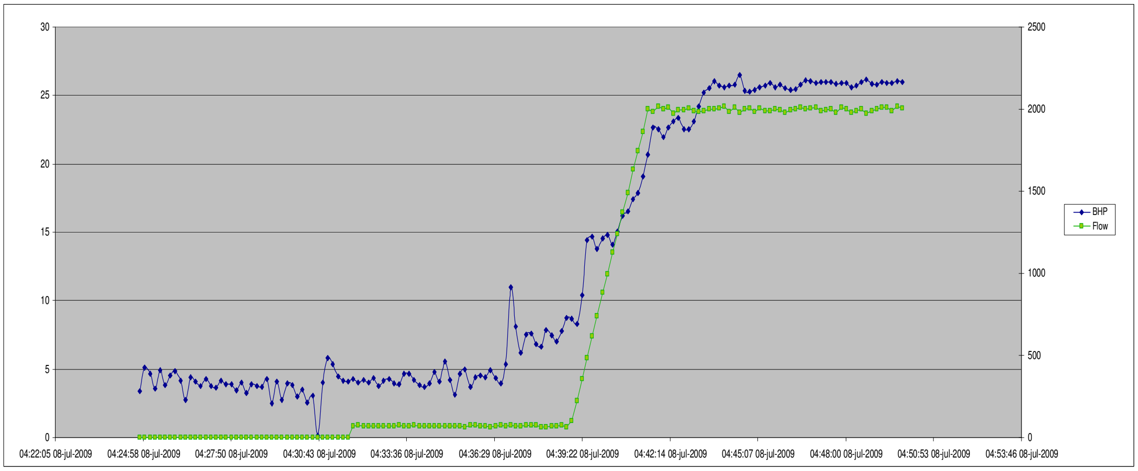
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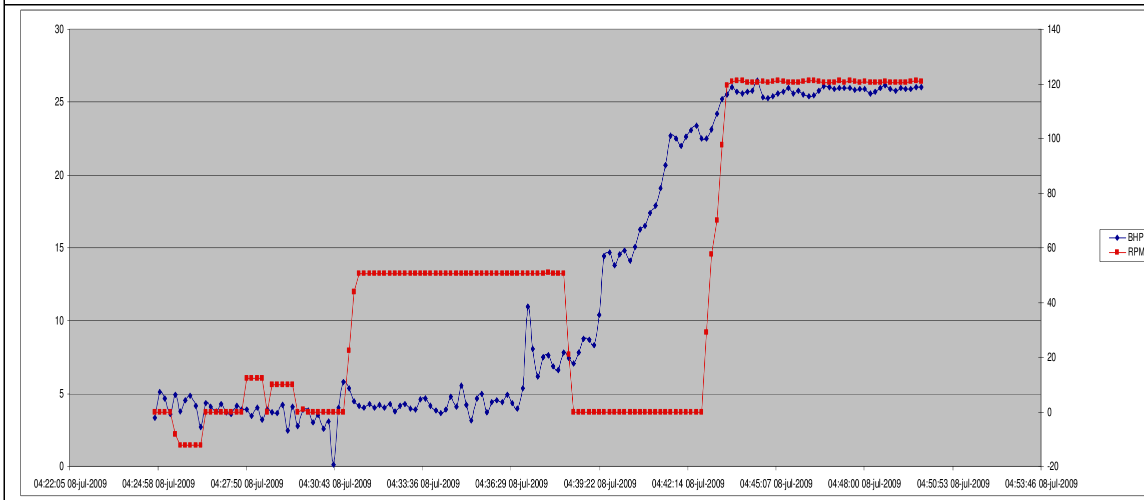
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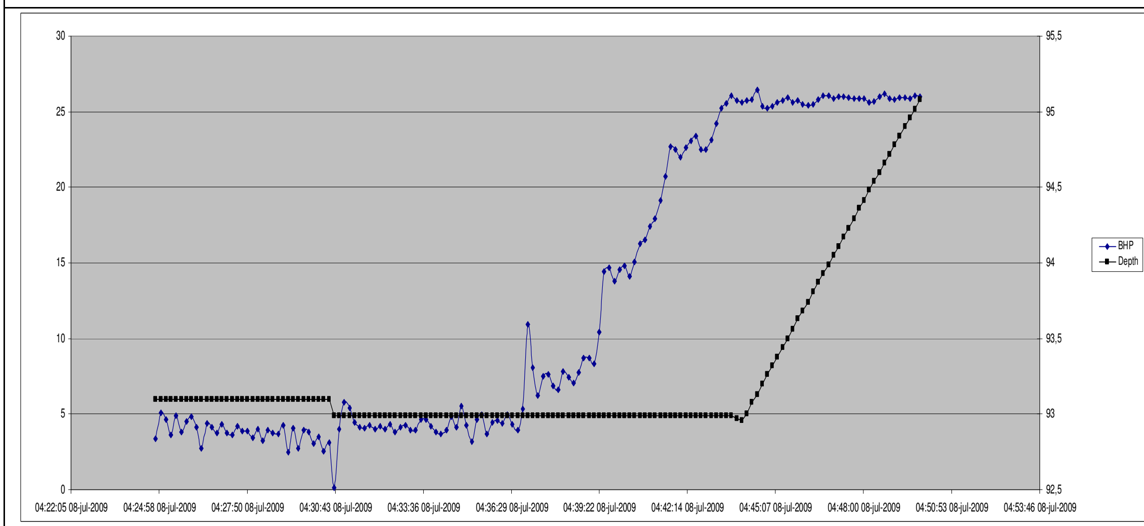
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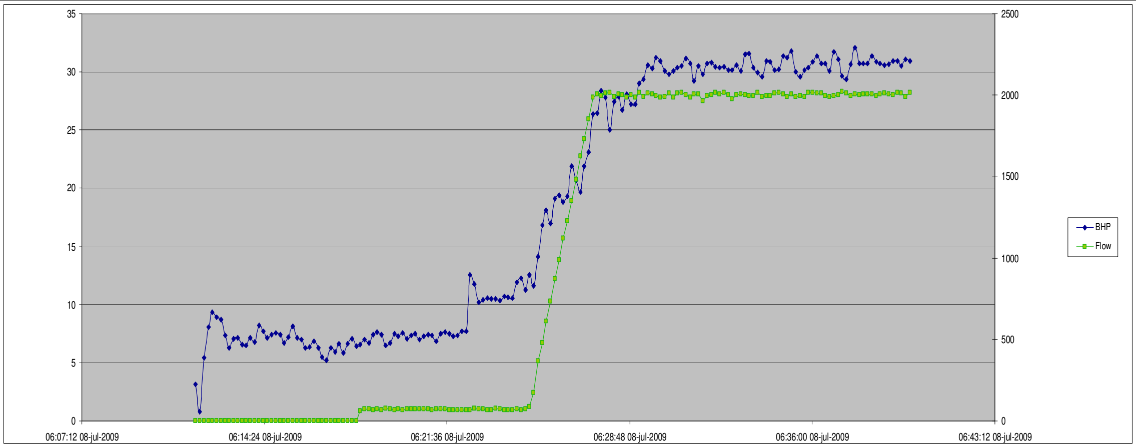

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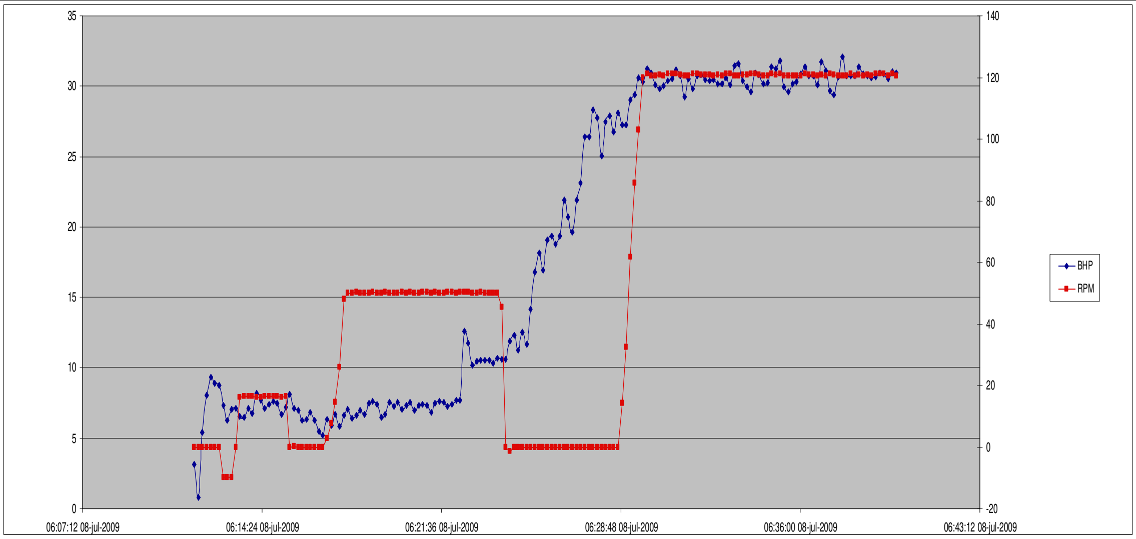

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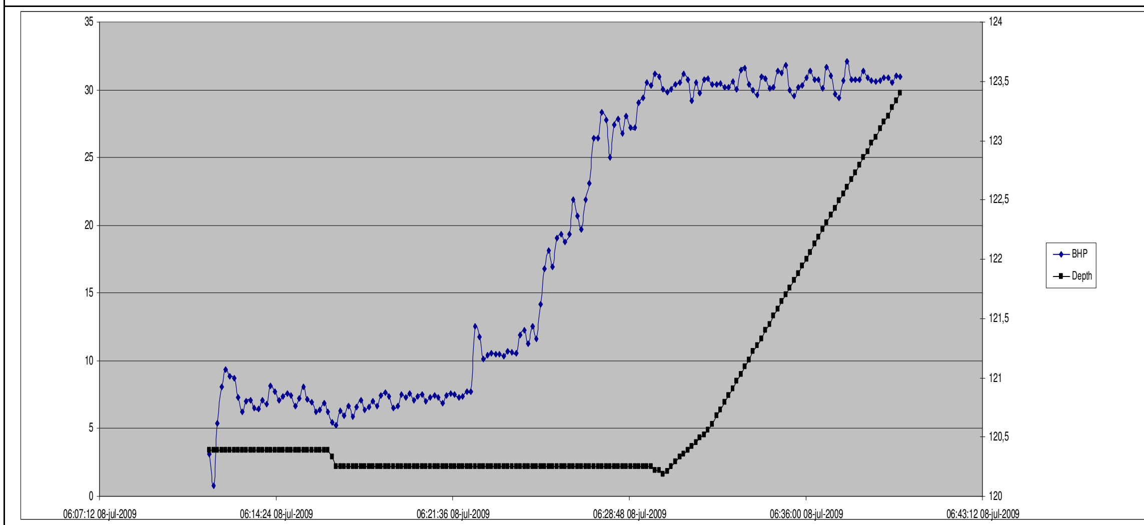

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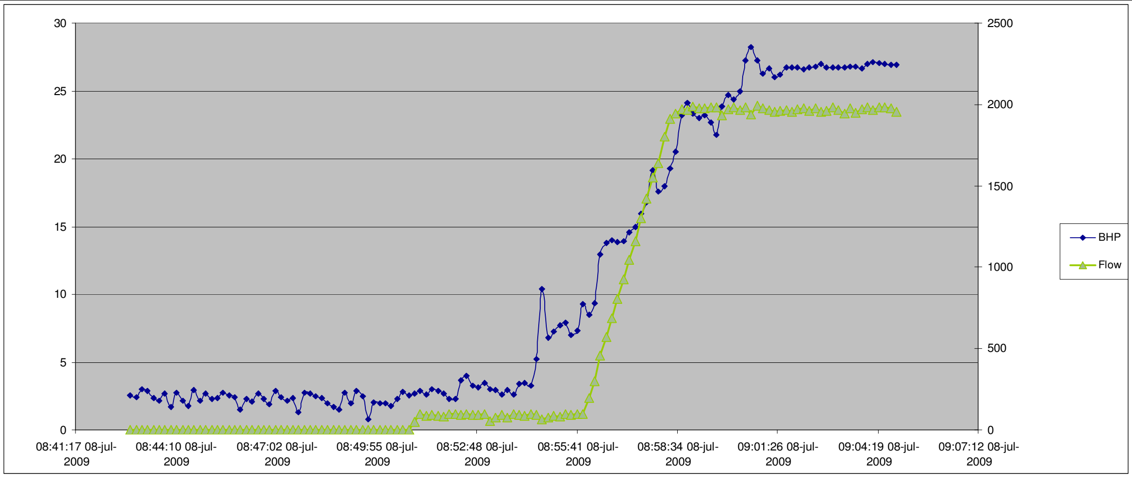
08/07/09 08:50



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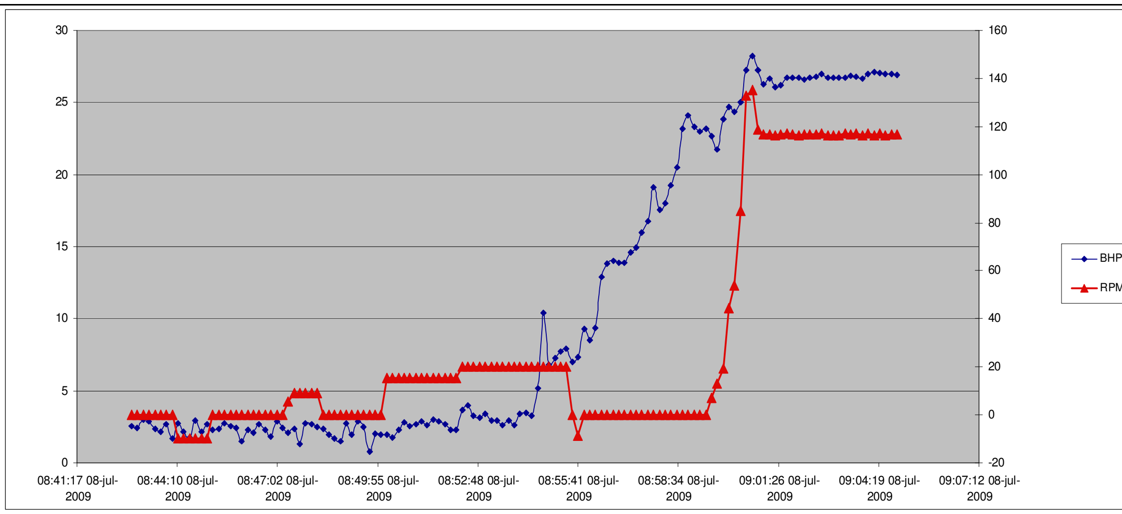

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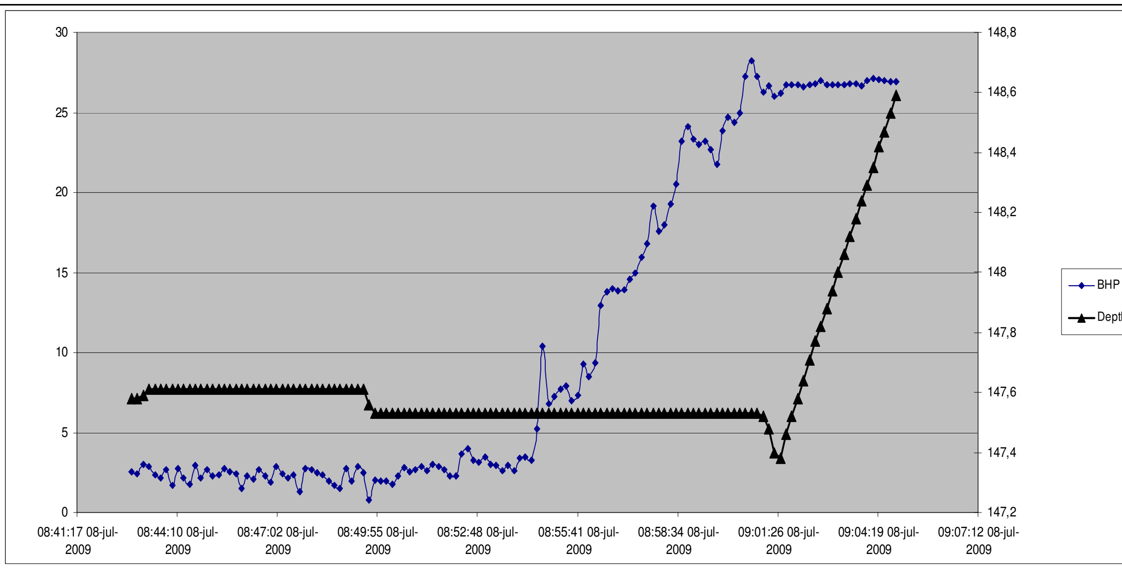

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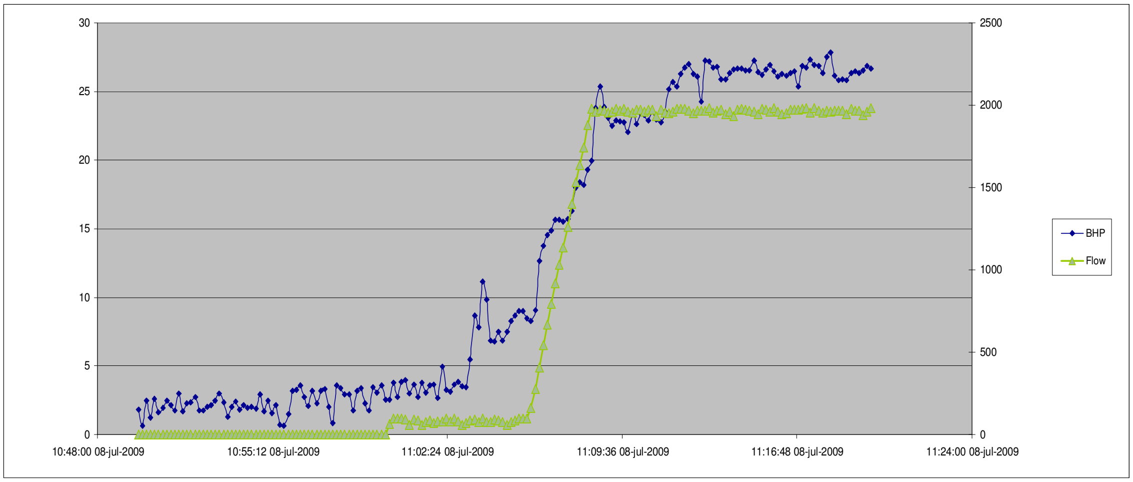

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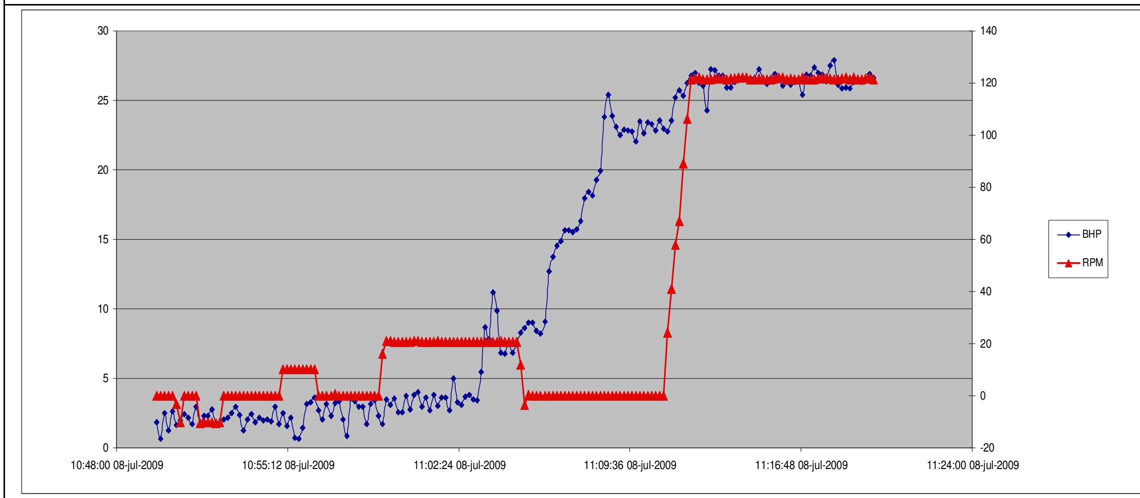
BHP
Flow



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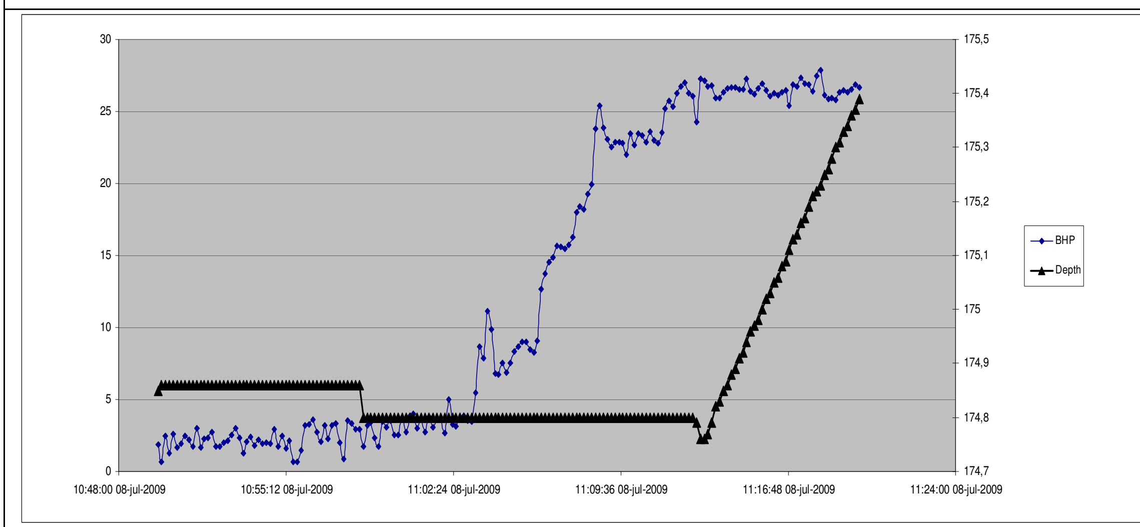

