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Evaluation of a dual relief well operation

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Utfyllende tekst/Extended text:

Background:
The Norwegian petroleum authority initiated a new regulation in 2012. All new wells on the Norwegian Continental Shelf originally designed to be killed by using two relief wells are rejected. A dual relief well operation is a concept not well covered in the literature. Internal research using dual relief well drilling has been initiated by some operating companies, but none of these reports are in the public domain. Based on using typical data, the main aim is to investigate the potential and limitations for these two options.

Task:
1) Describe the normal procedures for a single relief well operation.
2) Apply the blowout simulation tool, OLGA ABC and/or other relevant hydraulic pressure loss models to perform sensitivity analyses of important parameters used in single - and dual relief well operations.
3) Propose and describe the procedures for a dual relief well operation.
4) Apply the results from the tasks above and perform a comparison of these two options. Important issues to be considered are; safety, time to drill and kill the well, costs, logistics, etc.

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Sigbjørn Sangesland

SUMMARY

The Norwegian petroleum authority initiated a new regulation in 2012. All new wells on the Norwegian shelf originally designed to be killed by two relief wells, in case of a worst case scenario, are rejected. The reason is the lack of experience on killing a well by two relief wells. Internal research on dual relief well drilling has been initiated by some operating companies, but none of the reports are public. This thesis will use experience from established well killers and simulations done on single relief wells to evaluate the procedure of a dual relief well operation. Calculations are performed on sections evaluated as critical in a dual relief well drilling operation and the results have been discussed with experienced well killers from Norway and USA. The thesis will also do sensitivities on single relief well operations to evaluate the possibility of killing a high magnitude blowout with one relief well.

The main conclusions drawn from the results of this thesis are that the capacity of a single relief well cannot be enhanced to kill a well that normally require the rates of two relief wells. The dual relief well option focused on in this thesis is considered safer than the other comparing method. The background of this conclusion is primarily literature from single relief wells and through interviews with experienced well killers. The hydraulic differences between the two options are concluded to be fairly equal in this study.

Future experiments on the commingling section of the dual relief well method are recommended by the author. By using research on multilateral production wells, great similarities in experiments can be drawn when evaluating the flow regime. Additionally, improved blowout simulation software must be evolved, to handle inflow from two relief wells.

SAMMENDRAG

Det norske petroleumstilsynet innførte i 2012 en ny regulering. Alle nye brønner som skal bli boret på den norske sokkelen og som initielt er designet slik at den trenger to avlastningsbrønner for å drepes blir avslått. Grunnen til denne oppdateringen av regelverket er mangelen på erfaring ved å drepe en brønn med to uavhengige avlastningsbrønner. Intern forskning på dobble avlastningsbrønner er blitt gjennomført blant noen av operatørselskapene, men det er foreløpig ingen eller få detaljerte rapporter som er offentlig tilgjengelig. Dette studiet vil bruke erfaringer fra etablerte brønndrepere og simuleringer gjort på single avlastningsbrønner til å evaluere gjennomføringen av en dobbel avlastningsbrønn operasjon. Utregninger er utført på de seksjoner som naturlig er antatt mest kritiske under operasjonen. Resultatene har videre blitt konfrontert og diskutert med erfarne brønndrepere fra både Norge og USA. Dette studiet vil også utføre sensitivitetsanalyser på en single avlastningsbrønn operasjon for å evaluere muligheten for å drepe en høy-rate utblåsning med en avlastningsbrønn istedenfor to.

Hovedkonklusjonen fra resultatene i dette studiet er at den metoden basert på en dobbel avlastningsbrønn er tryggere å gjennomføre enn andre kjente metoder. Bakgrunnen for denne konklusjonem er primært literatur fra single avlastningsbrønner og gjennom intervjuer med erfarne brønndrepere. Den hydrauliske trykkdiferansen mellom de to metodene er konkludert til å være like. I tillegg blir det konkludert med at en singel avlastningsbrønn ikke har mulighet til å drepe en høy-rate utblåsning ved å endre hovedparameterne.

Fremtidig arbeid på kommiksjonsseksjonen i den dobble avlastningsmetoden er anbefalt av forfatteren av dette studiet. Å anvende forskning gjort på multilaterale produksjonsbrønner kan konklusjoner av evalueringen til strømmningsregime trekke sammenhenger fra disse eksperimenter. I tillegg, må simuleringsverktøyet til OLGA bli utviklet til å håndtere strømmning fra to avlastningsbrønner.

ACKNOWLEDGEMENTS

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1. OVERVIEW

Oil and gas are life important energy sources and the industry is constantly being pushed beyond new boundaries to supply the growing demand. Oil and gas extraction in harsh and vulnerable environments requires safe and efficient drilling operations. The Norwegian Petroleum Safety Authority (PTIL) has since 2012 stated that they will not approve any wells designed with the need of two relief wells if a blowout occurs. Several operating companies have had to change the original casing design to fit the new requirement from PTIL. Internal research on dual relief well drilling within the operating oil & gas companies has been initiated due to this new regulation. Statoil and Shell have separately done research on different dual relief well methods, but none of them are published to the public or shared beyond company boarders. This report will evaluate the practicality of dual relief well drilling and be one of the first public reports on the subject.

The subject of relief well drilling is not well known in the oil & gas industry. The discretion of the oil & gas companies when experiencing uncontrollable blowouts is the reason for the lack of public papers. After the Macondo accident more public research has been published about relief well drilling. However, dual relief well operations have never been performed offshore. This study is therefore based mainly on interviews with professionals within the well kill industry and the Well Manager Forum established by several operating companies. The main sources of information are the well kill companies Add Wellflow and John Wright CO along with the operating companies Statoil and GDF Suez E&P Norway.

The thesis will evaluate theoretical capacities of a single relief well based on the existing technology today and the practical knowledge of the well killers from Add Wellflow and John Wright co. The results will set constrains on single relief wells and also set the frames of a dual relief well operation procedure. Literature established from single relief wells can be directly applied in the evaluation of dual relief well drilling/killing operations and will together with hydraulic models conclude with the practicality of performing a dual relief well operation. In order to present the different killing scenarios and simulate the blowout situation, this study will apply the software OLGA ABC. The simulation tool is not good in reading pressure losses in the relief well and is therefore supported by the hydraulic pressure loss model by Espen Andreasen. When evaluating the results by changing the parameters a evaluation background is established, and together with the theoretical background will this give prediction of a dual relief well procedure.