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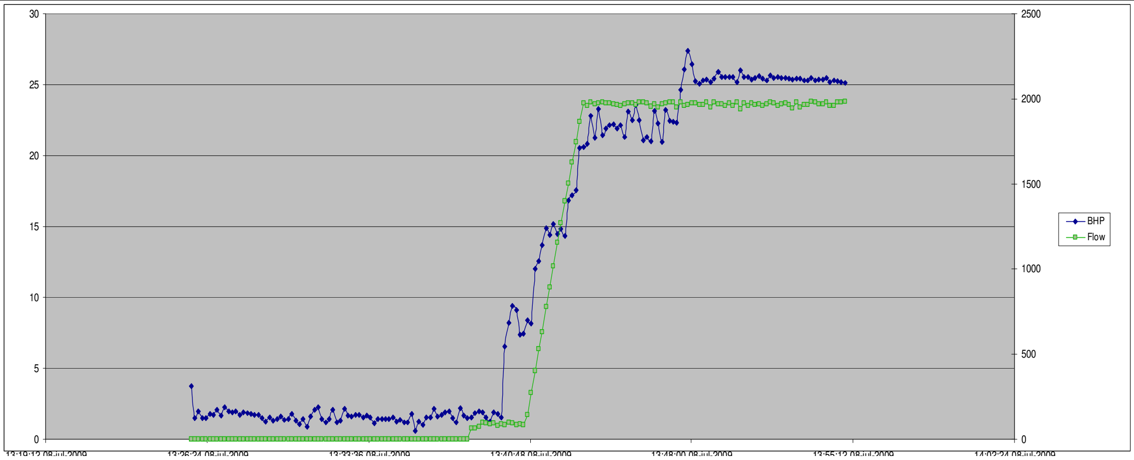
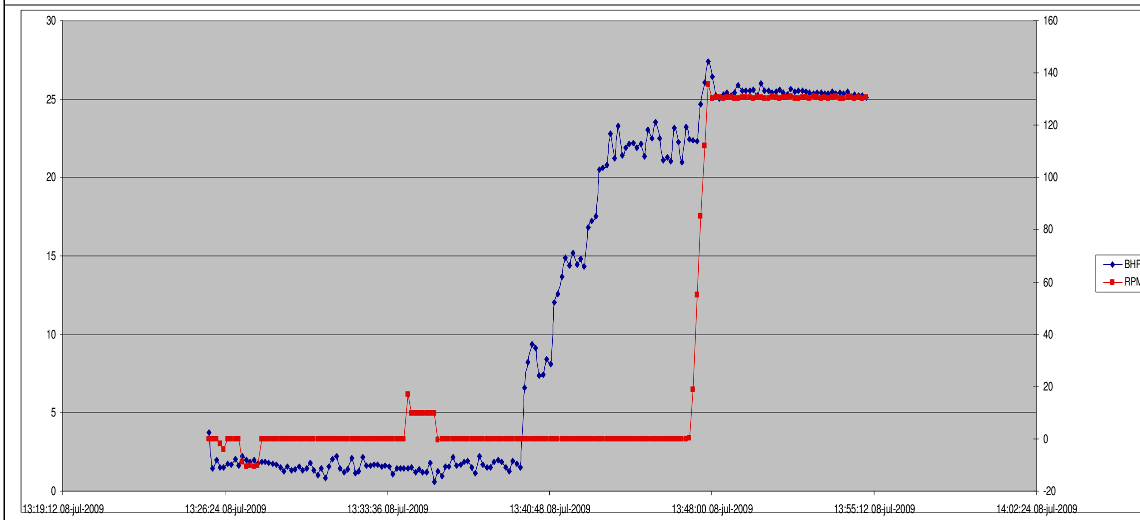
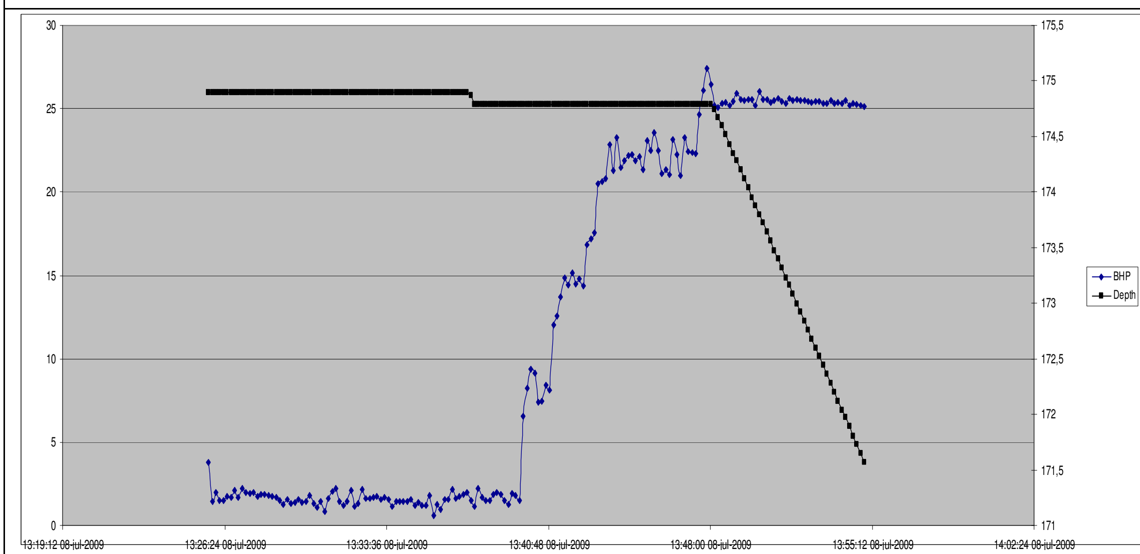
Depth

08/07/09 13:35







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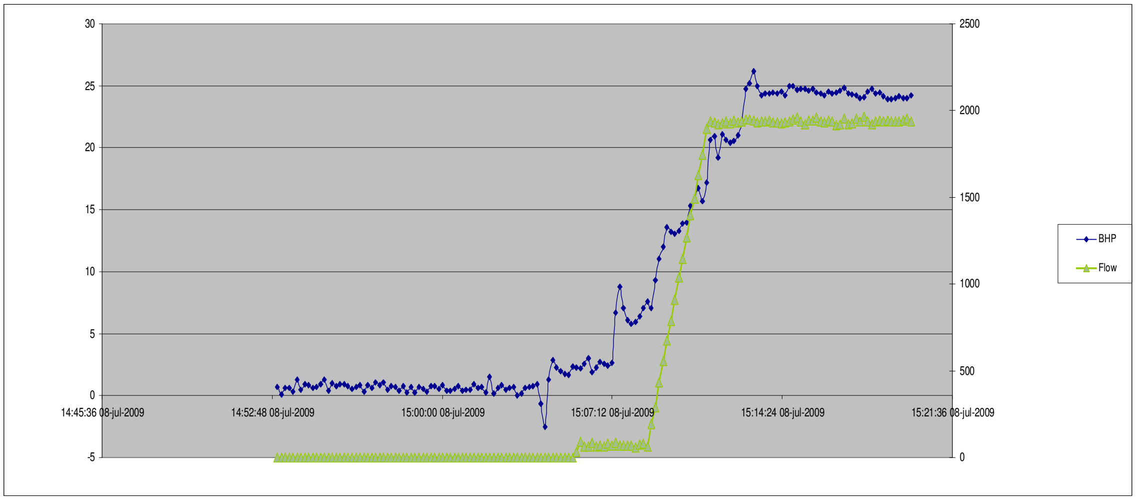

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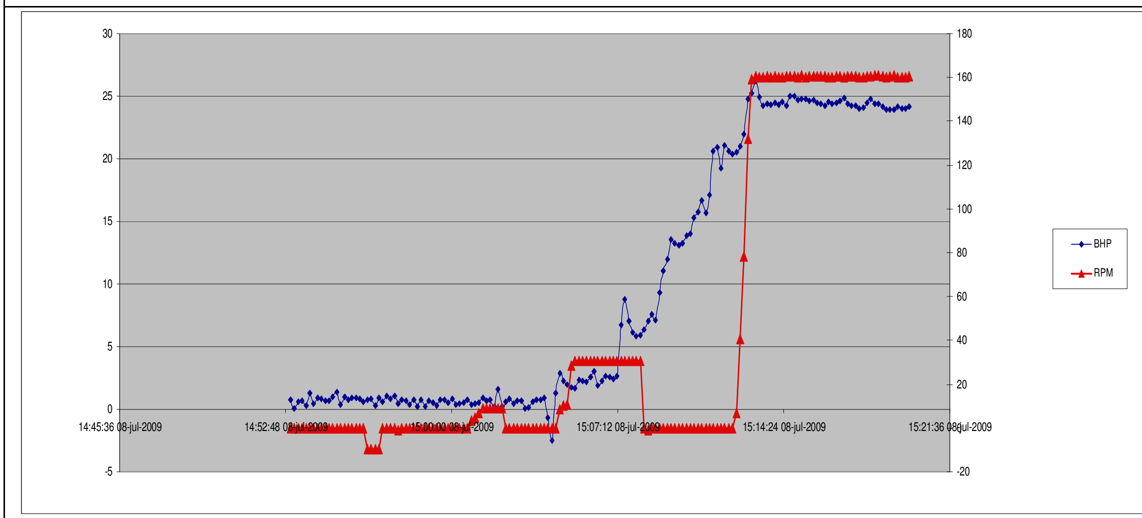
Flow



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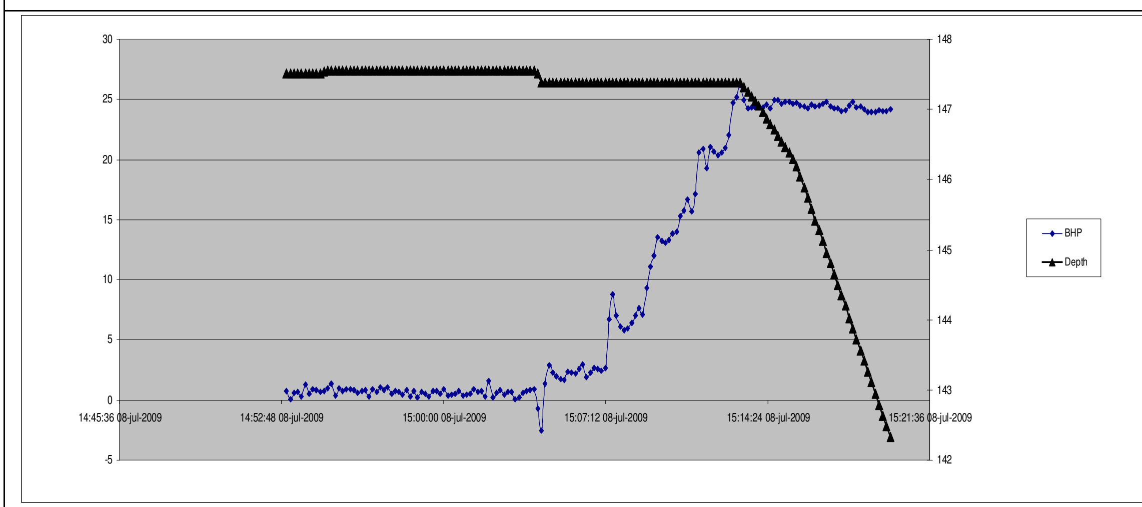
BHP
RPM



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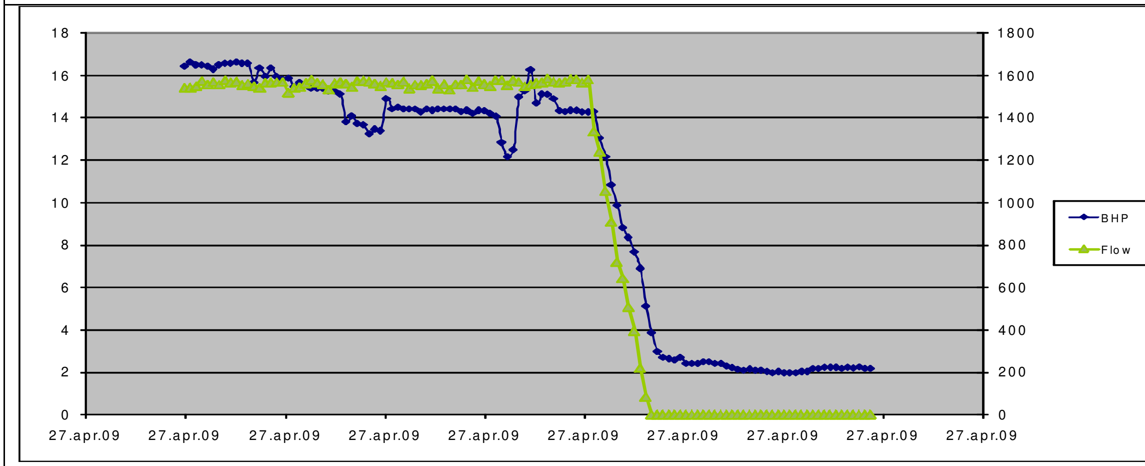
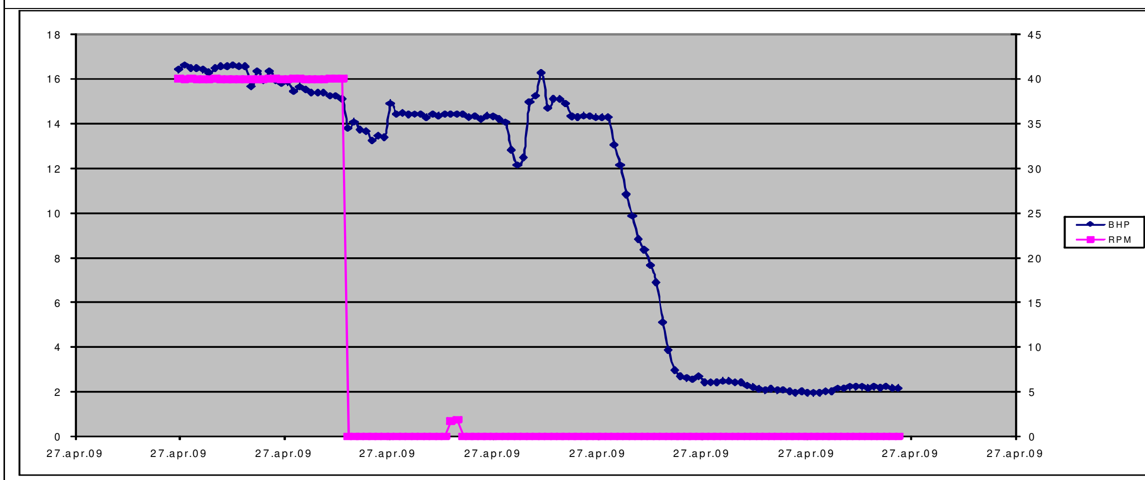
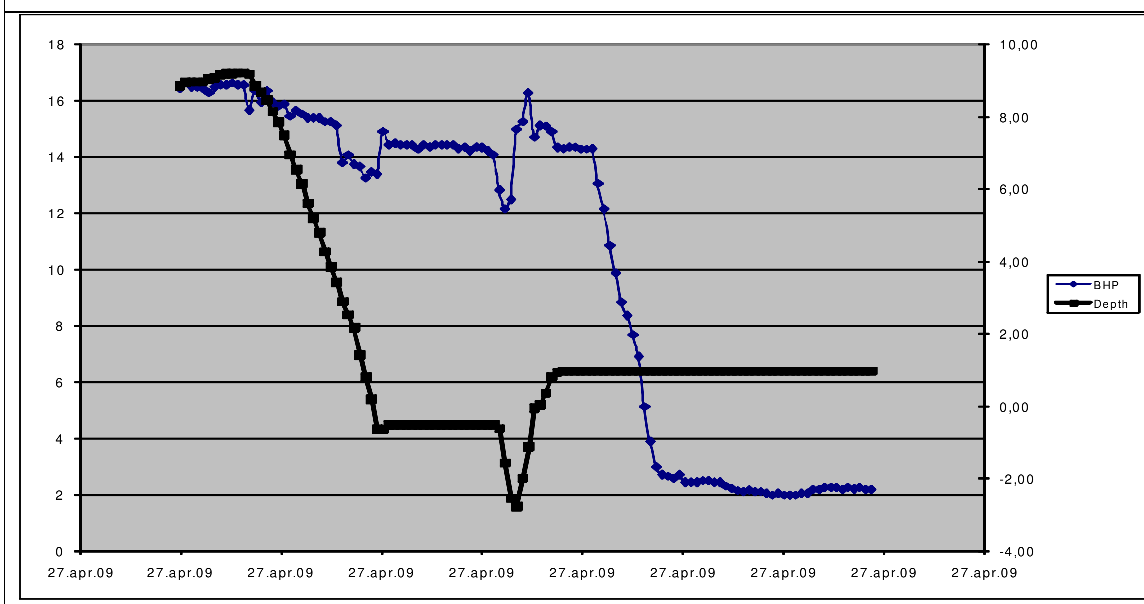
BHP
Depth

Break-up runs

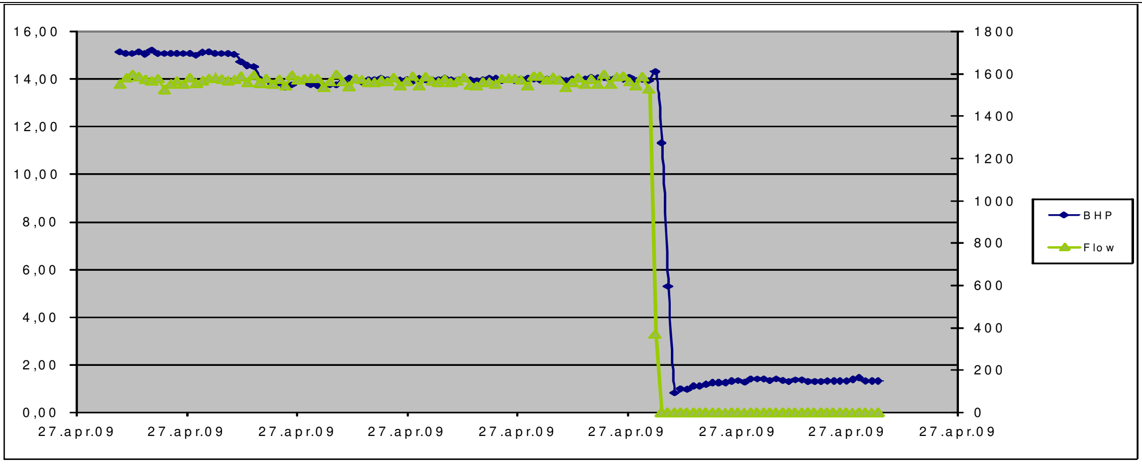
27/04/09 00:20







27/04/09 08:25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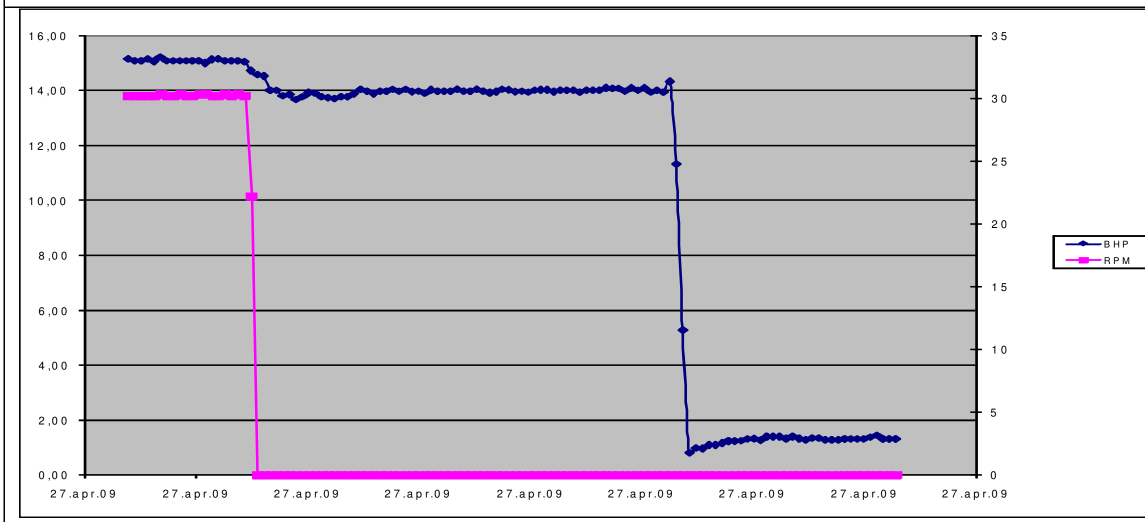
BHP
Flow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BHP
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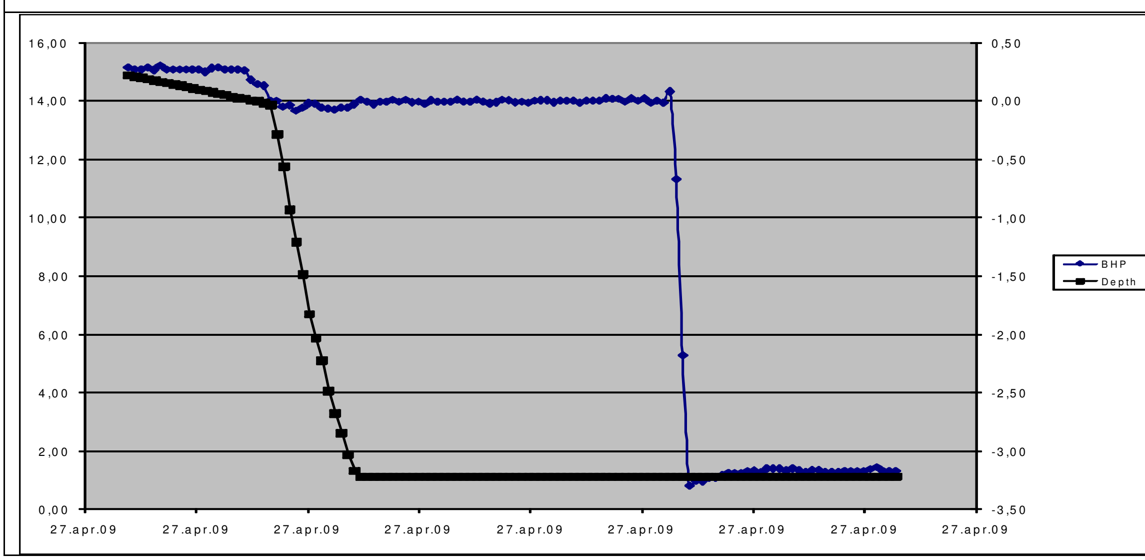
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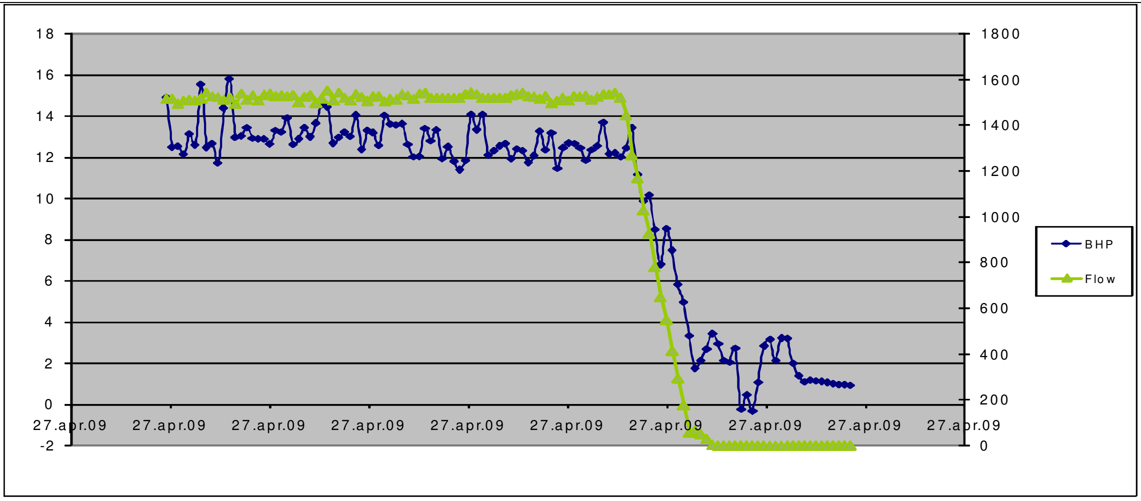
27/04/09 15:30



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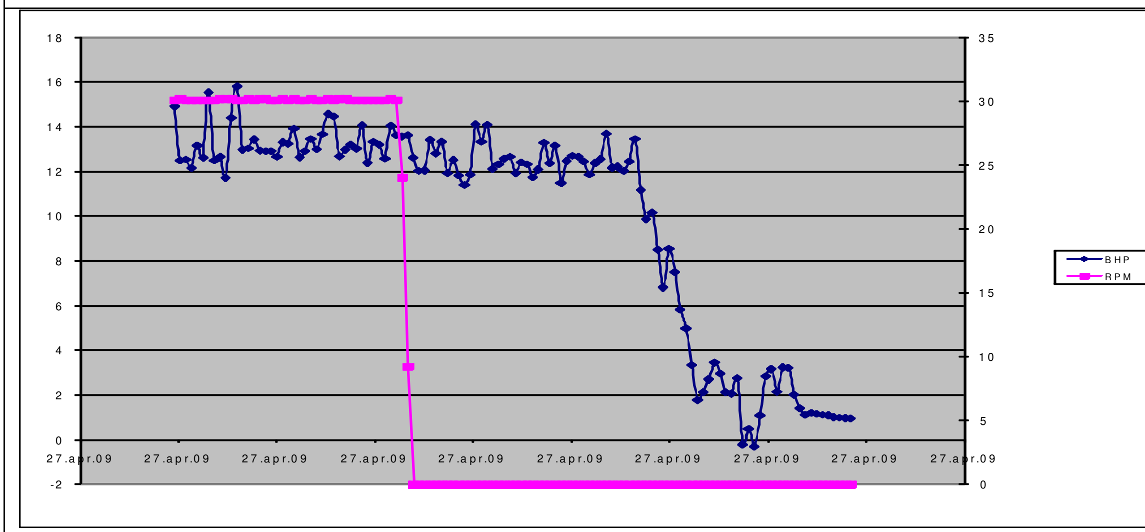

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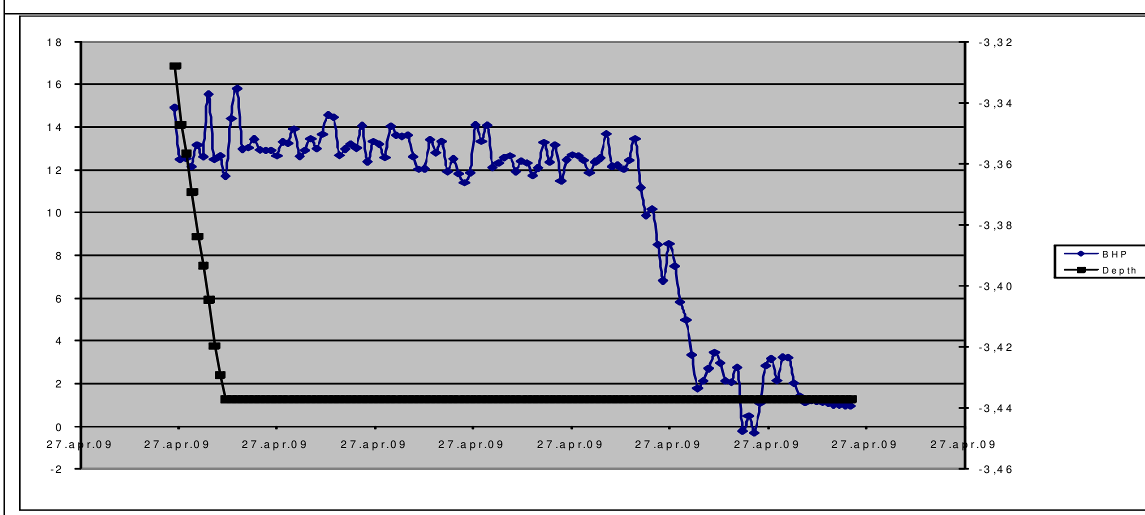
BHP
RPM



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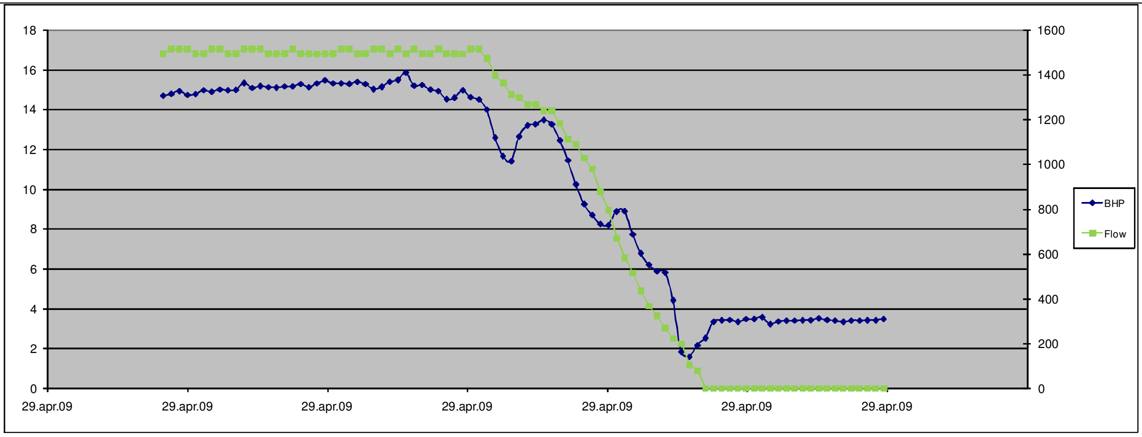
Depth

29/04/09 15:30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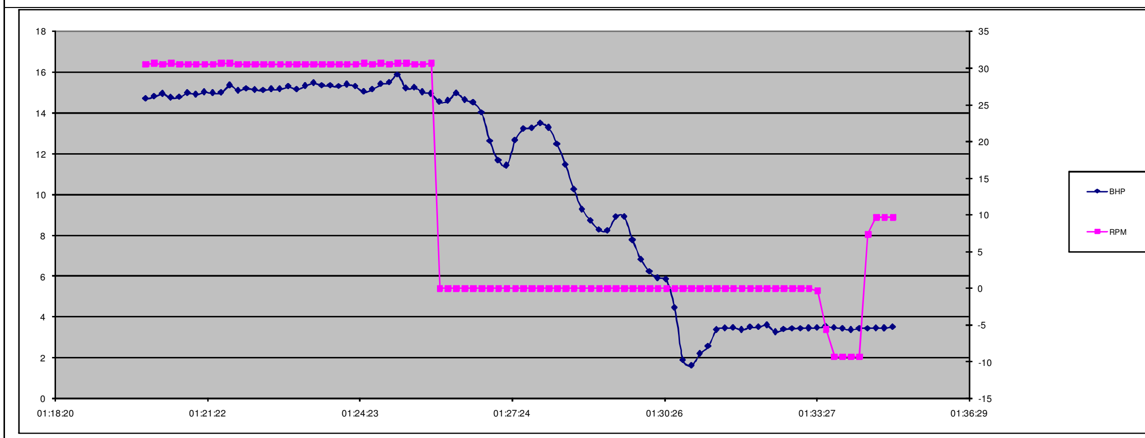
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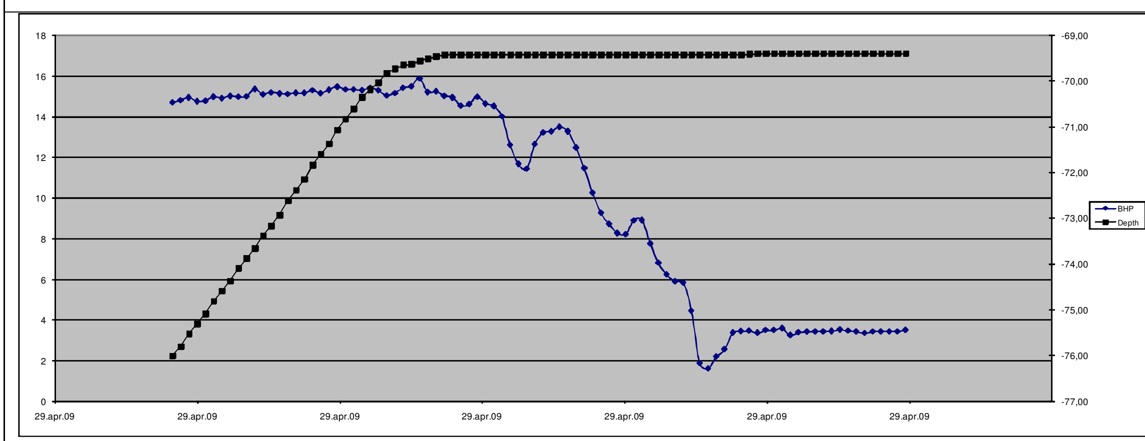
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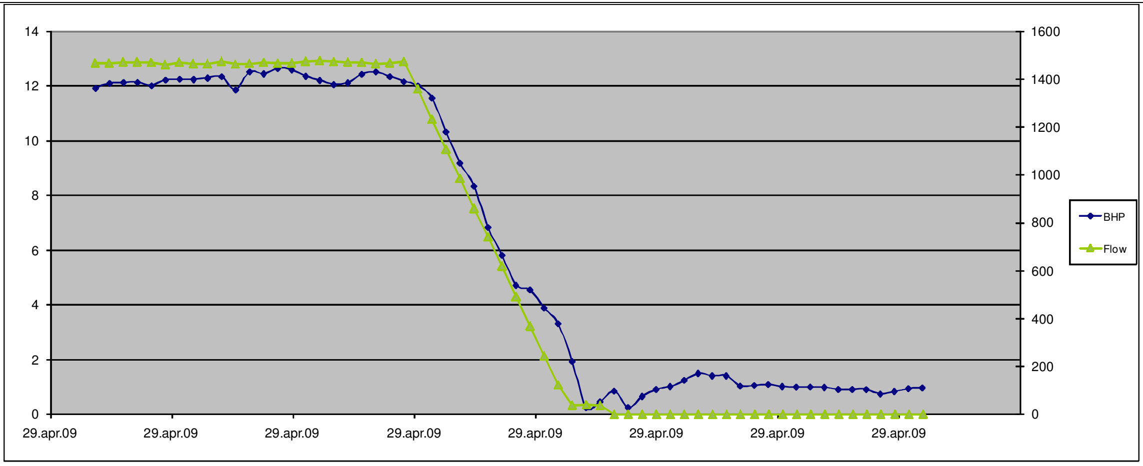
29/04/09 02:10



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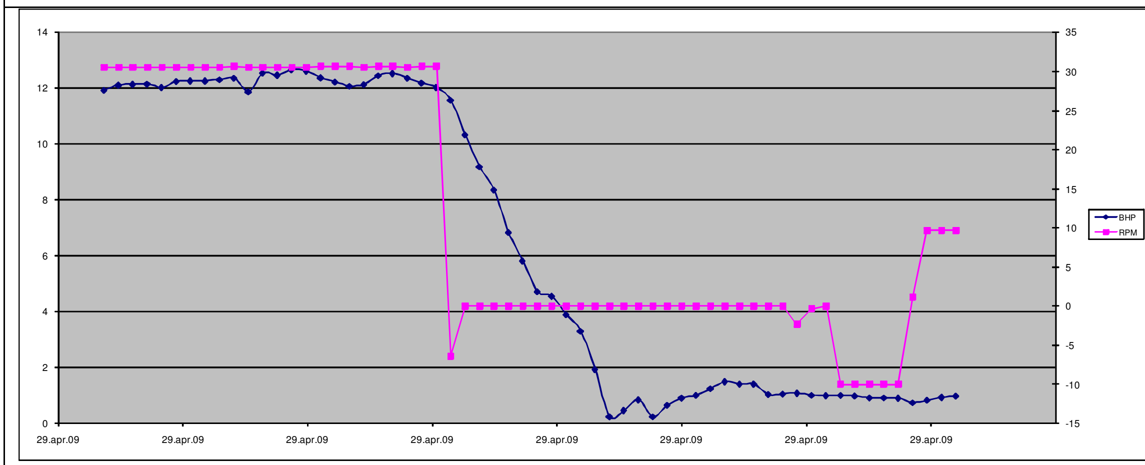
Flow



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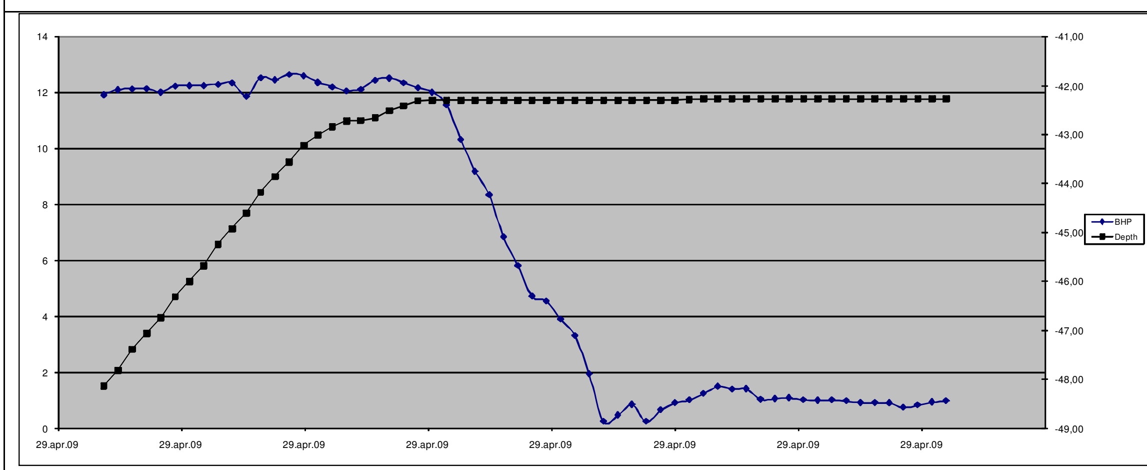
BHP
RPM



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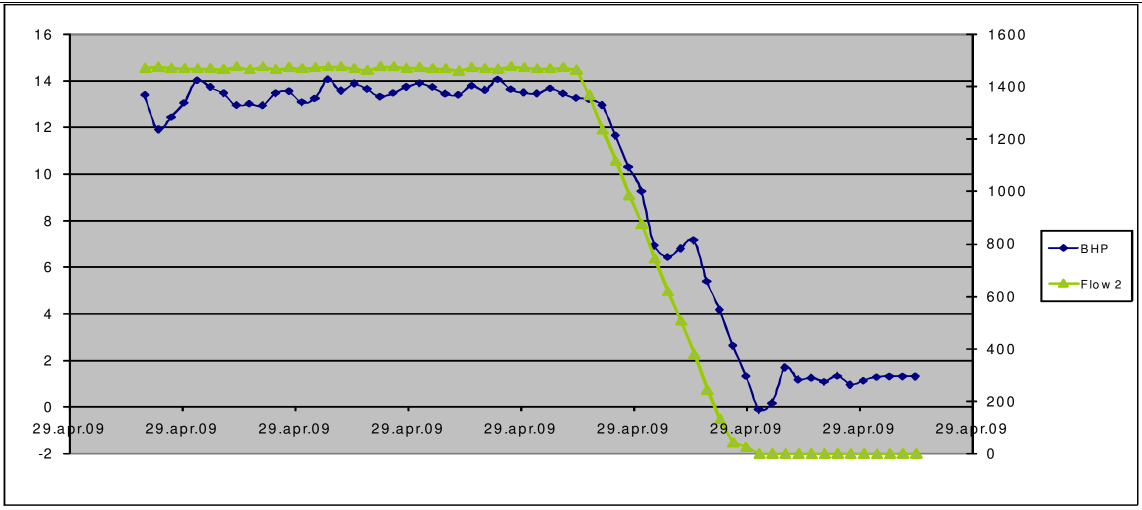
29/04/09 02:45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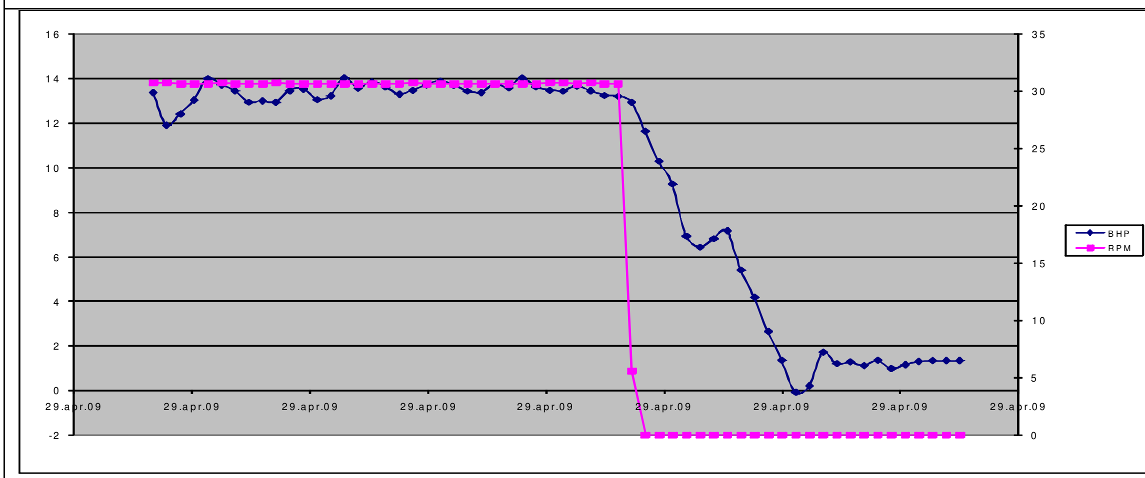
BHP
Flow 2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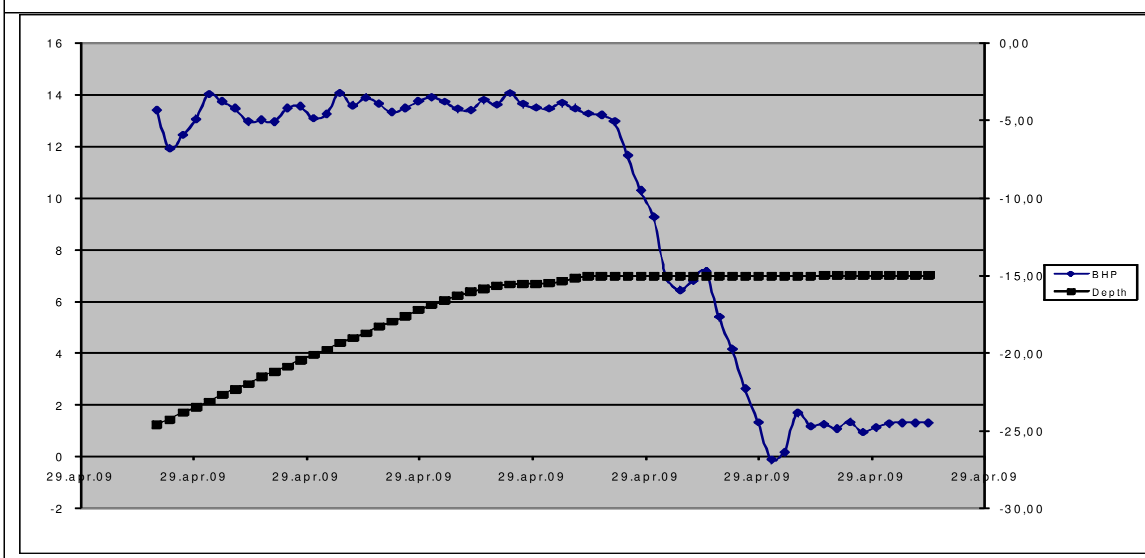
RPM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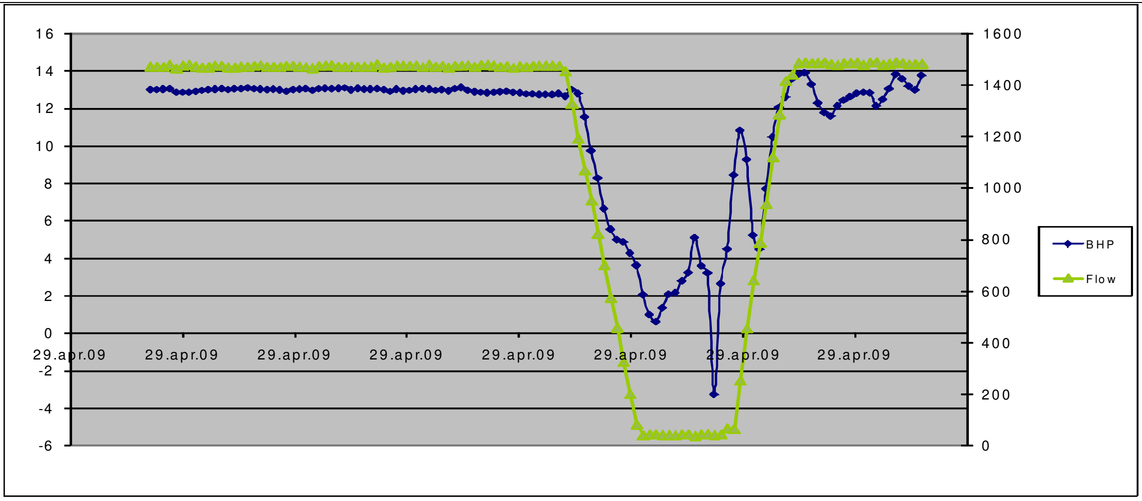
29/04/09 08:00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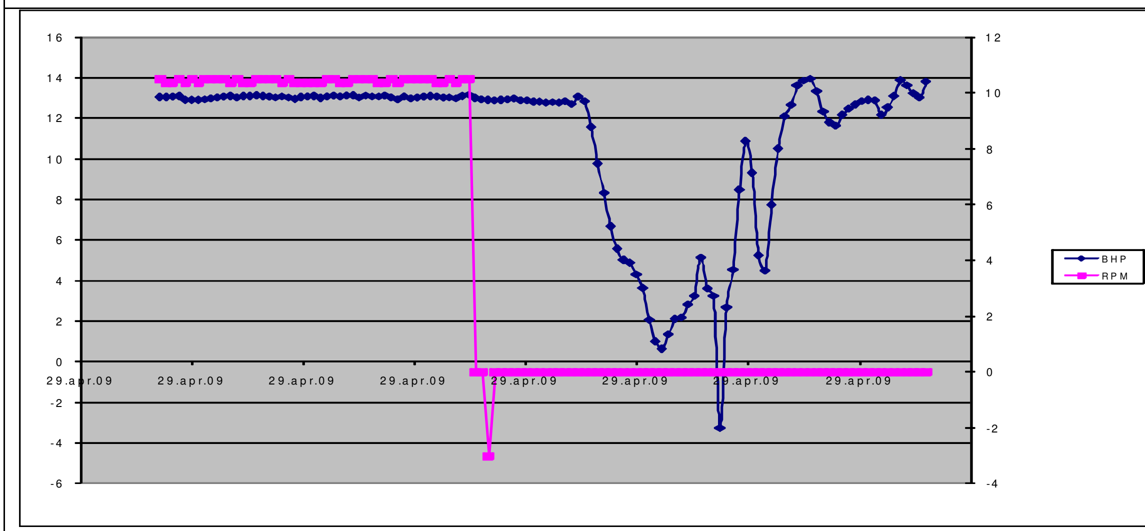
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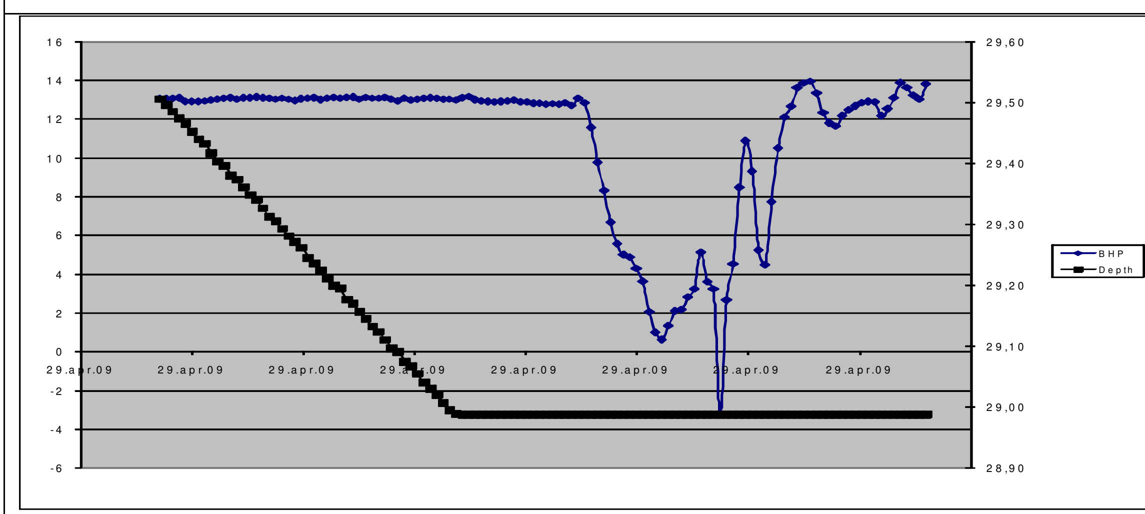
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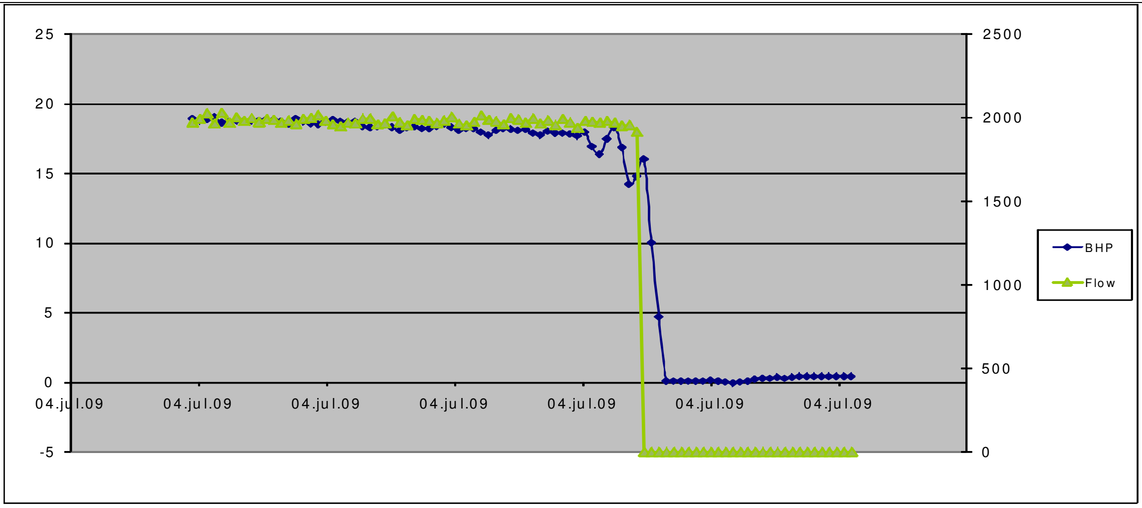
04/07/09 08:00