To be able to perform analyses of both a single and dual relief well operation a reference scenario has been established. This reference scenario is a real well in the North-sea operated by GDF Suez E&P Norway. The blowout magnitude is assumed constant with small pressure decay throughout the entire killing and drilling operation. The worst scenario of a blowout is in the 12 ¼" section and with a large open hole section below the last set casing shoe.

The dual relief well method focused on in this study is a modified option inspired by the Shell method. Comparisons will be performed with the more known and predictable Statoil option when explaining the procedure of the operation. The author of this thesis has not been able to refer to the internal research done by both Shell and Statoil.

Interviews with Ketil Inderberg in Statoil and Thomas Selbekk in Add Wellflow have given an impression of the main differences about the two options.

The assumptions applied in this study are strictly evaluated by sensitivity analyses and advices given by experienced well killers. Restrictions given by different drilling environments are discussed during the predicted procedure of the dual relief well option.
The thesis is set to give the reader a better understanding of relief wells in general and the restrictions they may have. A dual relief well operation will be evaluated based on the current knowledge and technology. The concern from PTIL about the practicality of successfully fulfill a dual relief well drilling operation is challenged by the author of this thesis.

2. LITERATURE STUDY

2.1. INTRODUCING BLOWOUT INTERVENTION

The constant need of more energy resources creates an urge to extract the unconventional oil and gas reserves. Deeper water, longer wells and harsher environments are constantly being explored for the potential of large hidden reserves. Human and technological errors are difficult to predict, and even though there are several safety barriers applied in a regular drilling operation incidents may occur. Such an event can be defined as a screwdriver falling from a bench or it can be the more catastrophic incident of a blowout.

A blowout is defined as an uncontrolled release of crude oil and/or natural gas from an oil well or gas well after pressure control systems have failed (Westergaard, 1987). After the Macondo (Gulf of Mexico) blowout in 2010 the national authorities have increased the requirements needed to drill. The Gulf of Mexico was closed for all deepwater drilling activity by the Obama administration for 6 months after the accident. A new and stricter regulative has been performed by the newly established Bureau of Safety and Environmental Enforcement and Bureau of Ocean Energy Management Regulation and Enforcement (Dupre, u.d.).

A recent and important regulation by PTIL on the Norwegian shelf the decision that wells designed to be killed in a worst case scenario by two or more relief wells will be rejected. PTIL is the governmental organ responsible for the safety of petroleum activities done on the Norwegian continental shelf (PTIL, u.d.). The new restriction compels the drilling engineers of the operating oil and gas companies to create new unconventional casing designs, which is expensive and more time consuming. Operating companies has by doing this been forced to do more research on the subject of dual relief well drilling. Some companies located in Norway have done some internal research on dual relief well drilling, but they have not shared the learning's of these reports (Hagenes, 2013). The dual relief well methods will be presented, evaluated and discussed in this report with a main focus on the anticipated best option.

As a part of the approval of drilling at a licensed field on the Norwegian continental shelf a blowout simulation must be performed. The simulation involves a detailed plan of what to do if an uncontrollable influx occurs in different sections of the drilling operations. Worst case scenario is when a long and wide open hole section is being flooded with uncontrollable gas influx. PTIL demands this scenario to be killed by one relief well. A dual relief well has never been performed offshore, Hence before discussing and evaluate the possibility of a dual relief well challenges related to single relief wells must be clarified.

2.1.1. Magnitude of a Blowout

Relief wells are initiated if the blowing wellbore is inaccessible and the rates are too large for normal surface intervention methods to be applied. The magnitude of a blowout is decided on the basis of two important physical behaviors. Inflow performance relationship (IPR) between the reservoir and flowing bottom hole pressure (FBHP) and fluid friction in the well.

IPR is directly related to productivity index (PI) and indicates the flow rate as the flowing bottom hole pressure falls under the reservoir pressure when the well is stated underbalanced. As shown in the schematics in Fig. 2.1, an increase of hole increases the flow rate of the blowing well. An increased drawdown (P_R - P_W) will also increase the magnitude of the blowout. Due to lower density of the influx fluid the hydrostatic pressure will decrease and enhance the magnitude of the blowout.

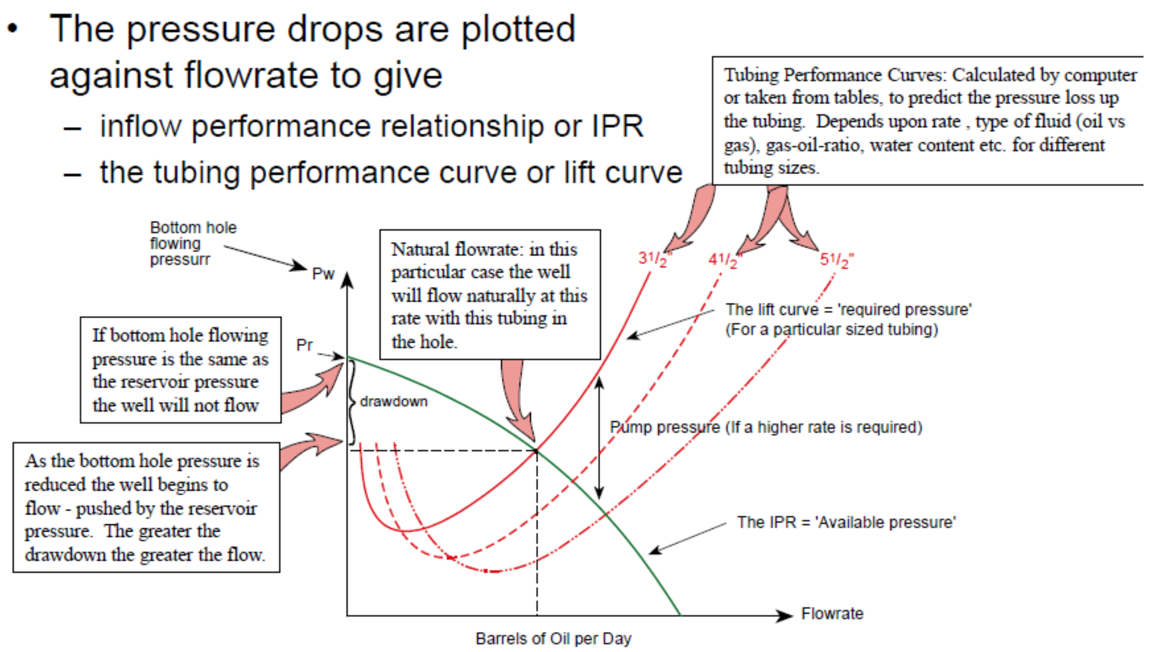

Fig. 2.1 - Schematic of Inflow Performance Relationship in tubing (Kallhovd, 2012)

Fluid friction in the blowing well is dependent on two important parameters. The hole size and the fluid properties: viscosity and density. Gas is less dense and viscous than oil/water and will not suffer the same friction loss in the transportation to surface. A gas blowout in a large open hole section without a drill string is therefore considered the worst case scenario of a blowout.