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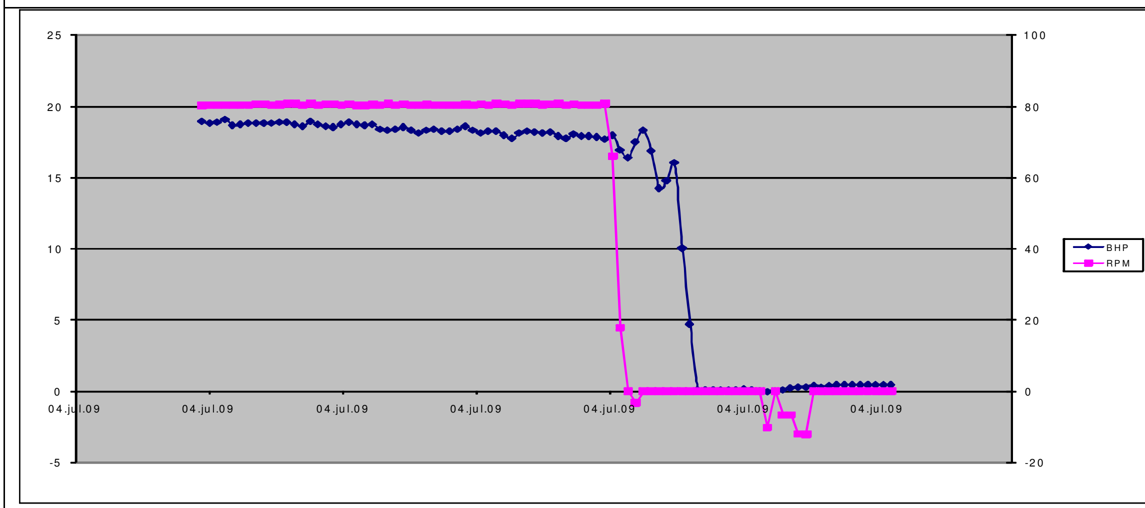

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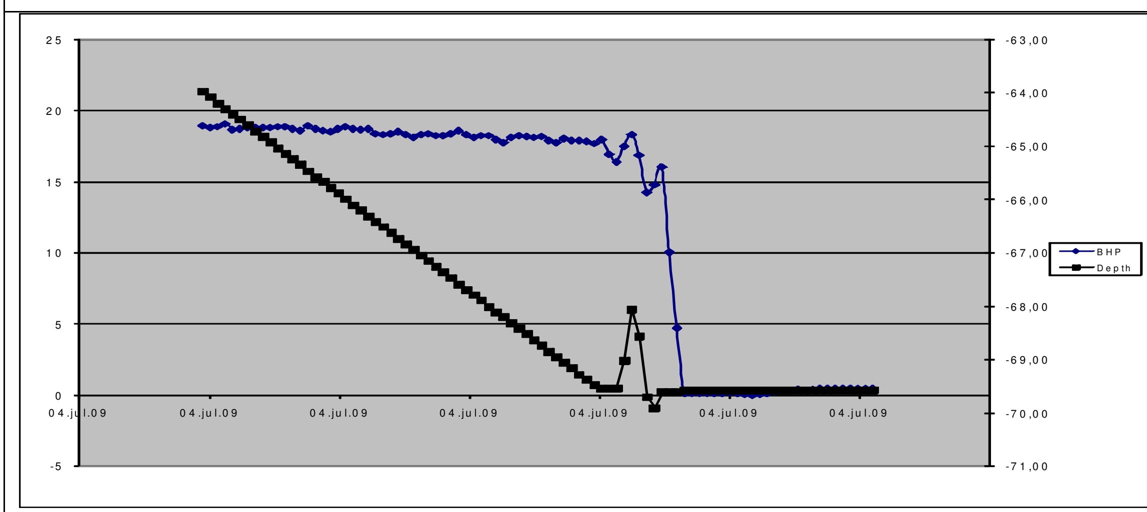

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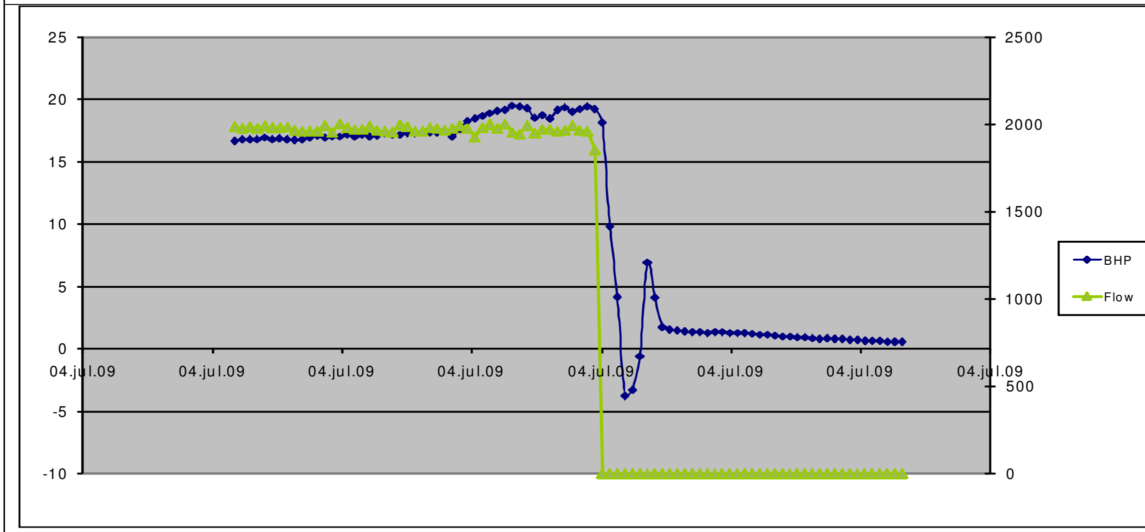
04/07/09 05:00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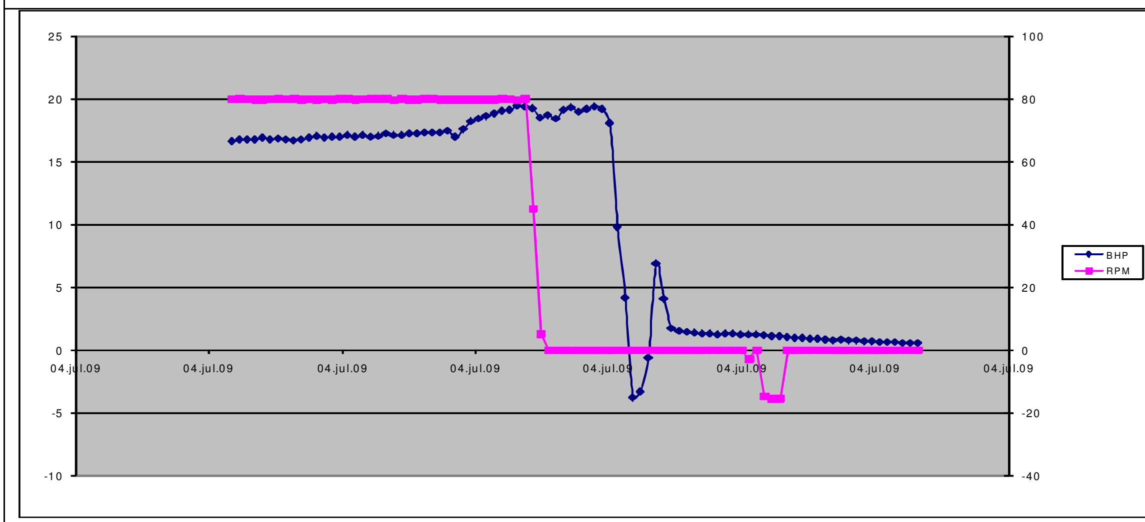
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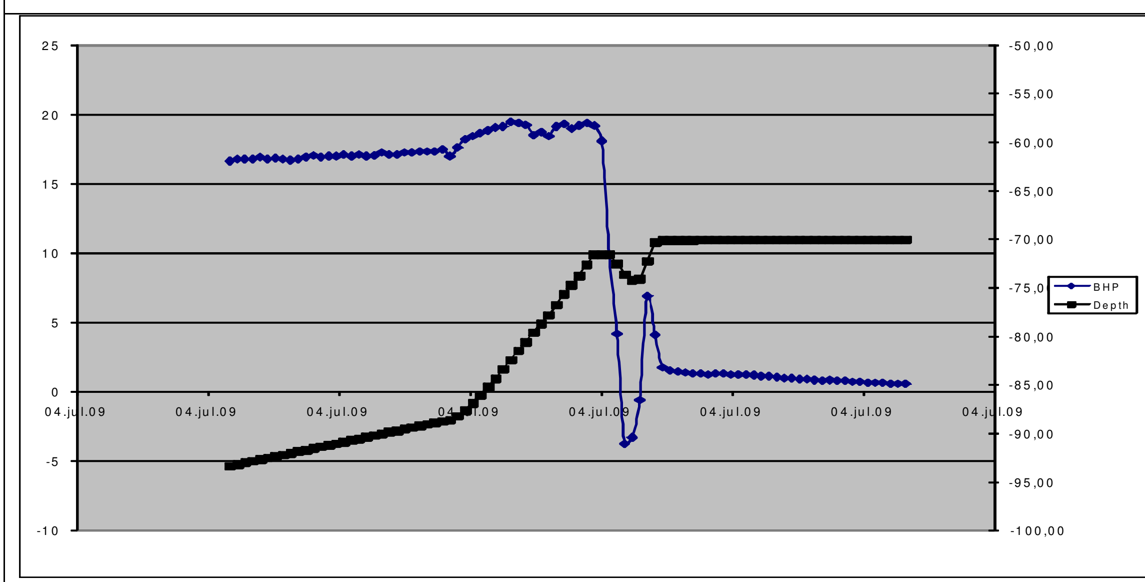
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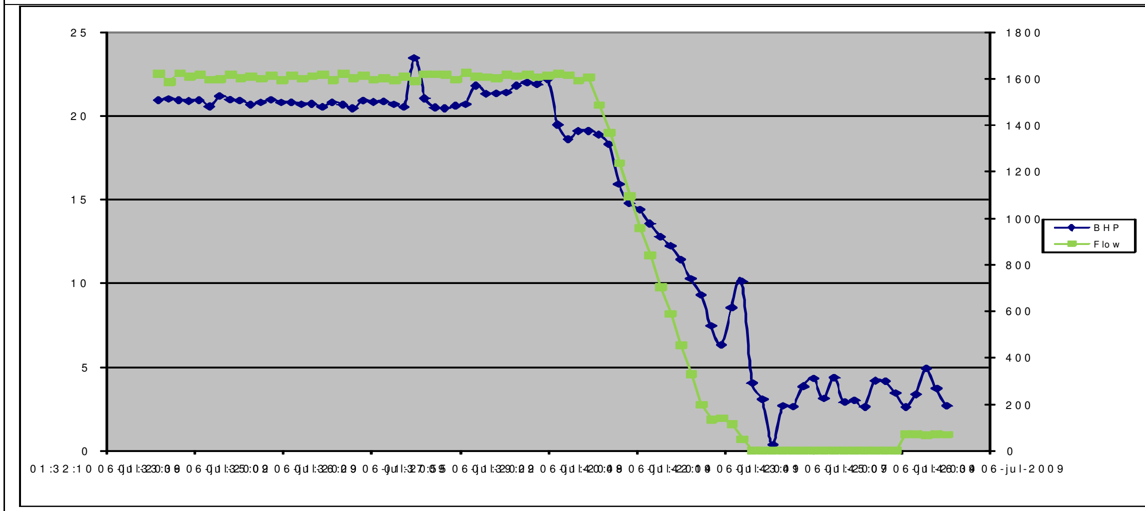
06/07/09 01:30



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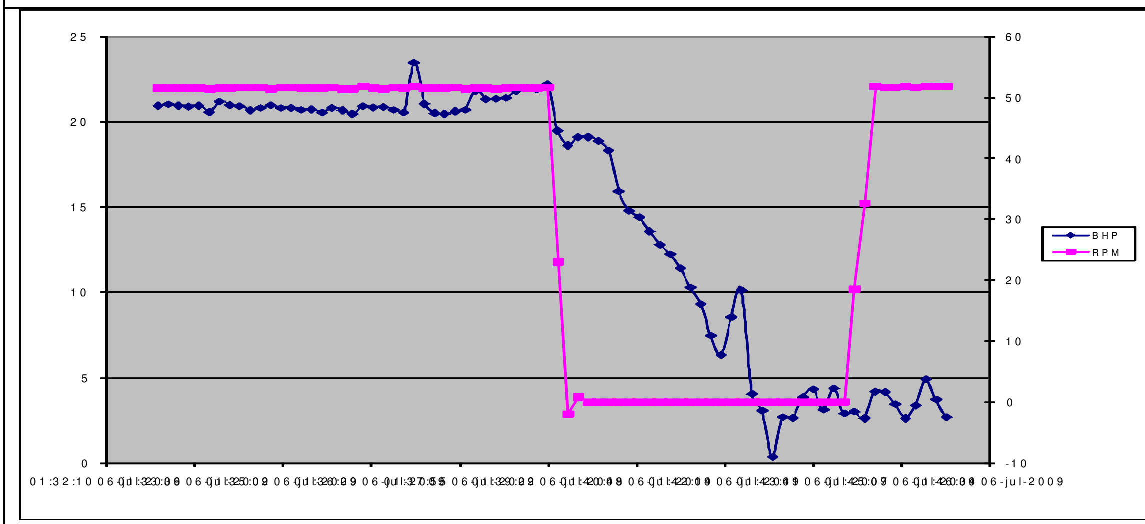

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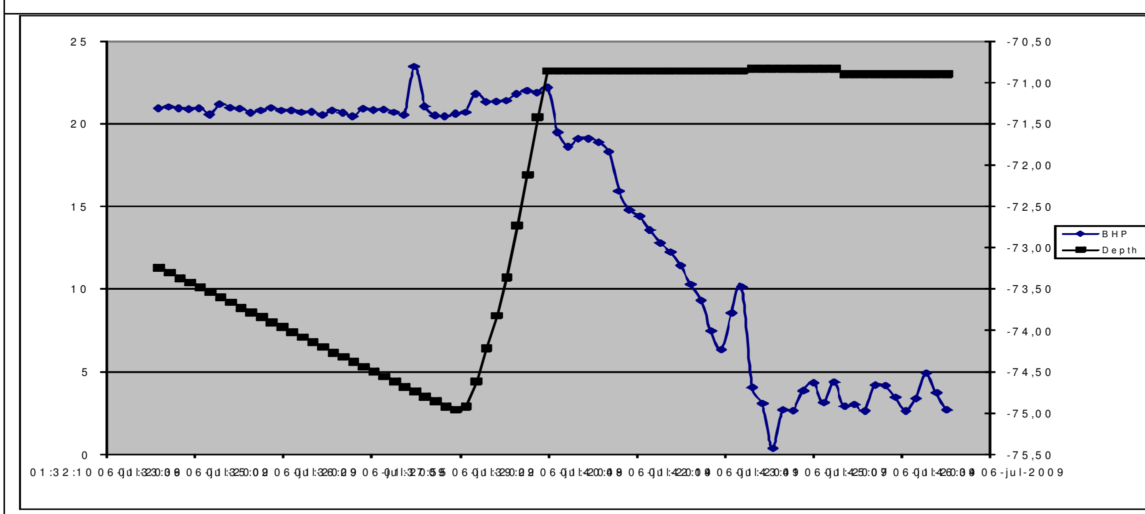

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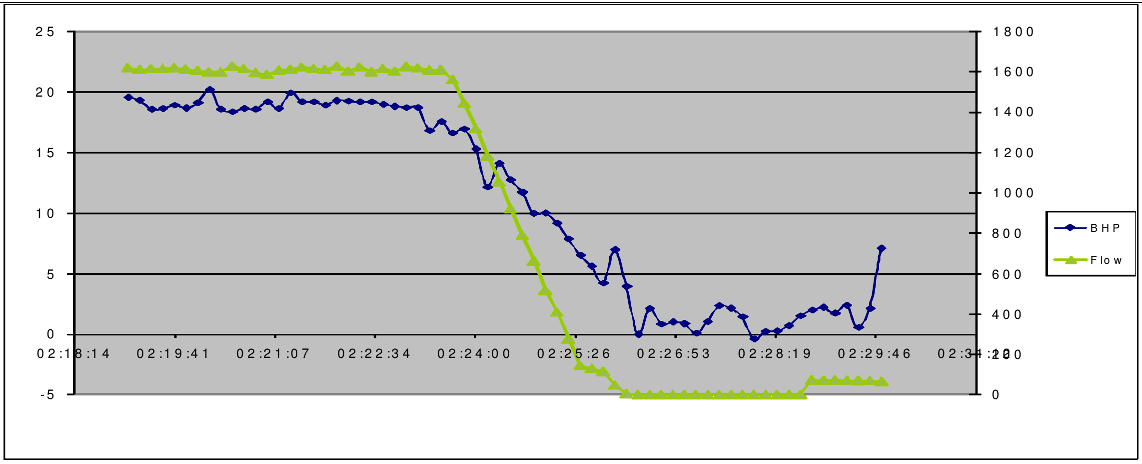
06/07/09 02:20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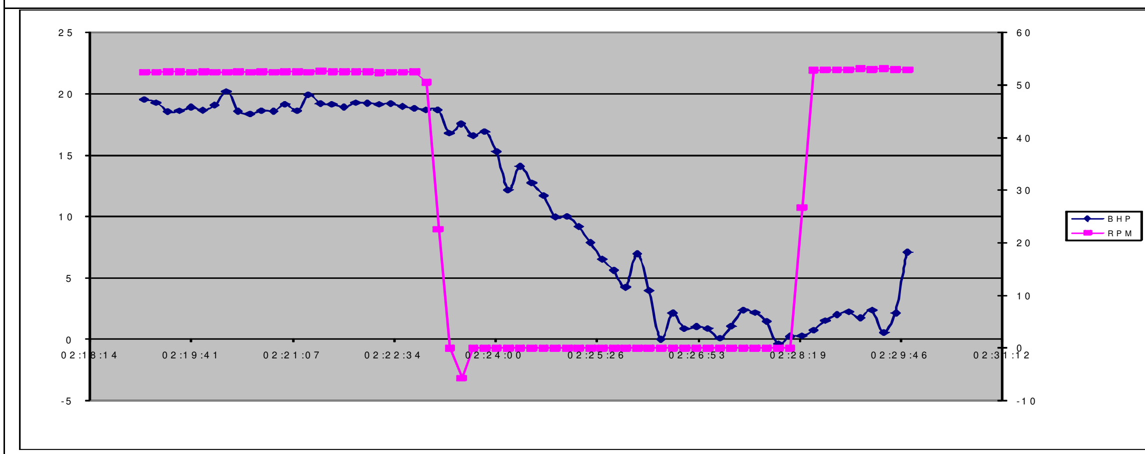
BHP
Flow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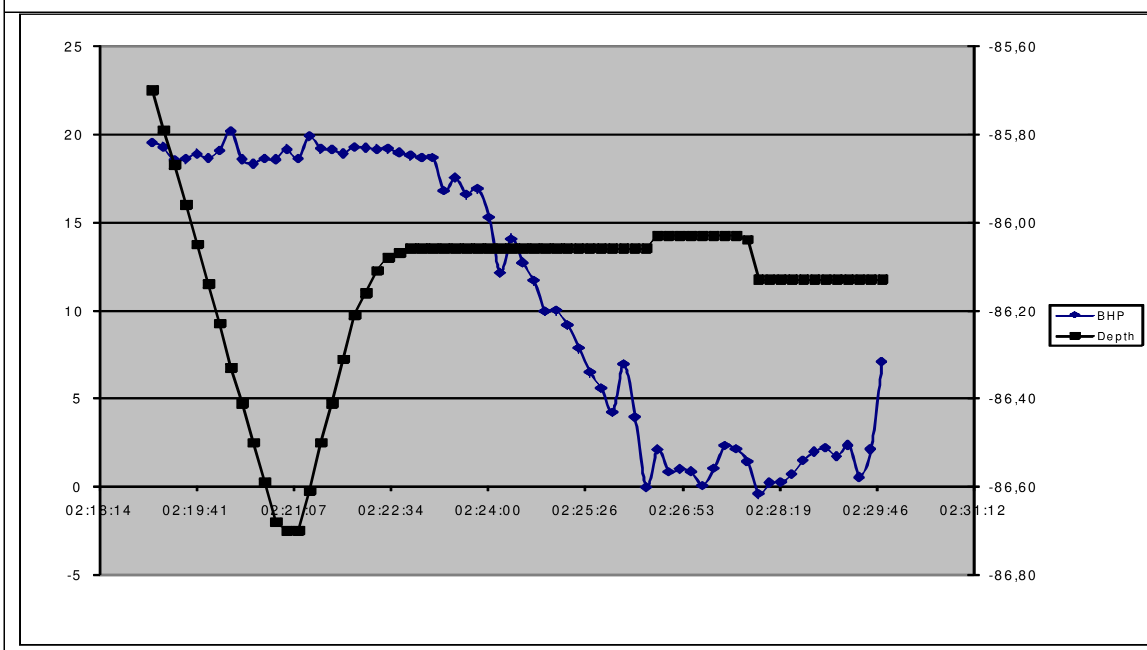
BHP
RPM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Depth

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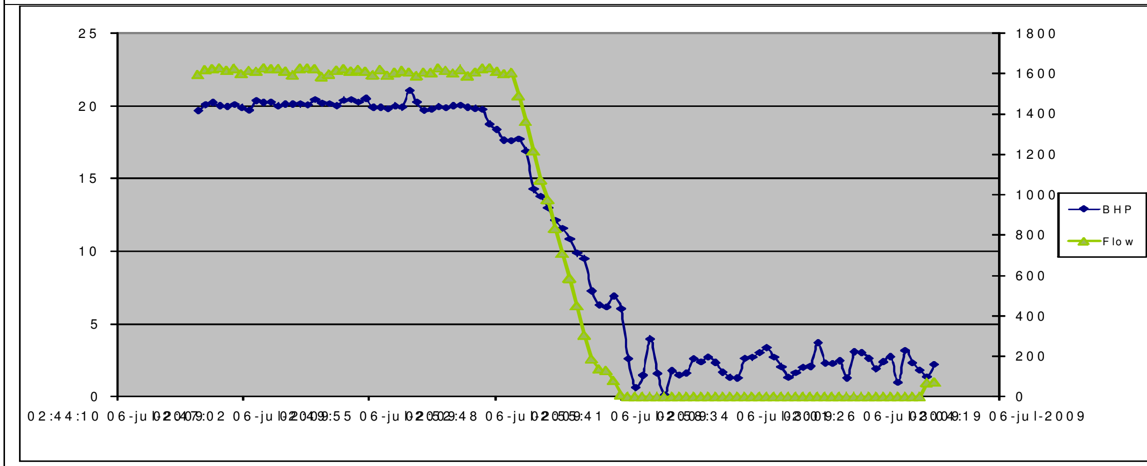