2.1.2. Surface intervention methods

Even though the relief wells are always simulated for each planned well, they are only initiated as an absolute last resort when trying to regain control over a well. “Surface kill”, or popular referred to as “Top-kill” by the media, is the first thing applied when all control systems have failed and a blowout has been stated. Performing a surface intervention method demands access to the wellhead, and is often dangerous if the blowout fluid is ignitable (Kallhovd, 2012). The main purpose of a surface kill is to reestablish the flowing bottomhole pressure and close in the well. When this is done the circulation of influx is initiated through the choke- & kill-line (Kallhovd, 2012). The late years more advanced and high pressure capping stacks have been developed. A capping stack is a pressure control system consisting of several valves able to suppress high scale pressures.

Unconventional Capping stack: The Macondo blowout was eventually killed by a capping stack able to suppress the great pressure induced by the flowing wellhead. Trendsetter engineering has created a high pressure capping stack (Fig. 2.2). Quoted from their company site (trendsetter, u.d.) “The Trendsetter Well capping Stack has a dual barrier design consisting of BOP ram plus containment cap and can be controlled subsea by ROV, if necessary. The HWCG has a well pressure tolerance of 15,000 psi and a depth capability of 10,000 ft. It includes the capability to capture/process 60,000 bbl of fluid per day, the system has two (vs. four) 5-1/8” 15,000 psi outlets built in for subsea dispersant injection capability”. By combining the pressure tolerance of 15000 psi to a HPHT reservoir (10000 psi) the capping stack should be able to hold quite large blowouts shut in (Kallhovd, 2012).

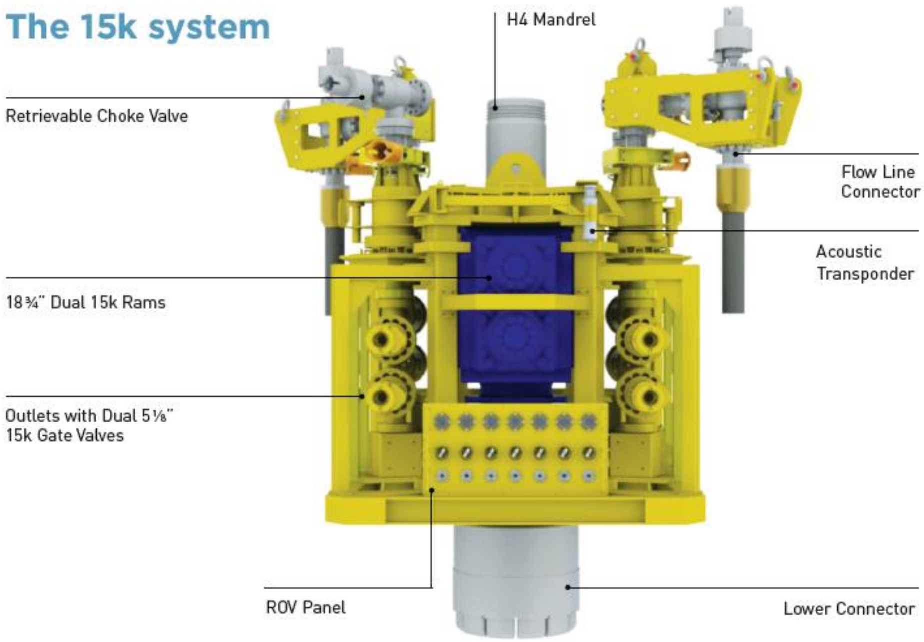

Fig. 2.2 - Technical schematic of a 15k psi capping stack (trendsetter, u.d.)

Regaining control of a blowing well by the use of surface intervention methods have some clear faults, and contains risks. The tools needed to be placed on top of the blowing wellhead suffer challenges like immense flow rates and poor visibility of the wellhead. If the flowing fluid is a gas all personnel is ordered at least one kilometer away from the wellhead site. The logistic issues make the operation difficult to handle.

The usual procedure when killing a well is first to circulate out the influx when pressure control systems still are intact. If this fails a surface intervention method is initiated. Relief well planning is initiated while the well is trying to be shut in by surface intervention methods (Selbekk, 2013). When all surface intervention methods fail the only option is to initiate the drilling of a relief well. A relief well operation is always initiated when the uncontrollable flow has not yet been controlled within 48 hours after the incident.

2.2. NORMAL RELIEF WELL DRILLING OPERATION

Before planning a dual relief well the single relief well operation must be understood. This section will give an overview of the drilling procedure of a single relief well displayed through a well control emergency response plan. The knowledge of this section is given through interviews with world class well killers from Add Wellflow, John Wright Company and Wild Well Control.

2.2.3. Well control emergency response plan

All operating gas & oil companies must have a well control emergency response plan for each drilled well. The response team consists of four different sub-groups: The Directional drilling & interception team, Drilling engineering/planning team, Kill/P&A operation team and the Hazard assessment team. All four teams are restricted to each other, so it is important to collaborate during the planning phase. The responsibilities of each team and details around each task will be presented below.

2.2.4. Directional drilling and interception team

The directional drilling and interception team is responsible for performing an efficient and safe drilling operation. The following optimizations must be evaluated by the team:

Survey tools

Relief well trajectories are dependable on the target well trajectory and different surface restrictions. As shown earlier in this report a typical relief well has an S-curve trajectory. Intercepting the target well is like finding a needle in the haystack this make the ranging tools accuracy very important when drilling a relief well(de Wardt. et al, 2013). The most critical part of the relief well drilling operation is when closing in on the target well, normally 30 m lateral and 300 m above the interception point(Vectormagnetics, u.d.). When inside this area the proximity ranging is initiated and proximity ranging tools are applied. In the starting phase of the drilling process regular MWD and primitive LWD will be sufficient to stay on course towards the target well. (Maehs. et al, 2008)

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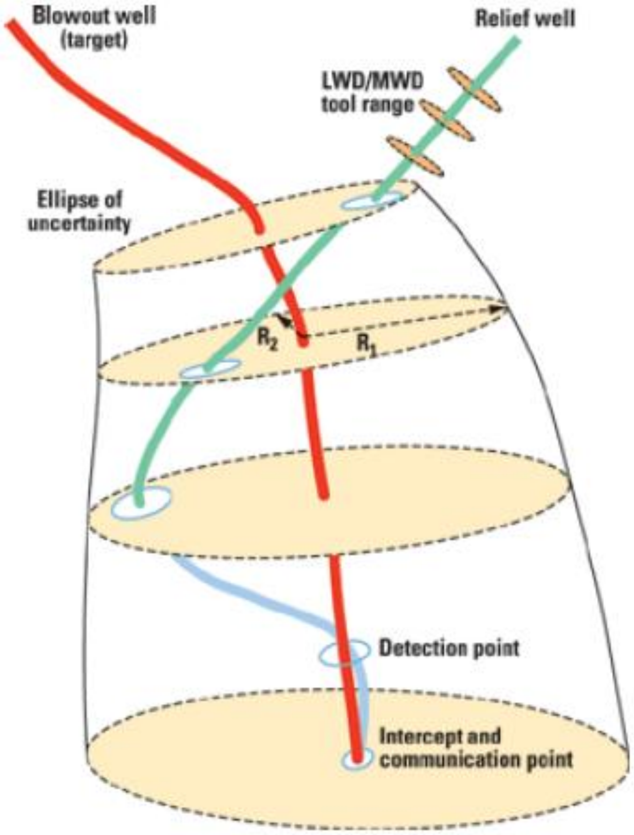
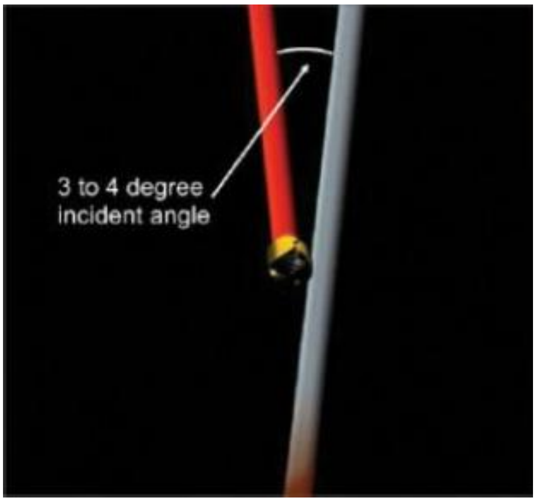
There are two types of magnetic ranging methods. Passive ranging is when only using the magnetic field of the earth and the casing steel magnetism to locate the target well. Active ranging is when adding an external current and enhancing the magnetic field of the earth and therefore decreases the error of the survey tool, called the ellipsoid of uncertainty (EOU) (Fig. 2.3). The EOU increases with measured depth (MD) of the relief well.



(a)



(b)

Fig. 2.3 - (a) Relief well Trajectory (S-curve) (Haugen, 2011) (b)The relief well is aligned towards the blowing well with an angle of 3-4 degrees.(Haugen, 2011)

The active ranging tool is the most frequently used proximity survey tool (de Wardt. et al, 2013). The *Electromagnetic downhole current injection system* uses an electrode around 50 m above the AC (Alternating Current) magnetometer array to inject AC current into the formation (Fig. 2.4). This ranging system will not be effective in high resistivity layers, like salt.

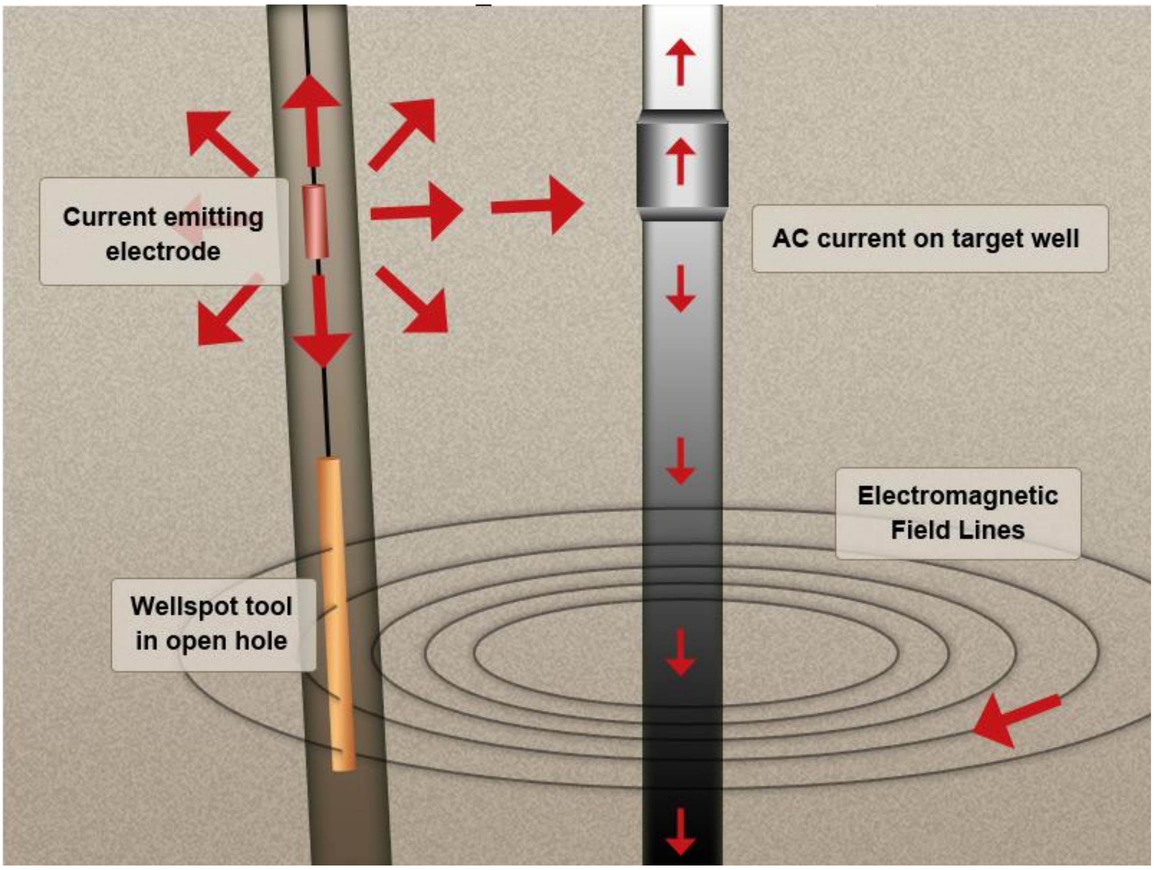


Fig. 2.4 – Active ranging tool, Wellspot™ (Vectormagnetics, u.d.)