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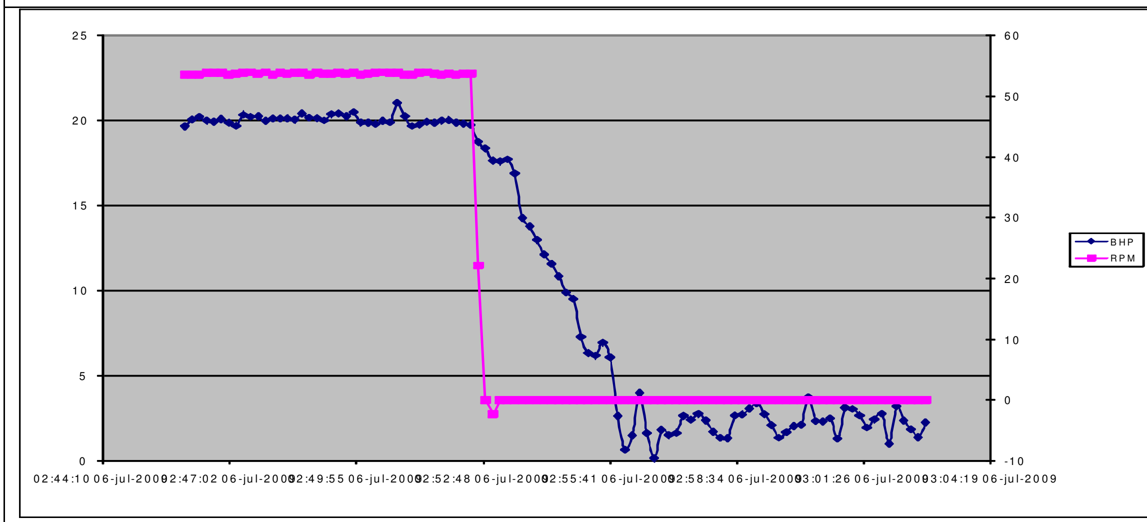

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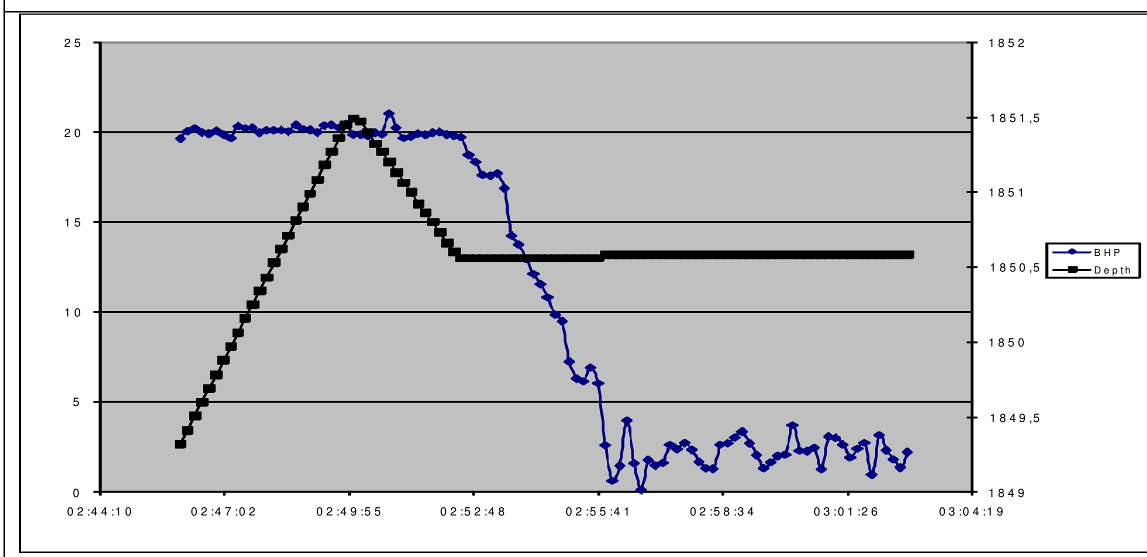
RPM



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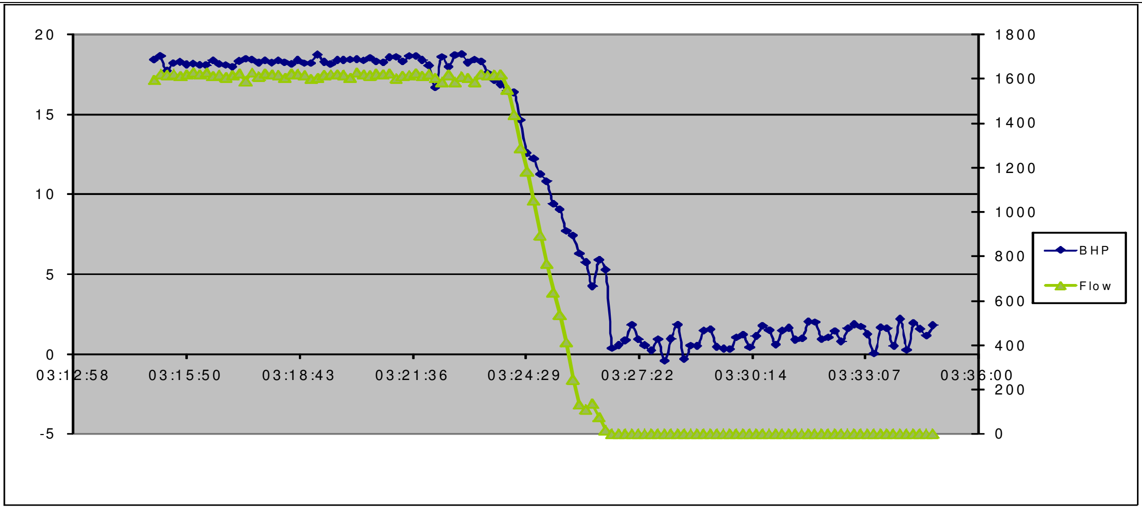
Depth

06/07/09 03:15



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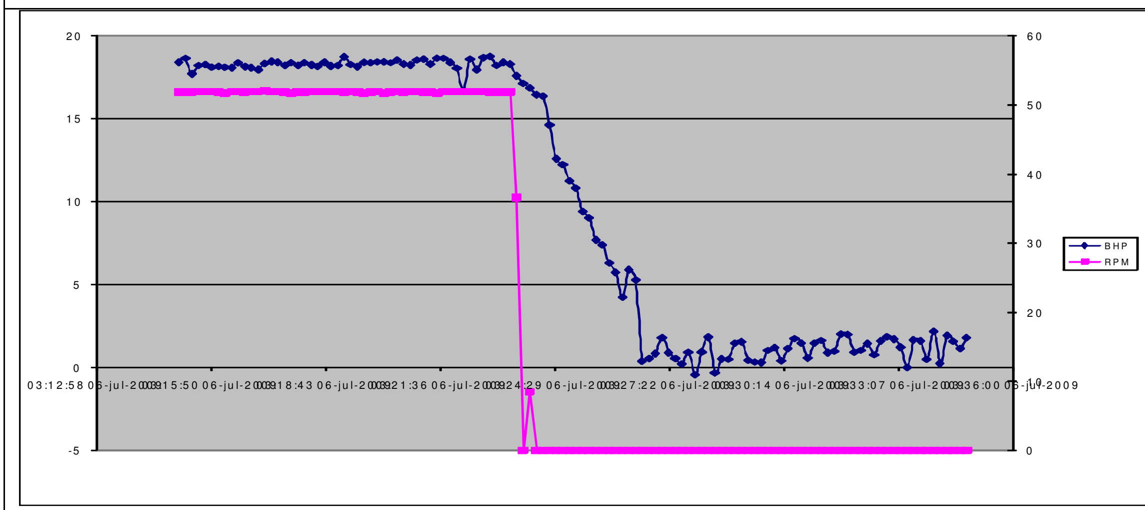
Flow



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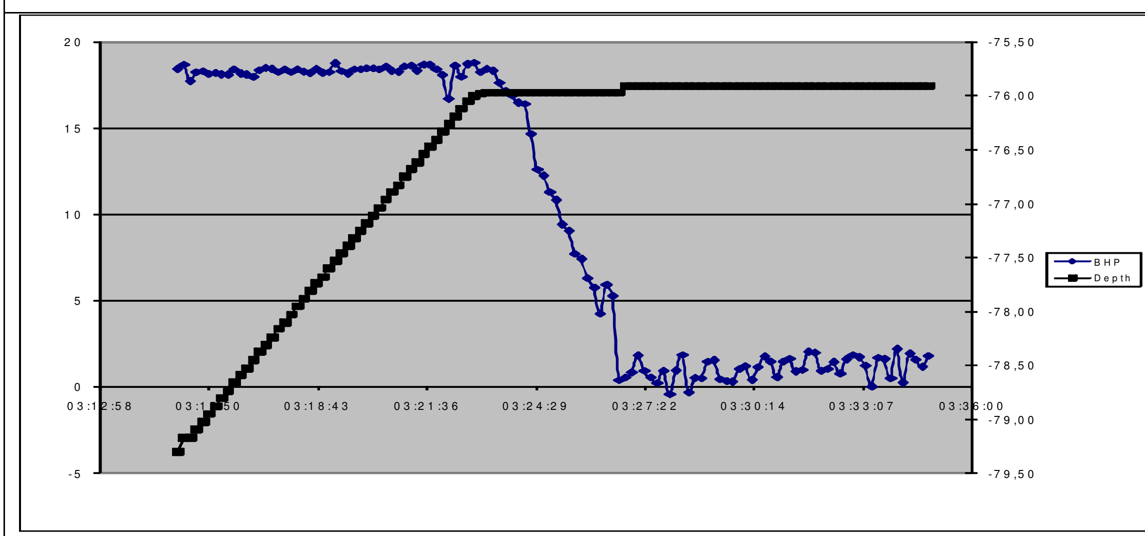
RPM



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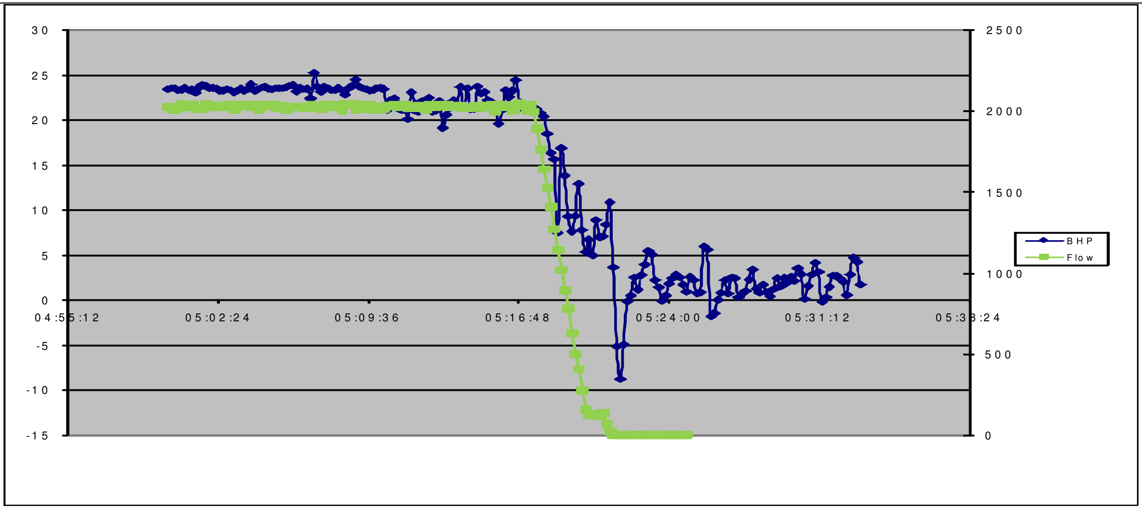
Depth

07/07/09 05:00



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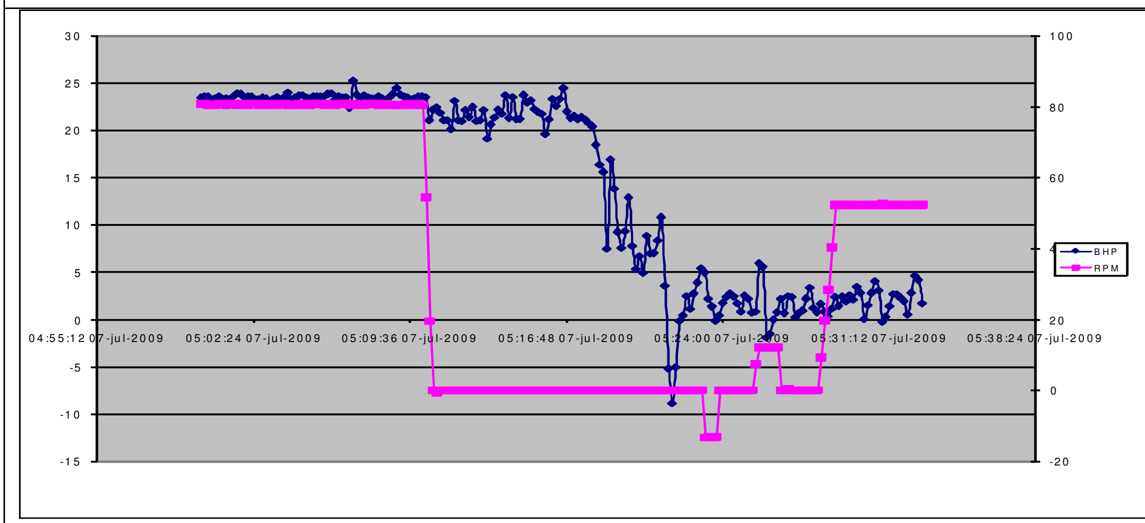
Flow



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-20
04:55:12 07-jul-2009
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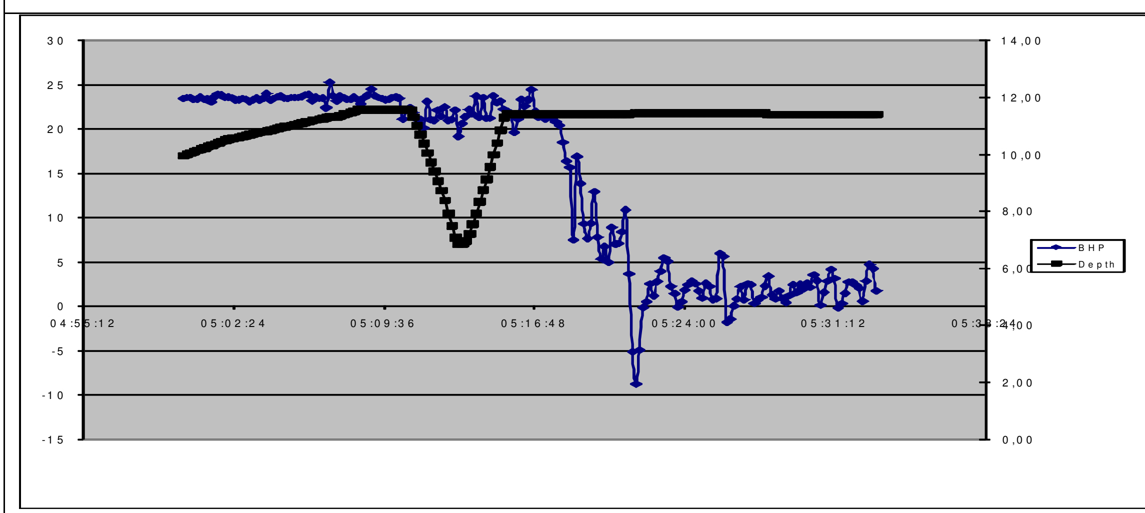
BHP
RPM



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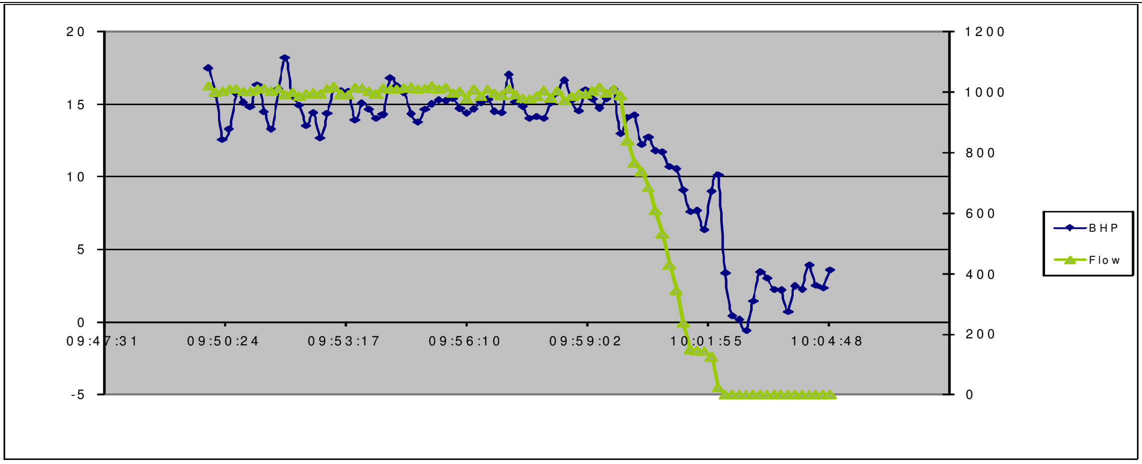
Depth

07/07/09 09:50



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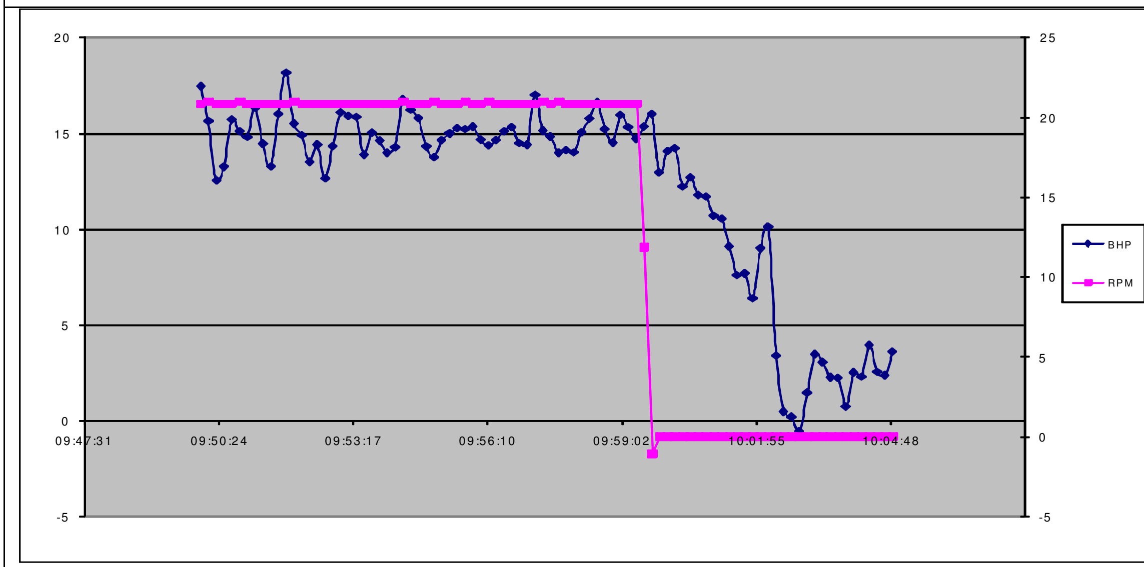
Flow



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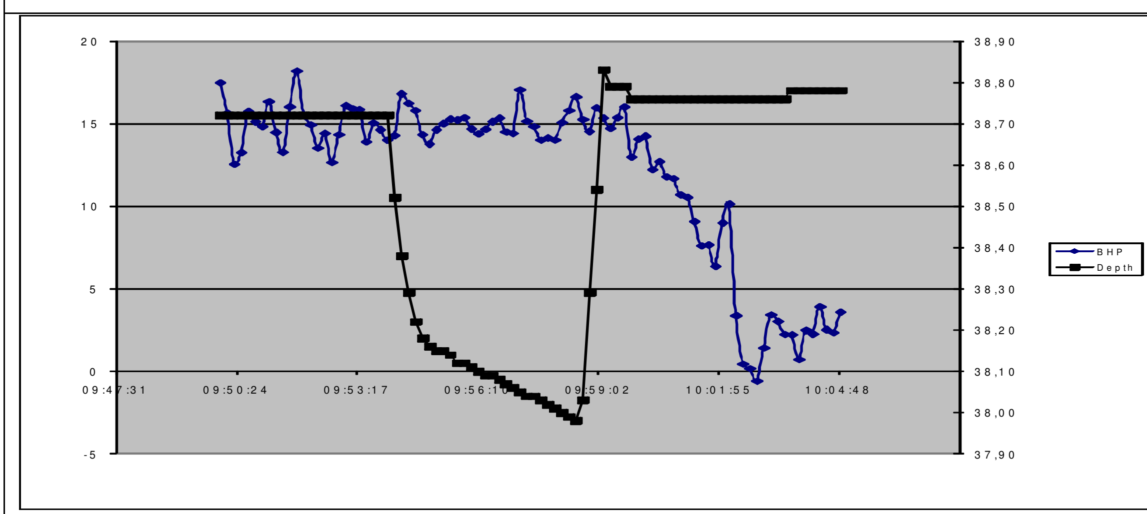
BHP
RPM



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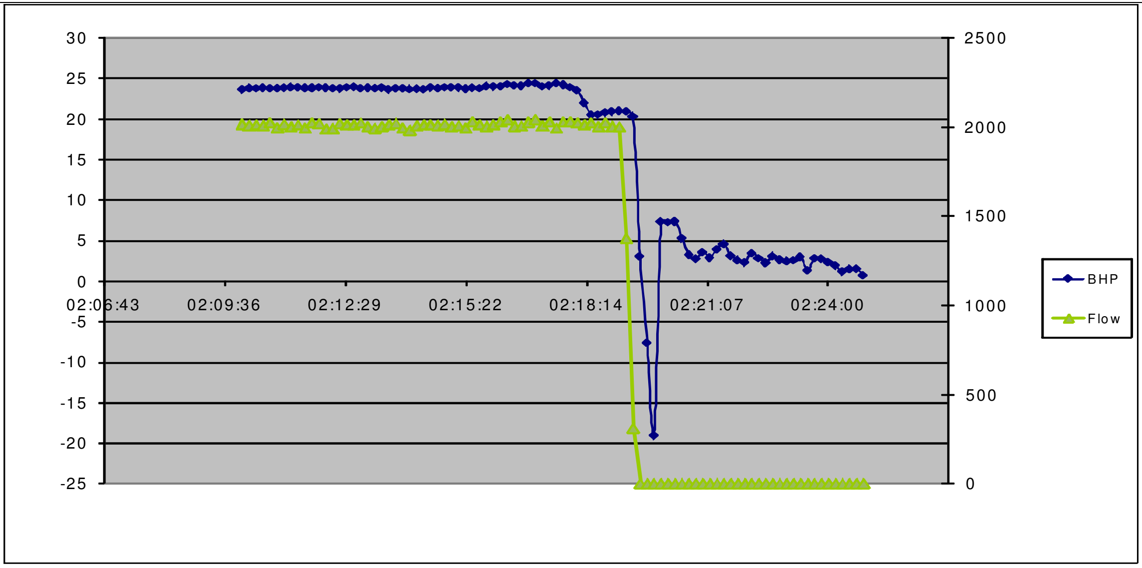
BHP
Depth