According to two of the most respected well kill companies in the world the most common survey tool that is used when drilling a relief well is the Halliburton owned Vectormagnetics™ (Oskarsen, 2013).

Conventional proximity logging procedure: The first logging point is 30 m lateral of the target well. As mentioned earlier the last set casing shoe will have to be set outside of the AC producing electrode of the ranging tool (Fig. 2.4). If not possible a proximity survey will have to take place before setting the casing and then drill around 30-45 m before logging again (Oskarsen, 2013). The next generation proximity tool however has a precise near bit electrode able to shorten that distance and still remain accurate (Fig. 2.5) (Vectormagnetics, u.d.). When having sufficient distance from the casing of the relief well the accuracy is very good and low interference is located. If a nearby well is drilled within the proximity boundaries (30 m lateral distance) the active proximity ranging tools cannot be applied at the same time. Due to magnetic interference this may be a problem in dual relief well drilling.

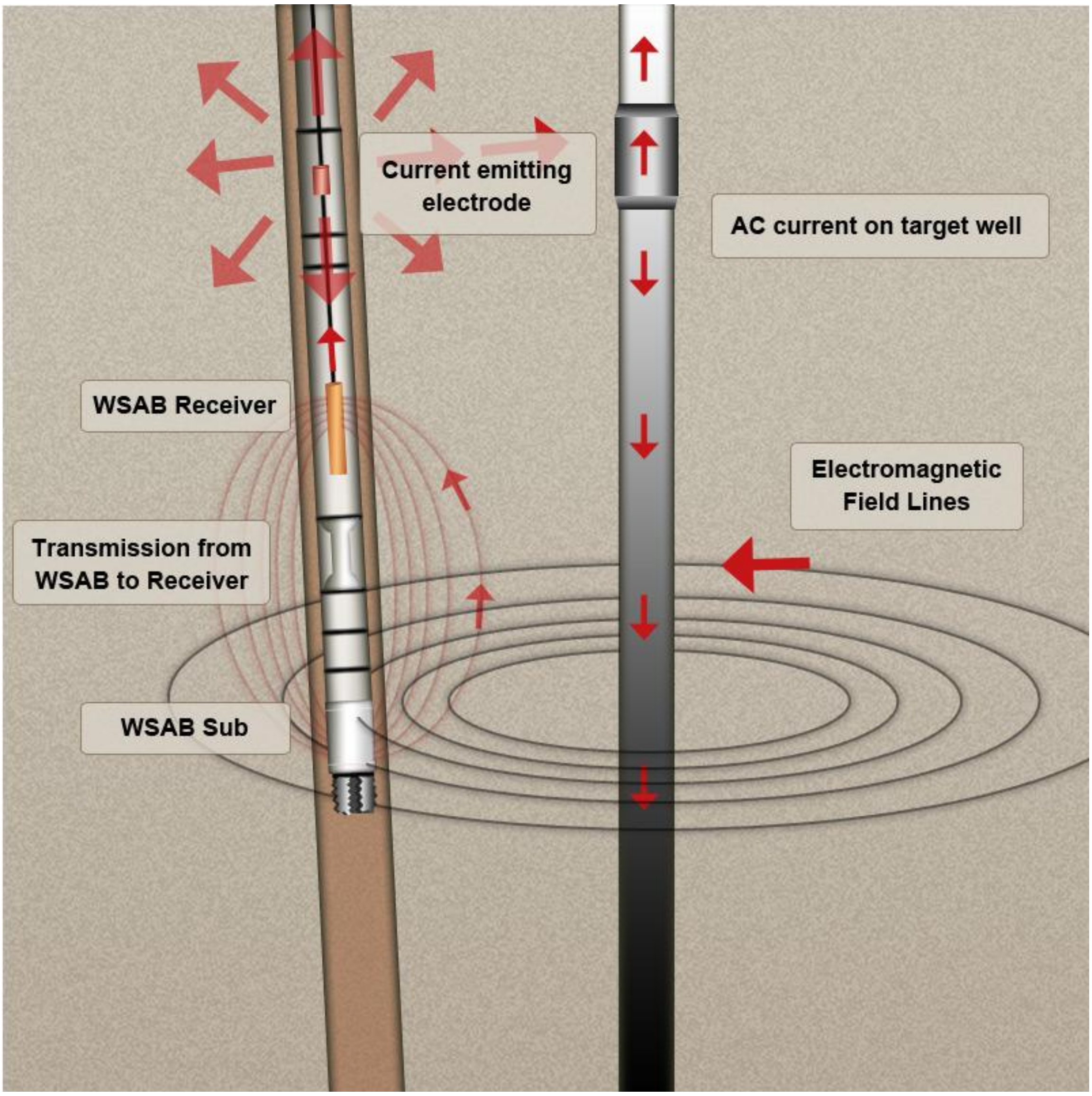


Fig. 2.5 – Active ranging tool, Wellspot at bit (WSAB) (Vectormagnetics, u.d.)

Interception phase:
Several loggings must be performed when initiating the homing-in phase of the relief well drilling to guarantee successful interception of the target well. The homing-in phase is when approaching the blowing well with the given attack angle. When only being 0,5 m in lateral distance from the target well, conventional gyro tools can predict the location of the target well with centimeters of uncertainty. The homing-in process usually takes some time, due to several tripping-outs for logging.

High angle interceptions: The Montara blowout intervention in Australia in 2009 was an example of high deviation relief well interception. This obviously make the survey procedure challenging. The Vector Magnetic active ranging tool, *Wellspot*^{TM}, becomes unable to report inclination above 70 degrees. Then again the inclination from this tool is only used for comparing the target well survey and is not critical. A problem is to physically get the tool to the bottom of the relief well. Common ways to solve this issue is to apply the same procedures as when drilling an extended reach well (ERD). Using a weighted tool string or snubbing the logging tool through an open ended drill pipe are some solutions.

Rig placement
Local and national authorities have strict restrictions of where to place the relief well drilling rig. The most decisive parameters of rig placement offshore are:

Marine parameters: If the water depth is less than 300 m the rig must be placed further away from the blowing wellhead than if the water depth is more than 300 m (Inderberg, 2013). Also Dependable on the water streams and wind forecasts the rig must be placed a minimum of 500 m from the blowing wellhead. In worst cases the lateral distance between the relief rig and the blowing wellhead can be as distant as 3000 m.

Shallow gas: If it is a potential danger of hitting shallow gas in the area of the blowing well, the rig placement must be carefully chosen on these terms.

Due to minimization of the measured depth of the relief well the rig is always placed as close as possible to the blowing wellhead. Normally, are offshore relief rigs placed around 1000 m away from the blowing wellhead (Oskarsen, 2013).

Trajectory
The trajectory, as shown earlier in this report, is formed as an S-curve. The detailed design of the S-curve is usually dependent on the formation behavior and the limitation of the survey tools.

Formation strength: If the formation consists of unconsolidated rocks or weak shale, there can be a great challenge when drilling at the desired doglegs. Maximum dogleg is 4-5 degrees/30 meter, but it is kept as low as possible to avoid borehole instabilities (Oskarsen, 2013). A smaller interception hole in the blowing well may be a result of weak formation due to the need of an ineffective casing design.

Survey tools: Normal survey tools usually give a greater uncertainty if the angle is larger than 60 degrees. When approaching 30 m in lateral distance from the blowing well the proximity ranging survey is applied. This section needs to be long and relatively vertical to enhance the ranging tools results.

Design: The first section is vertical down to a depth that has a stable and strong formation. The deviation is performed with a maximum dogleg of 4 degrees/30 meter. When the trajectory is stabilized at a constant angle the relief well is turned slightly to avoid hitting the blowing well. 30 m lateral distance from the blowing well the proximity ranging survey is initiated. When passing the well the proximity ranging tool will note the location and then be able to intercept deeper below. When passing the blowing well of about 10 m the homing-in procedure is initiated. A 200-400 m long constant deviated with an attack angle of 3-8 degrees is performed before setting the last casing (Fig. 2.6). 10 m in measured depth (MD) and 1-2 m lateral from the blowing well the last casing is set and the interception operation is initiated. (Oskarsen, 2013)(Inderberg, 2013).

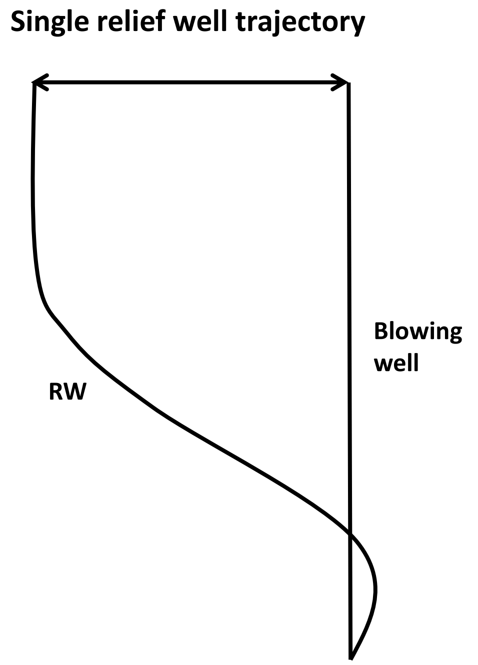


Fig. 2.6 – Schematic of a typical S-curved relief well.

Drilling tools

The drilling tools applied will have to be available within the planned response time. The most important tools are the MWD/LWD and directional tools specifically used to drill relief wells. These tools and the conventional drilling tools will have to be prepared at the usual logistic center onshore, and be ready to be shipped out to the relief rig as soon as possible.

Interception point
The interception point is restricted to be maximum 10 m below the deepest point of the blowing well where there are guarantees of finding sufficient steel sources or magnetic creating tools. A casing is often the only steel source able to create a sufficient magnetic field for the survey tools to register. Right below the last set casing shoe is the most frequent point of interception. The proximity ranging tools of today are not able to detect in a precise matter the blowing well unless there is a magnetic field to be detected.
There are two different interception points that are being applied around the last set casing shoe. The one is around 10 m above the last set casing shoe, the other one is 10-20 m below.

Interception method
There are a couple of different applied interception methods that has been performed when drilling a single relief well. The interception method is restricted by the proximity ranging tools technology. If intercepting above the last set casing shoe a mill is used to enter the blowing well. Milling with a constant attack angle of 3-8 degrees is the most frequently used method. There is also a possibility of setting the last casing parallel to the blowing well and mill through both casings by using a whipstock inclination tool. The last method is often used to minimize the open hole section and then avoid borehole stability issues. If intercepting below the casing shoe a usual attack angle of 3-8 degrees can be applied or a fixed directional perforation can establish contact between the wells (Oskarsen, 2013)[1]. The best practice interception method is dependent on the formation mechanics, but a minimization of the open hole section is always preferred to avoid the increased pressure loss in the relief well.

2.2.5. Drilling engineering/planning

Planning of the drilling operation involves the same planning as a conventional drilling operation where the important factors are casing design, mud program and rig selection.

Optimizing the casing design is important in terms of time consumption and pressure losses when doing a dynamic kill operation. Having the last set casing as large as possible is highly dependent on the formation strength. The most critical part is the setting of the last casing before intercepting. The last set casing shoe will have to be as close to the blowing well as possible without experiencing fluid migration from the blowing well and formation collapse. Developing a mud program for each drilling section is an essential part of the planning phase. The drillers have to evaluate the risk of having fractures and the potential of circulation loss while drilling. In addition, having a rig with sufficient capacity is important for a relief well drilling operation. Mud pits, mud reserve pits, pumping systems, low pressure fluid transfer and sufficient deck space are the capacities needed to be fulfilled when selecting a drilling rig. If an additional PSV (Platform Supply Vessel) are going to be used, the wave height must be below 3 ½ m (Inderberg, 2013). A PSV can store up to a 1000 m^3 extra drilling fluid and refill the mud pits of the relief rig (Oskarsen, 2013).

[1] These statements are also confirmed by other independent sources.

2.2.6. Kill/P&A operations

Dynamic kill modeling

When intercepting the blowing well the BOP of the relief well is shut in due to potential of losing the hydrostatic column in the relief well and experiencing influx to the relief well. Kill fluid, which is the calculated fluid needed to regain the stable hydrostatic pressure, is injected through the kill and choke line past the closed relief well BOP. The Relief well BOP is opened after a short period of time and fluid is pumped through the relief well drill pipe in addition to the already pumping kill & Choke-line to monitor the downhole pressure environment (Blount, 1978).

The dynamic killing procedure uses friction in the blowing well to regain hydrostatic pressure and increase the Flowing Bottom Hole Pressure (FBHP) so that the well will regain overbalanced pressure environment. A heavy kill fluid will together with the kinetic friction increase the hydrostatic pressure (Eq. 2.1). The procedure can easily be explained by the U-tube effect. If pumping with the needed pump rate pressure equilibrium will eventually be established between the relief well and the blowing well and regain control.

$$\mathrm{P_{FBH}} = \mathrm{P_{hydr}} + \mathrm{P_{friction}} \tag{2.1}$$

P_{FBH} is the Flowing bottom hole pressure, P_{hydr} is the hydrostatic pressure and $P_{friction}$ is the friction pressure.