08/07/09 02:10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5
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-15
-20
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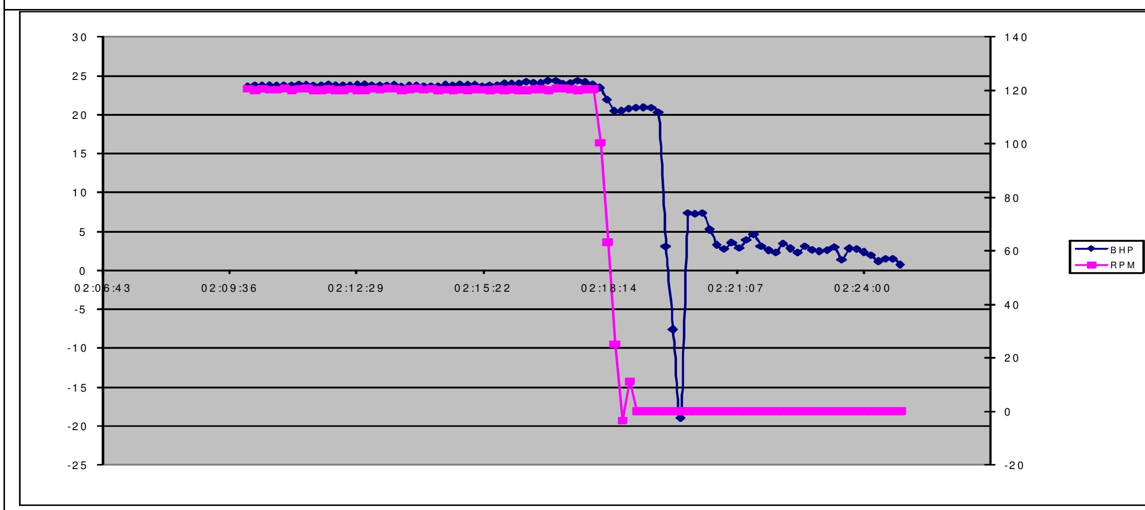
02:21:07
02:24:00
2500
2000
1500
1000
500
0
BHP
Flow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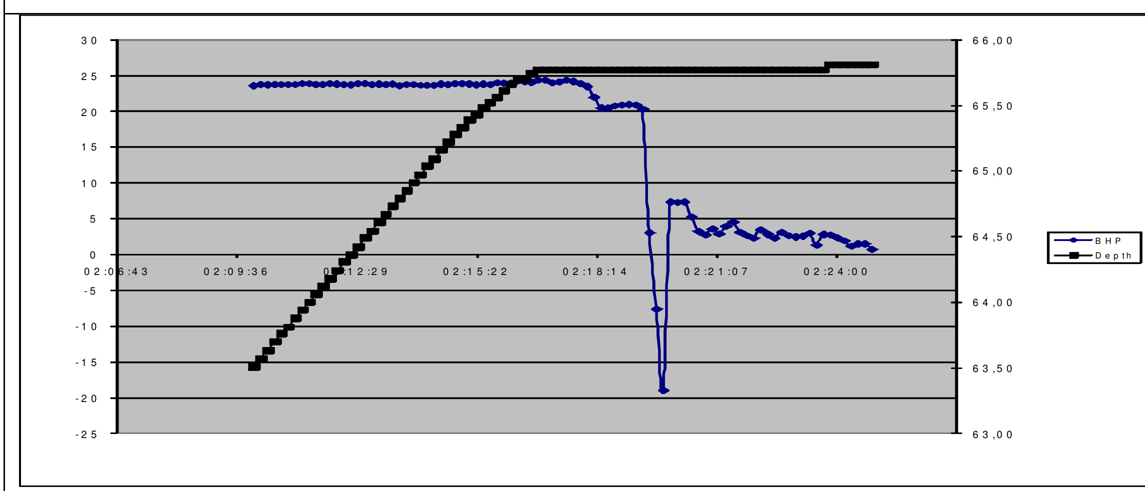
80
60
40
20
0
-20
BHP
RPM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02:15:22
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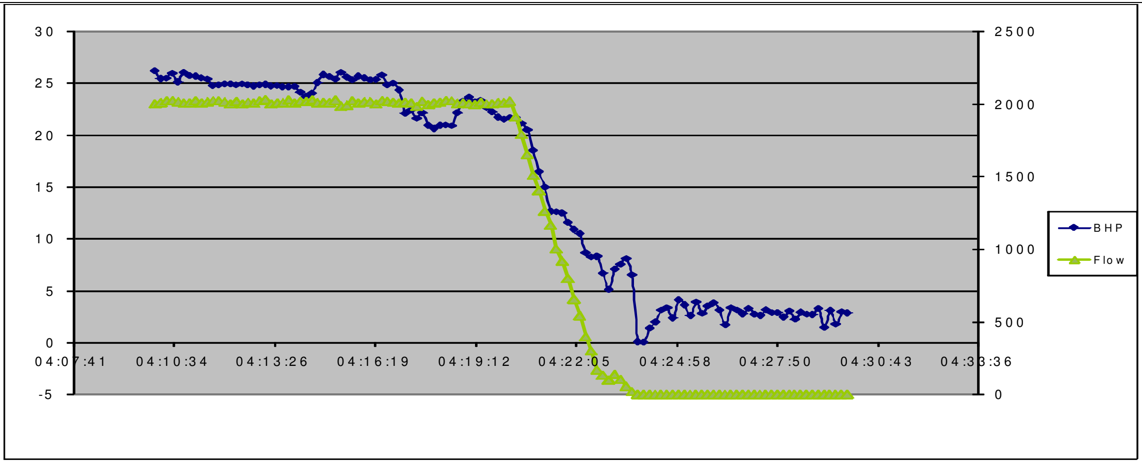
63,50
63,00
BHP
Depth

08/07/09 04:10



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04:19:12
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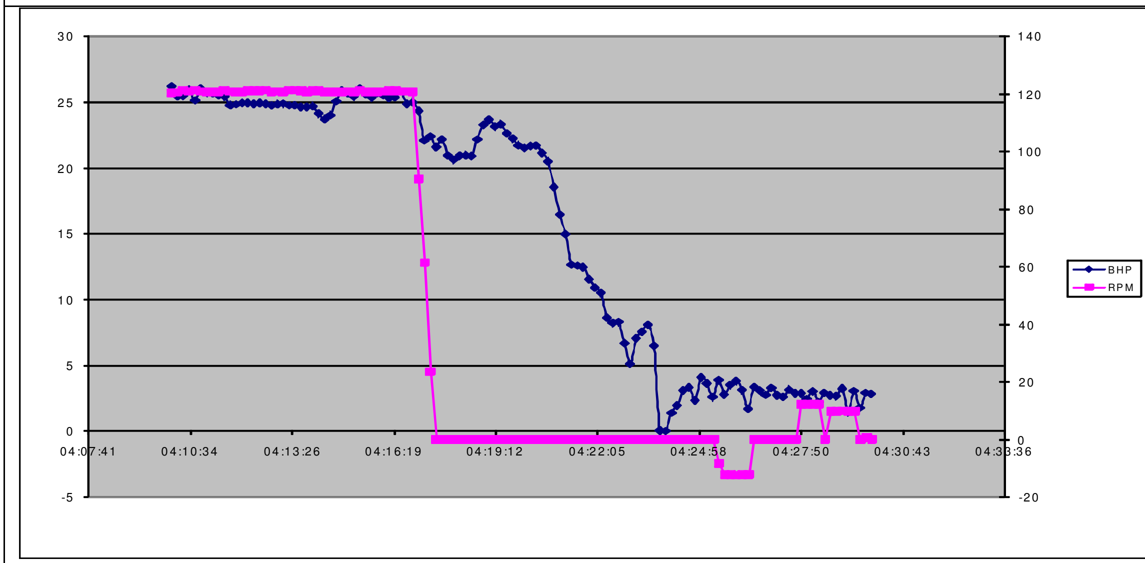
04:33:36
2500
2000
1500
1000
500
0
BHP
Flow



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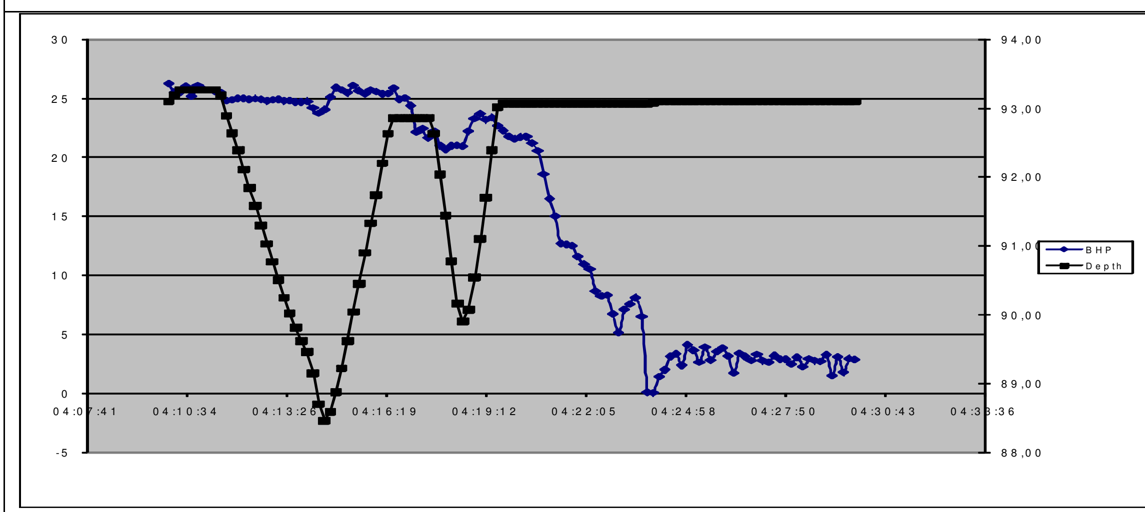
BHP
RPM



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93,00
92,00
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90,00
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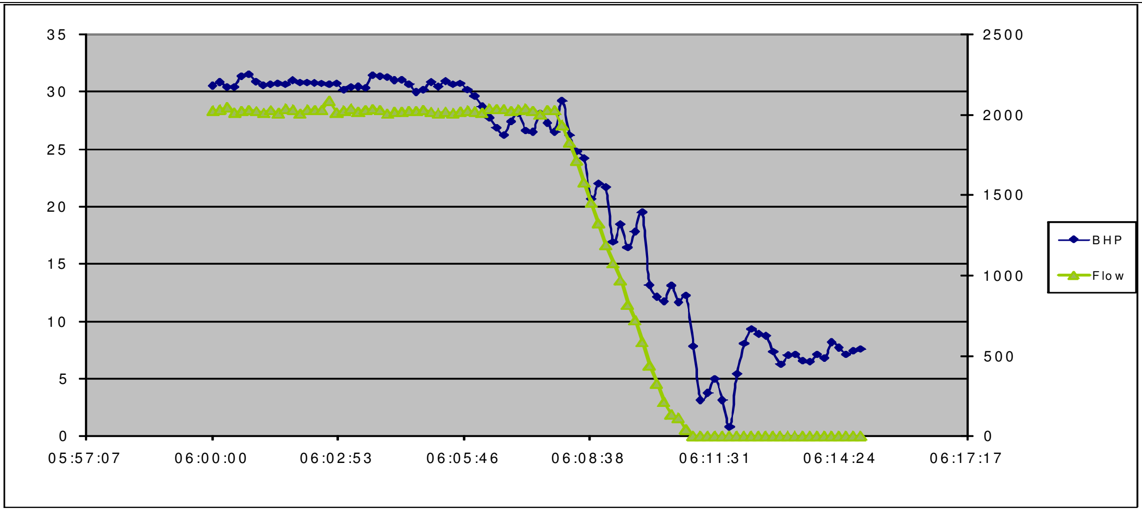
88,00
BHP
Depth

08/07/09 06:00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1000
500
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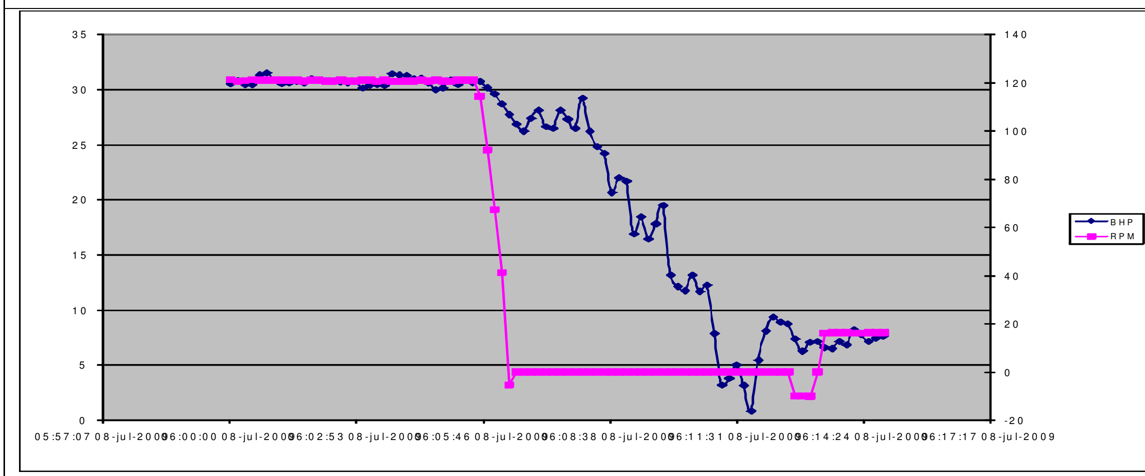
06:17:17
BHP
Flow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-20
05:57:07 08-jul-2009
06:00:00 08-jul-2009
06:02:53 08-jul-2009
06:05:46 08-jul-2009
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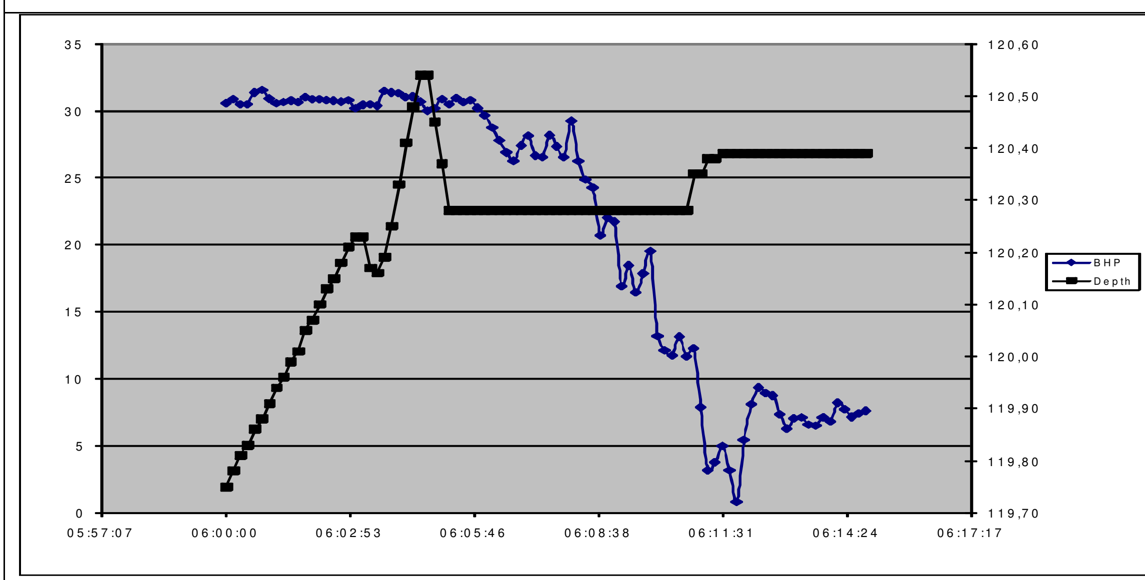
06:14:24 08-jul-2009
06:17:17 08-jul-2009
BHP
RPM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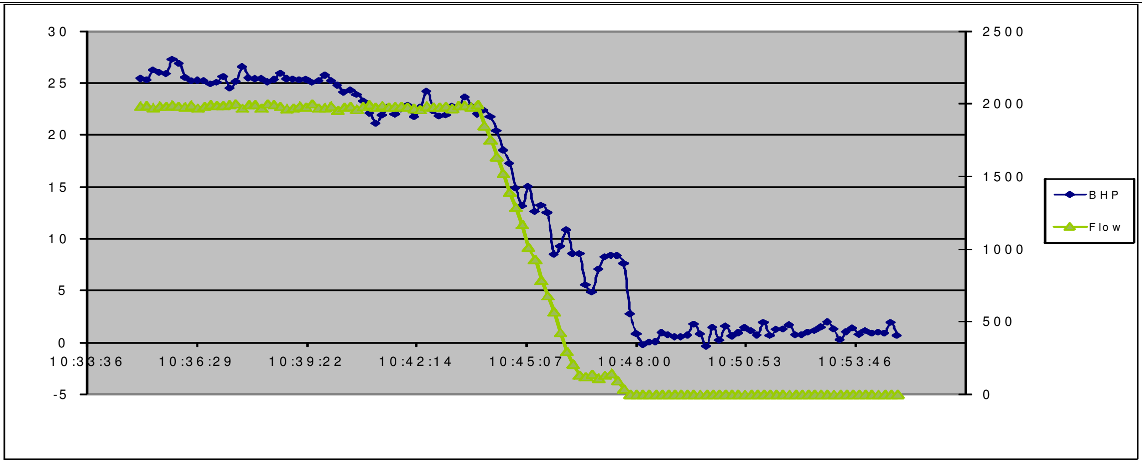
06:11:31
06:14:24
06:17:17
BHP
Depth

08/07/09 10:35



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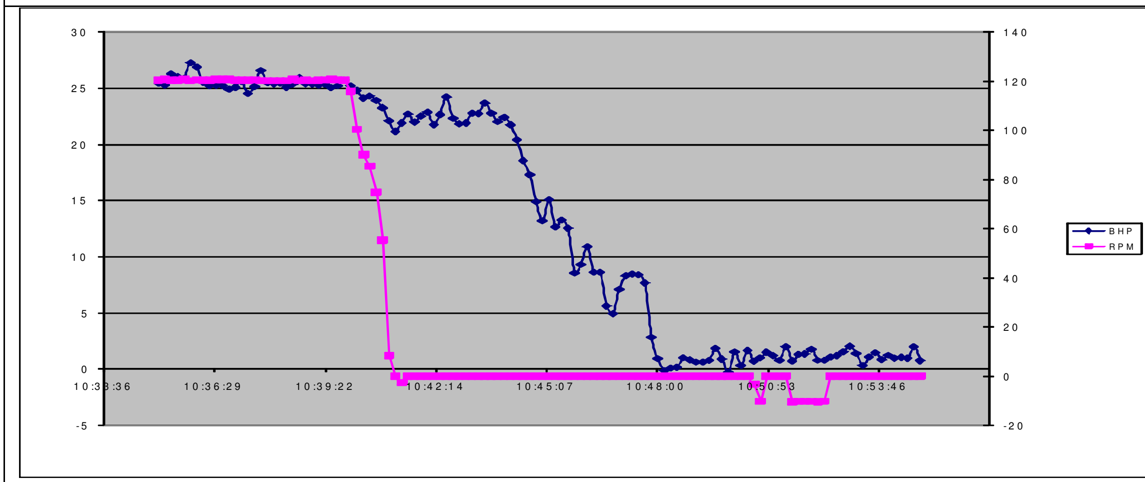
BHP
Flow



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20
0
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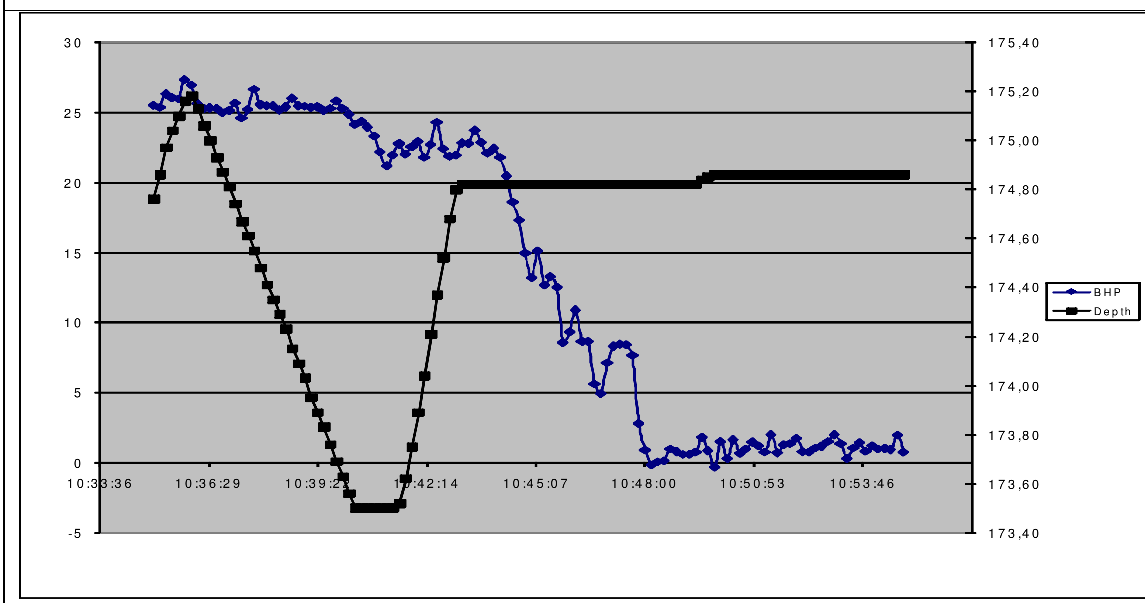
BHP
RPM



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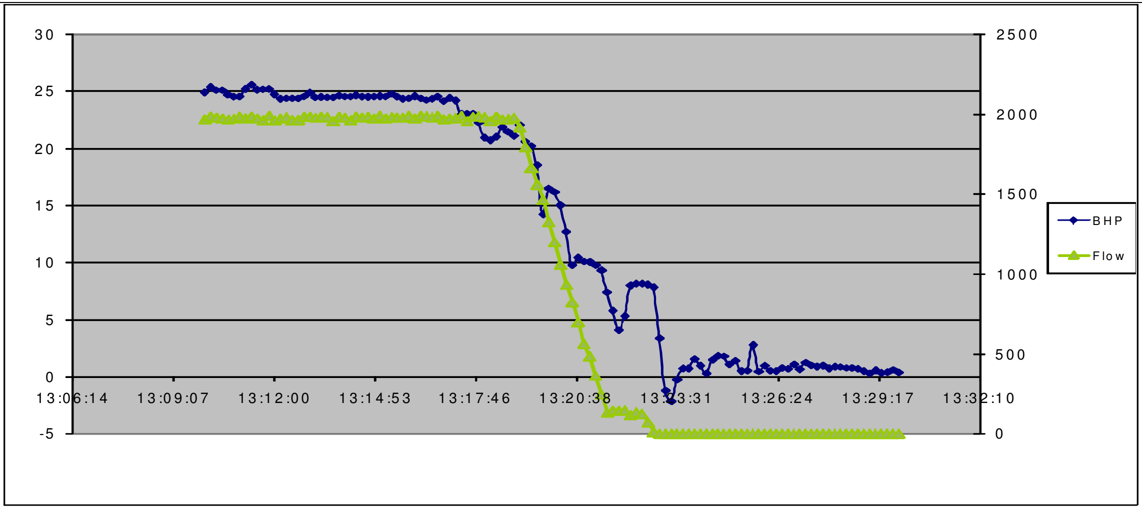
BHP
Depth