The flowing bottomhole pressure is also defined by the following equilibrium (Eq. 2.2):

$$P_{FBH} = P_{surf} + \Delta P_{friction} + \mathit{\Delta} P_{hydr} \tag{2.2}$$

Where Psurf is the surface pressure, $\Delta P_{friction}$ is the frictional pressure loss and $\mathit{\Delta} P_{hydr}$ is the hydrostatic pressure in the blowing well.

The kill fluid is found by the two equations Eq. 2.1-2 and the U-tube model. The frictional pressure loss plus the hydrostatic pressure must be greater than the reservoir pressure to stop the influx. When calculating the kill fluid an investigation of the fracture pressure at the last set casing shoe must be taken into account. If a fracture occurs while injecting kill fluid an underground blowout. An underground blowout is when the well is fractured and fluid is transported towards a lower pressurized zone. The last set casing shoe is the most likely place for a fracture to occur; due to the largest open hole hydrostatic pressure gradient. The dynamic kill rate is high at the start of the killing operation. When the FBHP is above the reservoir pressure the pump rate is adjusted to a lower level to avoid using all the kill fluid (Fig. 2.7).

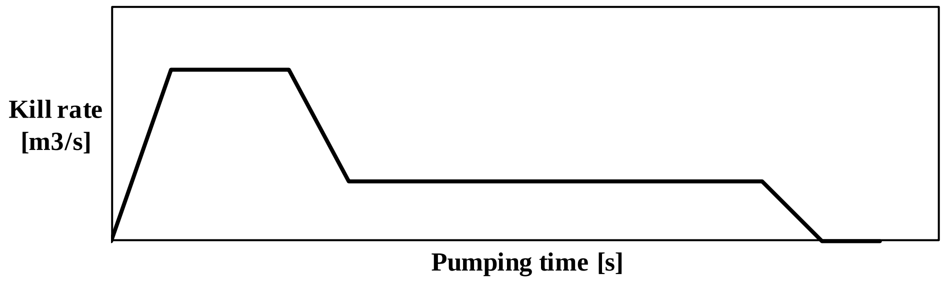


Fig. 2.7 - Schematic of kill rate as function of time.

When regaining control of the blowing well, it must be shut-in, plugged and abandoned. The plug used is usually just cement columns defined by the governmental regulations.

Contingencies and safety factors

Different scenarios that may occur are evaluated and taken into account by adding safety factors. Contingencies will have to be performed on the following factors:

Mud loss: Large mud reserves must be available to continuously pump fluid through the relief well and avoid a potential loss of hydrostatic pressure. Usually a relief well kill is performed as an off-bottom dynamic kill operation. There are large uncertainties regarding the amount of kill fluid needed. A safety factor of 100% is assumed in all relief well operations (Inderberg, 2013)[2].

Fracture gradient: The fracture gradient of the last performed Leak Off Test (LOT) will have to be assured not is exceeded. A fracture at the last set casing shoe may lead to a underground blowout and this can result in large loss of mud. A large mud loss is potentially dangerous and may cause uncontrollable fluid flow into the relief well. A typical safety factor applied to the fracture gradient is 0,12 sg (Lyons, William. et al, 2012).

Wait on weather (WOW): If drilling in the winter season the risk of having to WOW is significant. A dynamic kill operation needs a 6 days window from start to finish (Inderberg, 2013).

Other: Pump reliability is good. The pumps are normally on for 24 hours for numerous days, and are rarely an issue in dynamic killing operations. Lack of equipment is a potential time consumer. Waiting for tools are not acceptable.

[2] Assumption confirmed by Oskarsen, Ray Tommy in Add Wellflow.

Kill equipment
The kill equipment is highly dependent on the dynamic kill calculations. Below are the most important equipment listed with the usual constraints

Pump capacity: A normal pump capacity per rig, assumed equipped with Halliburtons 2000HP Grizzly, has a maximum rate of around 11000 liters per minute (lpm) and a pressure potential of around 690 bar (Oskarsen, 2013).

Fluid volumes: The rig has only a given capacity of fluid storage. A PSV should always be nearby as a reserve mud pit if a large mud loss occurs.

Low pressure fluid transfer capacities: The pump capacities are also restricted by the ability to transfer fluid to the pumps from the mud pits. The rig company must inform that the rig has sufficient low pressure fluid transfer capacity. (Oskarsen, 2013)

BOP erosion: BOP erosion studies are usually done on sand grains flowing up the annulus. In a dynamic kill situation the hardest solid is the density increaser, barite. These particles are scaled as 3 to 3.5 on the Moh's scale. Sand grains have a hardness of 7. Evaluating this difference together with the fact that a dynamic kill operation only lasts for 8-10 hours implies that the erosion in the BOP is not a problem (Inderberg, 2013).

Plug & Abandon planning
The P&A of both the blowing well and the relief well has to be planned in advance. Typically a normal cement plug is used as plugging material.

2.2.7. Hazard assessment

Before starting the relief well drilling operation a hazard assessment must be performed. Technical reports on shallow seismic, shallow gas, potential well clusters nearby, formation strength and porous zones must be presented and taken into account for. Environmental damage plans is initiated as soon as the area is cleared as safe.
The team working on hazard assessment is responsible for making the drilling operation go as smooth as possible. Avoiding unexpected delays and potential risks are their main task.

3. THEORY

This section provides the reader theory to support the calculated results and literature of this study. Restrictions of a single relief well will be presented based on the literature study and available information from the industry. This section also introduce the concept of a dual relief well operation and why it is needed more research on the field of subject.

3.1. SINGLE RELIEF WELL RESTRICTIONS

A relief well is seen as the most secure way to regain control of a blowing well, but it still has its restrictions. The pumps at the relief well rig have a capacity of 690 bars and a pump rate of 11000 lpm of kill fluid (Selbekk, 2013). When calculating the kill rate this restriction is the main constrain of whether or not you are able to kill the well with one relief well.

Kill fluid density is maximized, but within range of the critical fracture pressure at the last set casing shoe of the blowing well. The kill fluid is rarely designed larger than 2,0 sg, but can be 2,2 sg if the formation can handle it. A heavy kill fluid will create more friction in the blowing well and enhance the killing process, but it will also have a negative effect if the hydrostatic pressure exceeds the fracture pressure. An underground blowout is potentially very hazardous for the relief well crew and may cause large scale loss of kill fluid, and lead to loss control of the relief well.