08/07/09 13:10



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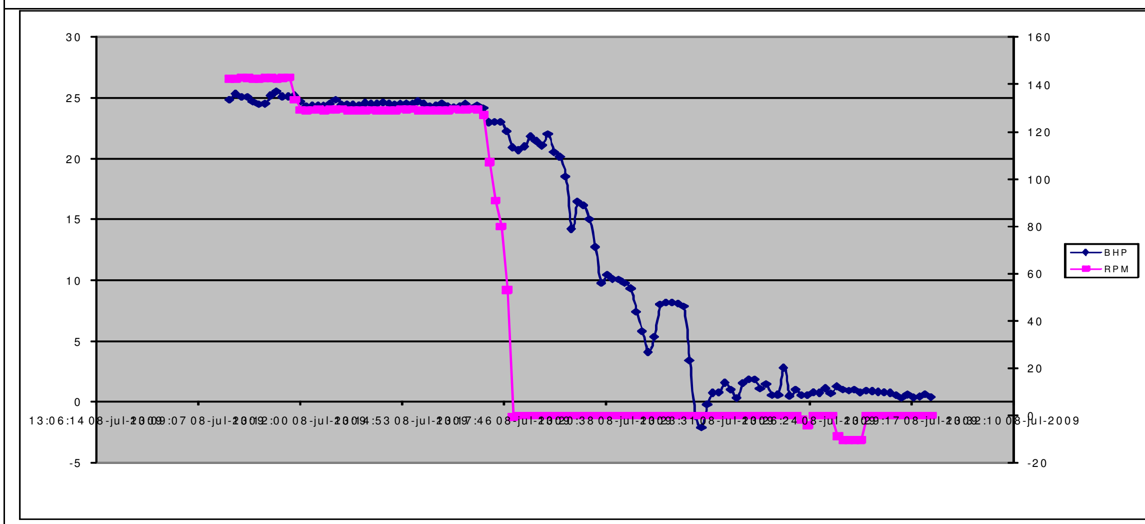
13:17:46
13:20:38
13:23:31
13:26:24
13:29:17
13:32:10
BHP
Flow



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60
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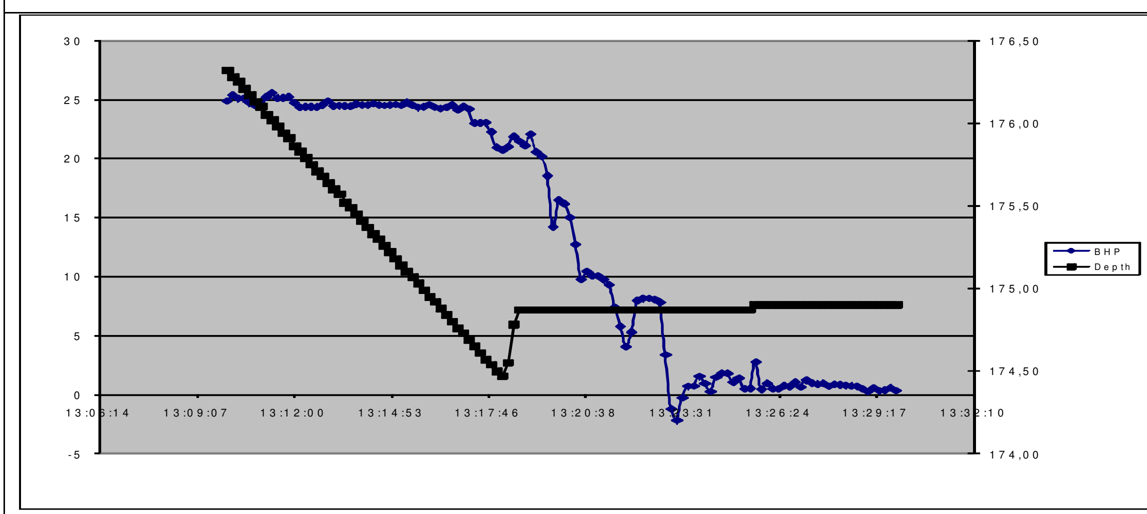
20
0
-20
BHP
RPM



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13:12:00
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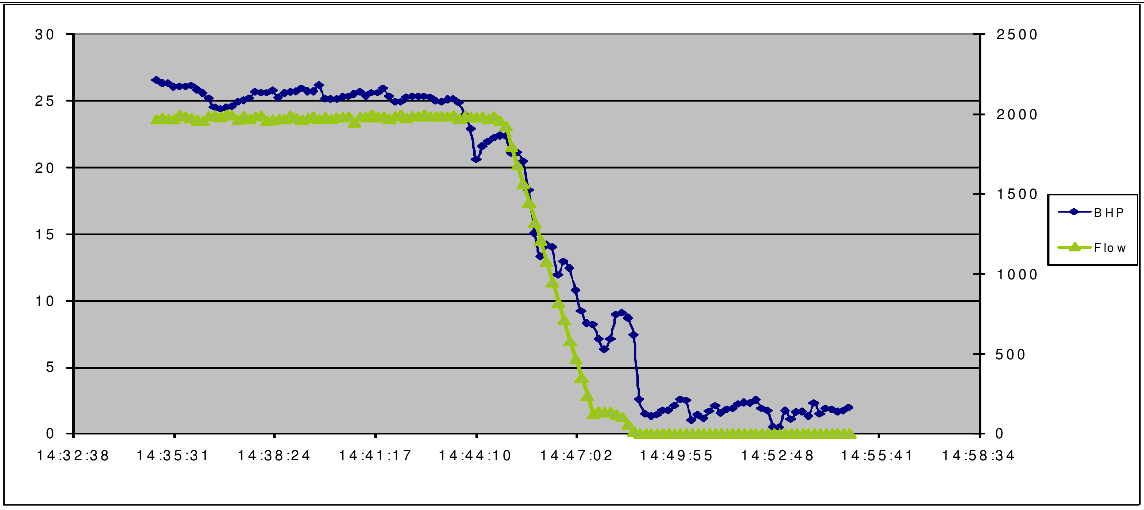
Depth

08/07/09 14:35



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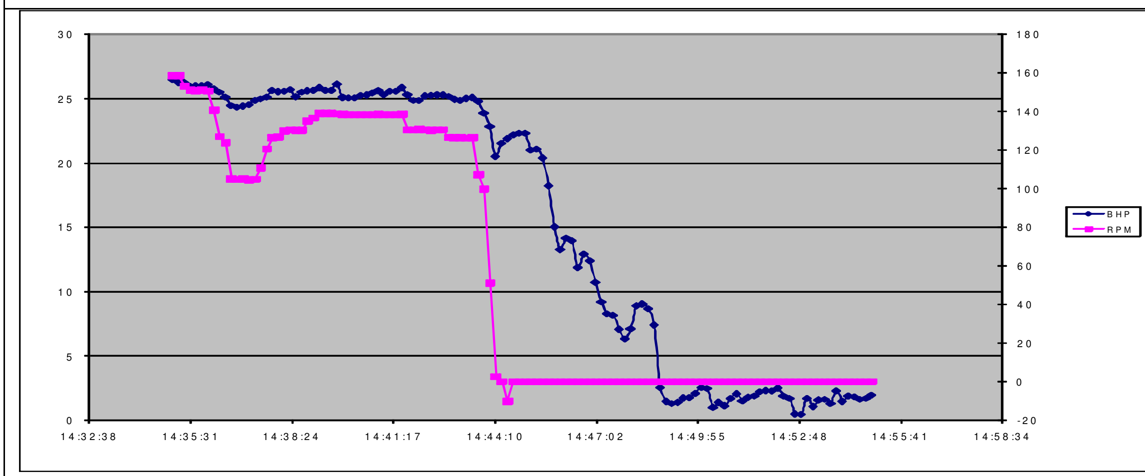
BHP
Flow



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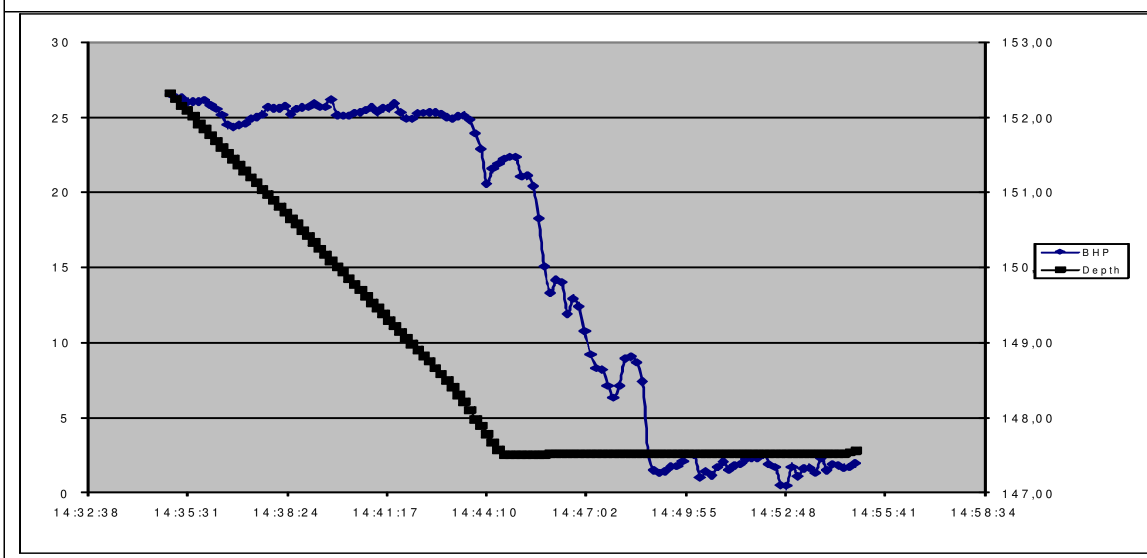
14:58:34
BHP
RPM



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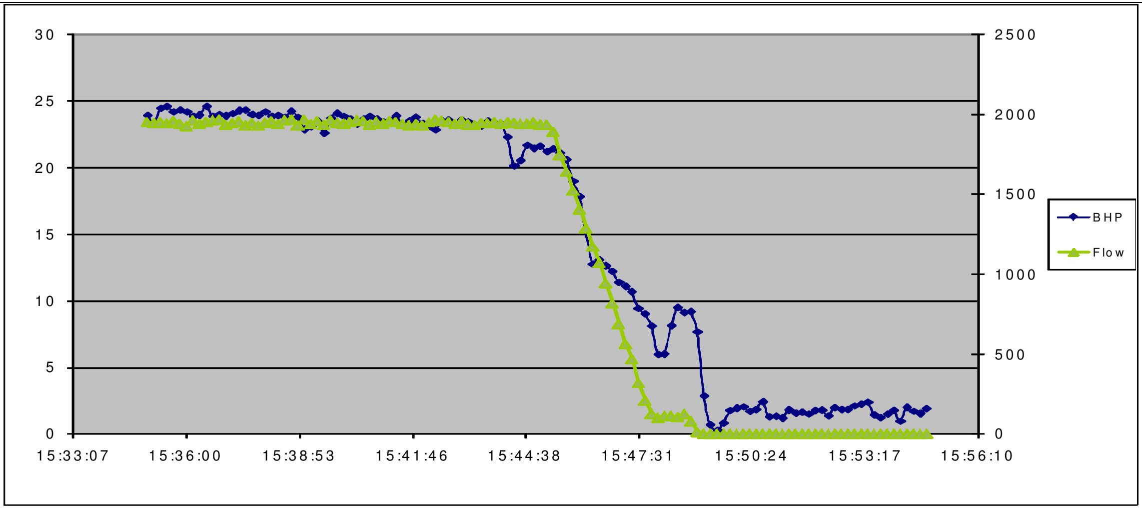
BHP
Depth

08/07/09 15:35



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500
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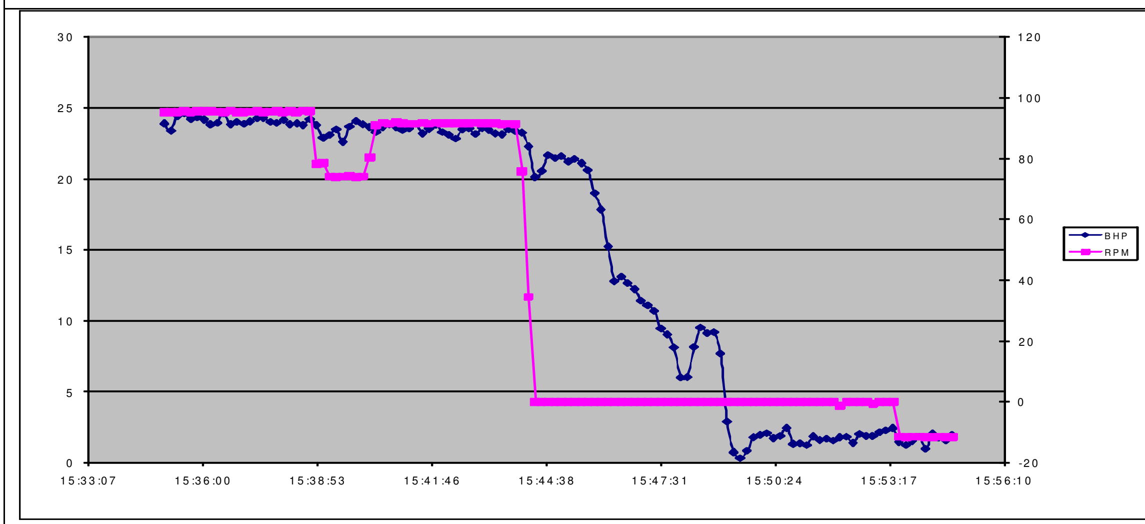
BHP
Flow



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-20
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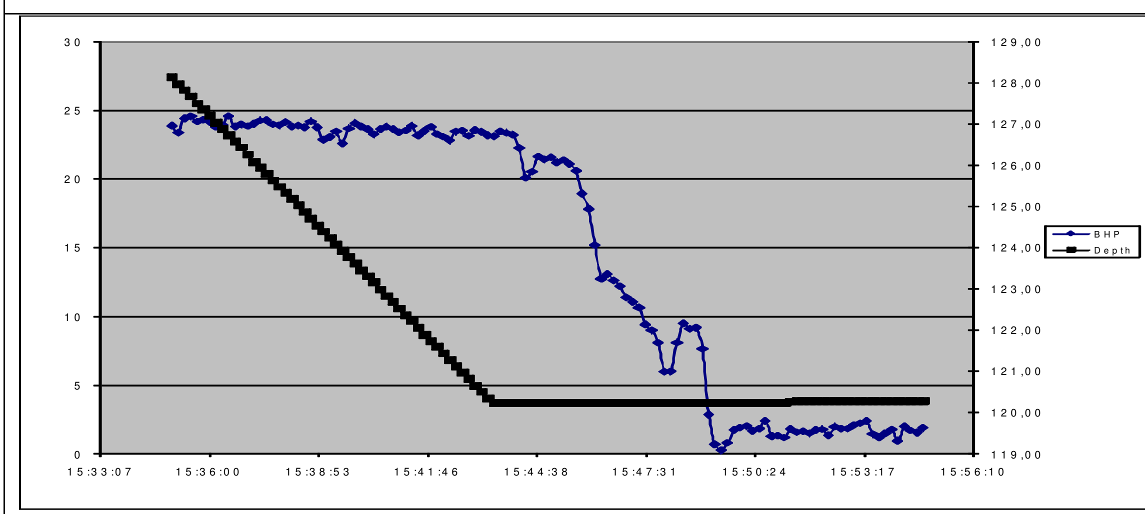
BHP
RPM



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15:47:31
15:50:24
15:53:17
15:56:10
BHP
Depth

Appendix B

Data collected for Start-up cases

Date	Time	Depth	BHP	Flow		RPM		Low Flow	RPM before flow		
				Magnitude	Effect	Magnitude	Effect		Magnitude	On	Off
28.04.2009	04:00	39	20,197	1975	12,691	100	3,138	3,063	55	1,022	0,283
29.04.2009	01:50	-71	11,505	1475	8,287	30	0,796	1,527	55	-0,322	1,218
29.04.2009	02:30	-41	11,662	1465	8,880	30	0,532	1,939	55	-0,460	0,772
29.04.2009	03:05	-16	12,461	1465	8,728	30	0,876	1,721	55	0,000	1,136
29.04.2009	03:45	14	13,577	1475	9,192	30	1,113	1,796	55	0,419	1,057
06.07.2009	01:20	-71	18,426	1600	9,904	50	2,584	3,196	55	0,970	1,773
06.07.2009	01:45	-71	18,127	1600	9,720	50	2,425	3,859	50	0,777	1,346
06.07.2009	02:30	-86	19,101	1600	10,748	55	2,570	2,950	55	1,721	1,112
06.07.2009	03:00	-81	17,801	1600	11,059	50	2,681	4,094	50	-0,575	0,542
06.07.2009	03:35	-76	18,154	1600	10,743	50	2,274	3,028	50	1,138	0,971
07.07.2009	05:35	9	21,800	2000	15,670	60	1,795	2,468	55	1,147	0,721
07.07.2009	10:15	39	23,001	2000	14,822	110	2,870	4,223	20	0,065	1,021
08.07.2009	02:25	66	22,968	2000	14,428	120	3,214	2,837	50	0,845	1,645
08.07.2009	04:35	54	22,976	2000	13,923	120	3,290	2,830	50	1,457	1,477
08.07.2009	06:20	121	25,379	2000	15,307	120	3,365	3,138	50	2,149	1,421
08.07.2009	08:50	148	24,784	1980	14,594	115	3,628	4,249	20	1,418	0,896
08.07.2009	11:00	174	23,532	1970	14,261	120	3,547	3,712	20	0,359	1,653
08.07.2009	13:35	174	23,837	1970	13,870	130	3,270	6,697	0	0,000	0,000
08.07.2009	15:05	147	23,811	1945	13,380	160	3,777	3,668	30	1,685	1,302

Date	Time	Percentage of total BHP change				
		Flow	RPM	Low Flow	RPM1	RPM2
28.04.2009	04:00	0,6284	0,1554	0,1516	0,0506	0,0140
29.04.2009	01:50	0,7203	0,0692	0,1327	-0,0280	0,1058
29.04.2009	02:30	0,7614	0,0456	0,1663	-0,0394	0,0662
29.04.2009	03:05	0,7004	0,0703	0,1381	0,0000	0,0912
29.04.2009	03:45	0,6770	0,0820	0,1323	0,0308	0,0778
06.07.2009	01:20	0,5375	0,1402	0,1734	0,0526	0,0962
06.07.2009	01:45	0,5362	0,1338	0,2129	0,0428	0,0743
06.07.2009	02:30	0,5627	0,1346	0,1544	0,0901	0,0582
06.07.2009	03:00	0,6213	0,1506	0,2300	-0,0323	0,0304
06.07.2009	03:35	0,5917	0,1253	0,1668	0,0627	0,0535
07.07.2009	05:35	0,7188	0,0823	0,1132	0,0526	0,0331
07.07.2009	10:15	0,6444	0,1248	0,1836	0,0028	0,0444
08.07.2009	02:25	0,6282	0,1399	0,1235	0,0368	0,0716
08.07.2009	04:35	0,6060	0,1432	0,1232	0,0634	0,0643
08.07.2009	06:20	0,6031	0,1326	0,1236	0,0847	0,0560
08.07.2009	08:50	0,5888	0,1464	0,1714	0,0572	0,0361
08.07.2009	11:00	0,6060	0,1507	0,1577	0,0152	0,0702
08.07.2009	13:35	0,5819	0,1372	0,2810	0,0000	0,0000
08.07.2009	15:05	0,5619	0,1586	0,1540	0,0707	0,0547

Data collected for Break-up cases

Date	Time	Depth	BHP	Depth correction	Flow		Low Flow		RPM	
					Magnitude	Effect	Magnitude	Effect	Magnitude	Effect
27.04.2009	00:20	9	13,115	-0,505	1550	12,310	0	0,000	40	1,310
27.04.2009	08:25	-1	13,744	0,502	1550	12,703	0	0,000	30	0,539
27.04.2009	15:30	-4	12,184	0,000	1525	11,335	0	0,000	30	0,849
29.04.2009	01:20	-71	11,888	0,000	1500	11,239	0	0,000	30	0,648
29.04.2009	02:10	-41	11,302	0,000	1470	10,618	0	0,000	30	0,684
29.04.2009	08:00	29	11,024	0,000	1470	10,656	0	0,000	10	0,368
04.07.2009	00:20	-66	17,858	0,345	2000	15,927	0	0,000	80	1,586
04.07.2009	05:00	-71	18,103	-0,690	2000	17,919	0	0,000	80	0,873
06.07.2009	01:30	-71	18,614	0,000	1615	12,707	140	2,898	50	3,009
06.07.2009	02:20	-86	18,083	0,000	1605	12,724	140	3,251	50	2,108
06.07.2009	02:45	-81	17,669	0,000	1615	11,393	140	4,077	55	2,199
06.07.2009	03:15	-76	17,255	0,000	1610	12,177	130	3,172	50	1,906
07.07.2009	05:00	9	21,952	0,460	2040	15,731	130	4,058	80	1,703
07.07.2009	09:50	38	12,920	0,000	1000	7,782	150	4,138	20	1,000
08.07.2009	02:10	64	21,307	0,000	2015	18,115	0	0,000	120	3,193
08.07.2009	04:10	89	22,037	0,431	1993	14,067	130	4,665	120	2,874
08.07.2009	06:00	119	23,627	0,000	2025	15,000	130	5,215	120	3,413
08.07.2009	10:35	174	24,501	0,000	1980	14,391	130	7,131	120	2,979
08.07.2009	13:10	176	23,563	0,000	1970	13,301	130	7,154	120	3,108
08.07.2009	14:35	149	23,225	0,000	1980	13,460	120	7,145	125	2,620
08.07.2009	15:35	124	21,573	0,000	1955	12,187	120	7,538	95	1,847

Date	Time	Percentage of total BHP change		
		Flow	Low Flow	RPM
27.04.2009	00:20	0,9038	0,0000	0,0962
27.04.2009	08:25	0,9593	0,0000	0,0407
27.04.2009	15:30	0,9303	0,0000	0,0697
29.04.2009	01:20	0,9455	0,0000	0,0545
29.04.2009	02:10	0,9395	0,0000	0,0605
29.04.2009	08:00	0,9666	0,0000	0,0334
04.07.2009	00:20	0,9094	0,0000	0,0906
04.07.2009	05:00	0,9535	0,0000	0,0465
06.07.2009	01:30	0,6826	0,1557	0,1616
06.07.2009	02:20	0,7037	0,1798	0,1166
06.07.2009	02:45	0,6448	0,2308	0,1244
06.07.2009	03:15	0,7057	0,1838	0,1105
07.07.2009	05:00	0,7320	0,1888	0,0792
07.07.2009	09:50	0,6023	0,3203	0,0774
08.07.2009	02:10	0,8502	0,0000	0,1498
08.07.2009	04:10	0,6511	0,2159	0,1330
08.07.2009	06:00	0,6349	0,2207	0,1444
08.07.2009	10:35	0,5874	0,2910	0,1216
08.07.2009	13:10	0,5645	0,3036	0,1319
08.07.2009	14:35	0,5795	0,3077	0,1128
08.07.2009	15:35	0,5649	0,3494	0,0856

Appendix C

Data obtained form Drillbench © simulations

Drillstring Configuration	Mud Weight	Depth	Flow	RPM	Delta BHP Start-up				Delta BHP Break-up				Fraction of Start-up			Break-up		
					Before	Low Flow	Main Flow	RPM						Before	Low Flow	Main Flow	RPM	
BHA 1	1,63	0	2000	120	0	5,6	16,4	17,8	17,8	16,4	6,5	0	0,3146	0,6067	0,0787	0,0787	0,5562	0,3652
	1,63	0	2000	60	0	5,6	16,4	17,1	17,1	16,4	6,5	0	0,3275	0,6316	0,0409	0,0409	0,5789	0,3801
	1,63	0	2000	30	0	5,6	16,4	16,8	16,8	16,4	6,5	0	0,3333	0,6429	0,0238	0,0238	0,5893	0,3869
	1,63	0	1600	120	0	5,6	14,5	15,8	15,8	14,5	6,4	0	0,3544	0,5633	0,0823	0,0823	0,5127	0,4051
	1,63	0	1600	60	0	5,6	14,5	15,1	15,1	14,5	6,4	0	0,3709	0,5894	0,0397	0,0397	0,5364	0,4238
	1,63	0	1600	30	0	5,6	14,5	14,8	14,8	14,5	6,4	0	0,3784	0,6014	0,0203	0,0203	0,5473	0,4324
	1,63	0	1475	120	0	5,6	13,9	15,2	15,2	13,9	7,3	0	0,3684	0,5461	0,0855	0,0855	0,4342	0,4803
	1,63	0	1475	60	0	5,6	13,9	14,6	14,6	13,9	7,3	0	0,3836	0,5685	0,0479	0,0479	0,4521	0,5000
	1,63	0	1475	30	0	5,6	13,9	14,2	14,2	13,9	7,3	0	0,3944	0,5845	0,0211	0,0211	0,4648	0,5141
	1,63	165	2000	120	0	6	18	19,5	19,5	18	7	0	0,3077	0,6154	0,0769	0,0769	0,5641	0,3590
	1,63	165	2000	60	0	6	18	18,7	18,7	18	7	0	0,3209	0,6417	0,0374	0,0374	0,5882	0,3743
	1,63	165	2000	30	0	6	18	18,4	18,4	18	7	0	0,3261	0,6522	0,0217	0,0217	0,5978	0,3804
	1,63	165	1600	120	0	6	15,8	17,3	17,3	15,8	7	0	0,3468	0,5665	0,0867	0,0867	0,5087	0,4046
	1,63	165	1600	60	0	6	15,8	16,6	16,6	15,8	7	0	0,3614	0,5904	0,0482	0,0482	0,5301	0,4217
	1,63	165	1600	30	0	6	15,8	16,2	16,2	15,8	7	0	0,3704	0,6049	0,0247	0,0247	0,5432	0,4321
	1,63	165	1475	120	0	6	15,2	16,7	16,7	15,2	7	0	0,3593	0,5509	0,0898	0,0898	0,4910	0,4192
	1,63	165	1475	60	0	6	15,2	15,9	15,9	15,2	7	0	0,3774	0,5786	0,0440	0,0440	0,5157	0,4403
	1,63	165	1475	30	0	6	15,2	15,5	15,5	15,2	7	0	0,3871	0,5935	0,0194	0,0194	0,5290	0,4516
	1,63	655	2000	120	0	7,5	22,5	24,4	24,4	22,5	8,8	0	0,3074	0,6148	0,0779	0,0779	0,5615	0,3607
	1,63	655	2000	60	0	7,5	22,5	23,4	23,4	22,5	8,8	0	0,3205	0,6410	0,0385	0,0385	0,5855	0,3761
	1,63	655	2000	30	0	7,5	22,5	23	23	22,5	8,8	0	0,3261	0,6522	0,0217	0,0217	0,5957	0,3826
	1,63	655	1600	120	0	7,5	19,8	21,8	21,8	19,8	8,6	0	0,3440	0,5642	0,0917	0,0917	0,5138	0,3945
	1,63	655	1600	60	0	7,5	19,8	20,8	20,8	19,8	8,6	0	0,3606	0,5913	0,0481	0,0481	0,5385	0,4135
	1,63	655	1600	30	0	7,5	19,8	20,3	20,3	19,8	8,6	0	0,3695	0,6059	0,0246	0,0246	0,5517	0,4236
	1,63	655	1475	120	0	7,5	19	20,9	20,9	19	8,7	0	0,3589	0,5502	0,0909	0,0909	0,4928	0,4163
	1,63	655	1475	60	0	7,5	19	20	20	19	8,7	0	0,3750	0,5750	0,0500	0,0500	0,5150	0,4350
	1,63	655	1475	30	0	7,5	19	19,5	19,5	19	8,7	0	0,3846	0,5897	0,0256	0,0256	0,5282	0,4462
	1,67	0	2000	120	0	5,6	16,6	18	18	16,6	6,5	0	0,3111	0,6111	0,0778	0,0778	0,5611	0,3611
	1,67	0	2000	60	0	5,6	16,6	17,3	17,3	16,6	6,5	0	0,3237	0,6358	0,0405	0,0405	0,5838	0,3757
	1,67	0	2000	30	0	5,6	16,6	16,9	16,9	16,6	6,5	0	0,3314	0,6509	0,0178	0,0178	0,5976	0,3846
	1,67	0	1600	120	0	5,6	14,5	15,9	15,9	14,5	6,5	0	0,3522	0,5597	0,0881	0,0881	0,5031	0,4088
	1,67	0	1600	60	0	5,6	14,5	15,2	15,2	14,5	6,5	0	0,3684	0,5855	0,0461	0,0461	0,5263	0,4276
	1,67	0	1600	30	0	5,6	14,5	14,9	14,9	14,5	6,5	0	0,3758	0,5973	0,0268	0,0268	0,5369	0,4362
	1,67	0	1475	120	0	5,6	13,9	15,3	15,3	13,9	6,5	0	0,3660	0,5425	0,0915	0,0915	0,4837	0,4248
	1,67	0	1475	60	0	5,6	13,9	14,6	14,6	13,9	6,5	0	0,3836	0,5685	0,0479	0,0479	0,5068	0,4452
	1,67	0	1475	30	0	5,6	13,9	14,3	14,3	13,9	6,5	0	0,3916	0,5804	0,0280	0,0280	0,5175	0,4545

Drillstring Configuration	Mud Weight	Depth	Flow	RPM	Delta BHP Start-up				Delta BHP Break-up				Fraction of Start-up			Break-up		
					Before	Low Flow	Main Flow	RPM	Before	RPM off	Main Flow off	Low Flow off	Low Flow	Main Flow	RPM	RPM	Main Flow	Low Flow
BHA 2	1,63	0	2000	120	0	5,6	16,4	17,8	17,8	16,4	6,5	0	0,3146	0,6067	0,0787	0,0787	0,5562	0,3652
	1,63	0	2000	60	0	5,6	16,4	17,1	17,1	16,4	6,5	0	0,3275	0,6316	0,0409	0,0409	0,5789	0,3801
	1,63	0	2000	30	0	5,6	16,4	16,8	16,8	16,4	6,5	0	0,3333	0,6429	0,0238	0,0238	0,5893	0,3869
	1,63	0	1600	120	0	5,6	14,4	15,8	15,8	14,4	6,4	0	0,3544	0,5570	0,0886	0,0886	0,5063	0,4051
	1,63	0	1600	60	0	5,6	14,4	15,1	15,1	14,4	6,4	0	0,3709	0,5828	0,0464	0,0464	0,5298	0,4238
	1,63	0	1600	30	0	5,6	14,4	14,8	14,8	14,4	6,4	0	0,3784	0,5946	0,0270	0,0270	0,5405	0,4324
	1,63	0	1475	120	0	5,6	13,9	14,2	14,2	13,9	6,5	0	0,3944	0,5845	0,0211	0,0211	0,5211	0,4577
	1,63	0	1475	60	0	5,6	13,9	14,5	14,5	13,9	6,5	0	0,3862	0,5724	0,0414	0,0414	0,5103	0,4483
	1,63	0	1475	30	0	5,6	13,9	15,2	15,2	13,9	6,5	0	0,3684	0,5461	0,0855	0,0855	0,4868	0,4276

Appendix D

H-test: Effect of ramping up main flow sorted by main flow rate and RPM

H_0: The mean values of the populations are the same.

H_1: The mean values of the populations are the same.

	Raw data			Ranked Data			SUM
Group	n1	n2	n3	n1	n2	n3	
[redacted]	0,5619	0,5362	0,6770	3	1	15	
[redacted]	0,5819	0,5375	0,7004	5	2	16	
[redacted]	0,5888	0,5627	0,7203	6	4	17	
[redacted]	0,6031	0,5917	0,7614	8	7	18	
[redacted]	0,6060	0,6213		9,5	11		
[redacted]	0,6060			9,5			
[redacted]	0,6282			12			
[redacted]	0,6284			13			
[redacted]	0,6444			14			
Ri	[redacted]	[redacted]	[redacted]	80	25	66	171
Ri^2	[redacted]	[redacted]	[redacted]	6400	625	4356	
ni	[redacted]	[redacted]	[redacted]	9	5	4	18
Ri^2/ni	[redacted]	[redacted]	[redacted]	711	125	1089	1925

H-value: 10.548

$\chi_{2;0.05}$: 5.991

H-test: Effect of turning on rotation of drillstring sorted by main flow rate and RPM

H_0: The mean values of the populations are the same.

H_1: The mean values of the populations are the same.

	Raw Data			Ranked Data			SUM
Group	n1	n2	n3	n1	n2	n3	
[redacted]	0,1248	0,1253	0,0456	5	6	1	
[redacted]	0,1326	0,1338	0,0692	7	8	2	
[redacted]	0,1372	0,1346	0,0703	10	9	3	
[redacted]	0,1399	0,1402	0,0820	11	12	4	
[redacted]	0,1432	0,1506		13	15		
[redacted]	0,1464			14			
[redacted]	0,1507			16			
[redacted]	0,1554			17			
[redacted]	0,1586			18			
Ri	[redacted]	[redacted]	[redacted]	111	50	10	171
Ri^2	[redacted]	[redacted]	[redacted]	12321	2500	100	
ni	[redacted]	[redacted]	[redacted]	9	5	4	18
Ri^2/ni	[redacted]	[redacted]	[redacted]	1369	500	25	1894

H-value: 9.456

$\chi_{2;0.05}$: 5.991

H-test: Effect of turning off rotation of drillstring sorted by main flow rate and RPM

H_0: The mean values of the populations are the same.

H_1: The mean values of the populations are the same.

	Raw Data				Ranked Data				SUM
Group	n1	n2	n3	n4	n1	n2	n3	n4	
	0,0334	0,0962	0,0465	0,1128	1	11	3	13	
	0,0407	0,1105	0,0792	0,1216	2	12	8	15	
	0,0545	0,1166	0,0856	0,1319	4	14	9	17	
	0,0605	0,1244	0,0906	0,1330	5	16	10	18	
	0,0697	0,1616		0,1444	6	21		19	
	0,0774			0,1498	7			20	
Ri					25	74	30	102	231
Ri^2					625	5476	900	10404	
ni					6	5	4	6	21
Ri^2/ni					104	1095,2	225	1734	3158

H-value: 16.035

$\chi_{3;0.05}$: 7.815

H-test: Effect of ramping down main flow sorted by main flow rate and RPM

H_0: The mean values of the populations are the same.

H_1: The mean values of the populations are the same.

	Raw Data				Ranked Data				SUM
Group	n1	n2	n3	n4	n1	n2	n3	n4	
[redacted]	0,9226	0,8384	0,9094	0,8502	15	1	12	2	
[redacted]	0,9303	0,8756	0,9144	0,8556	16	6	13	3	
[redacted]	0,9395	0,8834	0,9208	0,8670	17	8	14	4	
[redacted]	0,9455	0,8895	0,9535	0,8681	18	10	19	5	
[redacted]	0,9593	0,9038		0,8784	20	11		7	
[redacted]	0,9666			0,8872	21			9	
Ri	[redacted]	[redacted]	[redacted]	[redacted]	107	36	58	30	231
Ri^2	[redacted]	[redacted]	[redacted]	[redacted]	11449	1296	3364	900	
ni	[redacted]	[redacted]	[redacted]	[redacted]	6	5	4	6	21
Ri^2/ni	[redacted]	[redacted]	[redacted]	[redacted]	1908	259,2	841	150	3158

H-value: 16.035

$\chi_{3;0.05}$: 7.815

t-test: Effect of turning off rotation of drillstring sorted by presence of a low flow rate

t_0: The mean values of the populations are the same.

t_1: The mean values of the populations are the same.

	Raw Data		(xi-Mean)^2	
Group	n1	n2	n1	n2
[redacted]	0,0774	0,0334	0,001539	0,001437
	0,0792	0,0407	0,001396	0,000937
	0,0856	0,0465	0,000959	0,000617
	0,1105	0,0545	3,76E-05	0,000282
	0,1128	0,0605	1,42E-05	0,000117
[redacted]	0,1166	0,0697	9,38E-10	2,62E-06
	0,1216	0,0906	2,49E-05	0,00037
	0,1244	0,0962	6,16E-05	0,000618
	0,1319	0,1498	0,000235	0,006165
	0,1330		0,00027	
	0,1444		0,000775	
	0,1616		0,002029	
Ri	1,399133276	0,641917		
ni	12	9		
Mean	0,11659444	0,071324		
Var	0,0006674	0,001318		
Var/n	5,56166E-05	0,000146		
Var^2	4,45422E-07	1,74E-06		
Sum			0,007341	0,010546

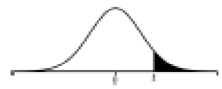
t-value: 3.185

$T_{14;0.05}$: 1.761

Appendix E

Critical values for Student's t-distribution

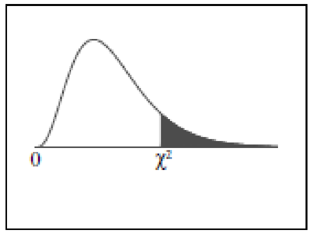
Critical Values for Student's t-Distribution.



df	0.2	0.1	0.05	0.04	0.03	0.025	0.02	0.01	0.005	0.0005
	Upper Tail Probability: $\Pr(T > t)$									
1	1.376	3.078	6.314	7.916	10.579	12.706	15.895	31.821	63.657	636.619
2	1.061	1.886	2.920	3.320	3.896	4.303	4.849	6.965	9.925	31.599
3	0.978	1.638	2.353	2.605	2.951	3.182	3.482	4.541	5.841	12.924
4	0.941	1.533	2.132	2.333	2.601	2.776	2.999	3.747	4.604	8.610
5	0.920	1.476	2.015	2.191	2.422	2.571	2.757	3.365	4.032	6.869
6	0.906	1.440	1.943	2.104	2.313	2.447	2.612	3.143	3.707	5.959
7	0.896	1.415	1.895	2.046	2.241	2.365	2.517	2.998	3.499	5.408
8	0.889	1.397	1.860	2.004	2.189	2.306	2.449	2.896	3.355	5.041
9	0.883	1.383	1.833	1.973	2.150	2.262	2.398	2.821	3.250	4.781
10	0.879	1.372	1.812	1.948	2.120	2.228	2.359	2.764	3.169	4.587
11	0.876	1.363	1.796	1.928	2.096	2.201	2.328	2.718	3.106	4.437
12	0.873	1.356	1.782	1.912	2.076	2.179	2.303	2.681	3.055	4.318
13	0.870	1.350	1.771	1.899	2.060	2.160	2.282	2.650	3.012	4.221
14	0.868	1.345	1.761	1.887	2.046	2.145	2.264	2.624	2.977	4.140
15	0.866	1.341	1.753	1.878	2.034	2.131	2.249	2.602	2.947	4.073
16	0.865	1.337	1.746	1.869	2.024	2.120	2.235	2.583	2.921	4.015
17	0.863	1.333	1.740	1.862	2.015	2.110	2.224	2.567	2.898	3.965
18	0.862	1.330	1.734	1.855	2.007	2.101	2.214	2.552	2.878	3.922
19	0.861	1.328	1.729	1.850	2.000	2.093	2.205	2.539	2.861	3.883
20	0.860	1.325	1.725	1.844	1.994	2.086	2.197	2.528	2.845	3.850
21	0.859	1.323	1.721	1.840	1.988	2.080	2.189	2.518	2.831	3.819
22	0.858	1.321	1.717	1.835	1.983	2.074	2.183	2.508	2.819	3.792
23	0.858	1.319	1.714	1.832	1.978	2.069	2.177	2.500	2.807	3.768
24	0.857	1.318	1.711	1.828	1.974	2.064	2.172	2.492	2.797	3.745
25	0.856	1.316	1.708	1.825	1.970	2.060	2.167	2.485	2.787	3.725
26	0.856	1.315	1.706	1.822	1.967	2.056	2.162	2.479	2.779	3.707
27	0.855	1.314	1.703	1.819	1.963	2.052	2.158	2.473	2.771	3.690
28	0.855	1.313	1.701	1.817	1.960	2.048	2.154	2.467	2.763	3.674
29	0.854	1.311	1.699	1.814	1.957	2.045	2.150	2.462	2.756	3.659
30	0.854	1.310	1.697	1.812	1.955	2.042	2.147	2.457	2.750	3.646
31	0.853	1.309	1.696	1.810	1.952	2.040	2.144	2.453	2.744	3.633
32	0.853	1.309	1.694	1.808	1.950	2.037	2.141	2.449	2.738	3.622
33	0.853	1.308	1.692	1.806	1.948	2.035	2.138	2.445	2.733	3.611
34	0.852	1.307	1.691	1.805	1.946	2.032	2.136	2.441	2.728	3.601
35	0.852	1.306	1.690	1.803	1.944	2.030	2.133	2.438	2.724	3.591
36	0.852	1.306	1.688	1.802	1.942	2.028	2.131	2.434	2.719	3.582
37	0.851	1.305	1.687	1.800	1.940	2.026	2.129	2.431	2.715	3.574
38	0.851	1.304	1.686	1.799	1.939	2.024	2.127	2.429	2.712	3.566
39	0.851	1.304	1.685	1.798	1.937	2.023	2.125	2.426	2.708	3.558
40	0.851	1.303	1.684	1.796	1.936	2.021	2.123	2.423	2.704	3.551
41	0.850	1.303	1.683	1.795	1.934	2.020	2.121	2.421	2.701	3.544
42	0.850	1.302	1.682	1.794	1.933	2.018	2.120	2.418	2.698	3.538
43	0.850	1.302	1.681	1.793	1.932	2.017	2.118	2.416	2.695	3.532
44	0.850	1.301	1.680	1.792	1.931	2.015	2.116	2.414	2.692	3.526
45	0.850	1.301	1.679	1.791	1.929	2.014	2.115	2.412	2.690	3.520
46	0.850	1.300	1.679	1.790	1.928	2.013	2.114	2.410	2.687	3.515
47	0.849	1.300	1.678	1.789	1.927	2.012	2.112	2.408	2.685	3.510
48	0.849	1.299	1.677	1.789	1.926	2.011	2.111	2.407	2.682	3.505
49	0.849	1.299	1.677	1.788	1.925	2.010	2.110	2.405	2.680	3.500
50	0.849	1.299	1.676	1.787	1.924	2.009	2.109	2.403	2.678	3.496
60	0.848	1.296	1.671	1.781	1.917	2.000	2.099	2.390	2.660	3.460
70	0.847	1.294	1.667	1.776	1.912	1.994	2.093	2.381	2.648	3.435
80	0.846	1.292	1.664	1.773	1.908	1.990	2.088	2.374	2.639	3.416
90	0.846	1.291	1.662	1.771	1.905	1.987	2.084	2.368	2.632	3.402
100	0.845	1.290	1.660	1.769	1.902	1.984	2.081	2.364	2.626	3.390
120	0.845	1.289	1.658	1.766	1.899	1.980	2.076	2.358	2.617	3.373
140	0.844	1.288	1.656	1.763	1.896	1.977	2.073	2.353	2.611	3.361
180	0.844	1.286	1.653	1.761	1.893	1.973	2.069	2.347	2.603	3.345
200	0.843	1.286	1.653	1.760	1.892	1.972	2.067	2.345	2.601	3.340
500	0.842	1.283	1.648	1.754	1.885	1.965	2.059	2.334	2.586	3.310
1000	0.842	1.282	1.646	1.752	1.883	1.962	2.056	2.330	2.581	3.300
∞	0.842	1.282	1.645	1.751	1.881	1.960	2.054	2.326	2.576	3.291
	60%	80%	90%	92%	94%	95%	96%	98%	99%	99.9%
	Confidence Level									

Chi-squared distribution

Chi-Square Distribution Table



The shaded area is equal to α for $\chi^2 = \chi^2_\alpha$.

df	$\chi^2_{.995}$	$\chi^2_{.990}$	$\chi^2_{.975}$	$\chi^2_{.950}$	$\chi^2_{.900}$	$\chi^2_{.100}$	$\chi^2_{.050}$	$\chi^2_{.025}$	$\chi^2_{.010}$	$\chi^2_{.005}$
1	0.000	0.000	0.001	0.004	0.016	2.706	3.841	5.024	6.635	7.879
2	0.010	0.020	0.051	0.103	0.211	4.605	5.991	7.378	9.210	10.597
3	0.072	0.115	0.216	0.352	0.584	6.251	7.815	9.348	11.345	12.838
4	0.207	0.297	0.484	0.711	1.064	7.779	9.488	11.143	13.277	14.860
5	0.412	0.554	0.831	1.145	1.610	9.236	11.070	12.833	15.086	16.750
6	0.676	0.872	1.237	1.635	2.204	10.645	12.592	14.449	16.812	18.548
7	0.989	1.239	1.690	2.167	2.833	12.017	14.067	16.013	18.475	20.278
8	1.344	1.646	2.180	2.733	3.490	13.362	15.507	17.535	20.090	21.955
9	1.735	2.088	2.700	3.325	4.168	14.684	16.919	19.023	21.666	23.589
10	2.156	2.558	3.247	3.940	4.865	15.987	18.307	20.483	23.209	25.188
11	2.603	3.053	3.816	4.575	5.578	17.275	19.675	21.920	24.725	26.757
12	3.074	3.571	4.404	5.226	6.304	18.549	21.026	23.337	26.217	28.300
13	3.565	4.107	5.009	5.892	7.042	19.812	22.362	24.736	27.688	29.819
14	4.075	4.660	5.629	6.571	7.790	21.064	23.685	26.119	29.141	31.319
15	4.601	5.229	6.262	7.261	8.547	22.307	24.996	27.488	30.578	32.801
16	5.142	5.812	6.908	7.962	9.312	23.542	26.296	28.845	32.000	34.267
17	5.697	6.408	7.564	8.672	10.085	24.769	27.587	30.191	33.409	35.718
18	6.265	7.015	8.231	9.390	10.865	25.989	28.869	31.526	34.805	37.156
19	6.844	7.633	8.907	10.117	11.651	27.204	30.144	32.852	36.191	38.582
20	7.434	8.260	9.591	10.851	12.443	28.412	31.410	34.170	37.566	39.997
21	8.034	8.897	10.283	11.591	13.240	29.615	32.671	35.479	38.932	41.401
22	8.643	9.542	10.982	12.338	14.041	30.813	33.924	36.781	40.289	42.796
23	9.260	10.196	11.689	13.091	14.848	32.007	35.172	38.076	41.638	44.181
24	9.886	10.856	12.401	13.848	15.659	33.196	36.415	39.364	42.980	45.559
25	10.520	11.524	13.120	14.611	16.473	34.382	37.652	40.646	44.314	46.928
26	11.160	12.198	13.844	15.379	17.292	35.563	38.885	41.923	45.642	48.290
27	11.808	12.879	14.573	16.151	18.114	36.741	40.113	43.195	46.963	49.645
28	12.461	13.565	15.308	16.928	18.939	37.916	41.337	44.461	48.278	50.993
29	13.121	14.256	16.047	17.708	19.768	39.087	42.557	45.722	49.588	52.336
30	13.787	14.953	16.791	18.493	20.599	40.256	43.773	46.979	50.892	53.672
40	20.707	22.164	24.433	26.509	29.051	51.805	55.758	59.342	63.691	66.766
50	27.991	29.707	32.357	34.764	37.689	63.167	67.505	71.420	76.154	79.490
60	35.534	37.485	40.482	43.188	46.459	74.397	79.082	83.298	88.379	91.952
70	43.275	45.442	48.758	51.739	55.329	85.527	90.531	95.023	100.425	104.215
80	51.172	53.540	57.153	60.391	64.278	96.578	101.879	106.629	112.329	116.321
90	59.196	61.754	65.647	69.126	73.291	107.565	113.145	118.136	124.116	128.299
100	67.328	70.065	74.222	77.929	82.358	118.498	124.342	129.561	135.807	140.169