By doing multi-phase simulations the pump rate and kill fluid density can be found and applied on a single relief well up to a certain level of blowout magnitude. The blowout magnitude is fixed and cannot be modified. The parameters that significantly has the potential of vary the span of a single relief wells capacity are:

- The choke/kill line diameter and length.
- Last set annulus area.
- Geometry and measured depth of relief well.
- Fluid properties (Density and viscosity).

3.1.1. During drilling operation

Minimizing the time consumption and ending with the largest possible annulus area is the main objective when drilling a relief well. There are several factors needed to allow for during the drilling operation. Below are the most important.

Burst/collapse of relief well casing

Burst/collapse of casing tubing is a common challenge in long vertical casing sections. As explained earlier a relief well design has long high deviation sections, and is therefore not often troubled with burst/collapse situations (Oskarsen, 2013). The burst and collapse boundaries are illustrated against the total overburden load in the figure below (Fig. 3.1).

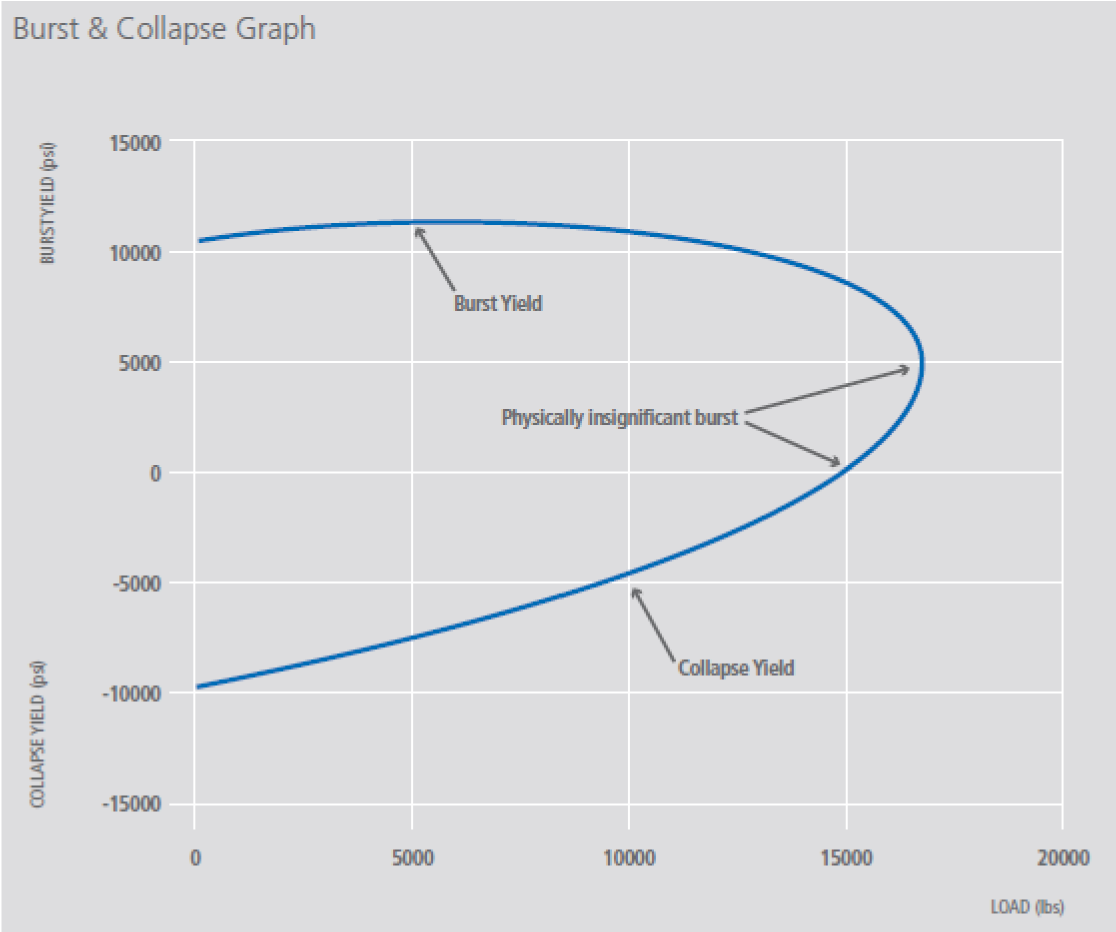


Fig. 3.1 – Burst/collapse yield graph

The potential critical section of a relief well is the presence of a long vertical 12 ¼ '' casing section. It is assumed that burst and collapse of the casing is not a restricting factor in this study, hence not explained in details.

Borehole Stability
A rock segment in the earth crust experiences a three dimensional compression from the overburden stress and tectonic movements. The balance of stresses is disturbed when drilling through it. Rock mechanics is strictly monitored due to the potential of instability in the formation drilled. The collapse and fracture gradient is constantly being calculated through different pressure tests and MWD tools (Tobing, et al, 2013). There are several factors important when evaluating borehole stability during the drilling operation.

Collapse and fracture avoidance: The casing design is limited by the collapse and fracture gradients found through different pressure tests. A LOT is performed at each casing shoe to find the maximum drilling mud weight. The collapse gradient is found from the logging data of the rock compressive strength (Hareland, 19967).

Weak formations: Unconsolidated rocks are potentially a huge time consumer in a drilling operation. The risk of having stuck pipe in the S-curved well trajectory is present and can in worst case lead to loss of the drill string. Having to re-drill the relief well can delay the operation by weeks or months while the blowout well continues to extrude reservoir fluids. Weak formation issues can be avoided by doing high rate hole cleaning and drill in high overbalance. A lower Rate of penetration (ROP) will then be the result and time will be lost. Evaluation of the formation rock is assumed well accounted for when planning the blowing well's drilling operation, and can most likely be applied in the relief well drilling operation.

Swelling shale: If drilling through reactive shale, the phenomena of swelling shale may occur. Swelling shale can lead to stuck pipe and are a potentially large time consumer if not expected. The best practice to avoid swelling shale is to add salt to the drilling mud and equalize the activity between the mud and the shale (Holt, 2012)

Deep unconsolidated sediments: The start of deviation in a relief well is initiated as shallow as possible. If there are unconsolidated sediments located deep in the formation the start of deviation may not be initiated at the planned depth. A higher angle in the well is then the result and it may increase the error of the Measurements While Drilling (MWD) tools.

Temperature effects: Large temperature differences between the drilling mud and the formation (cool mud and warm formation) may decrease the mud window. This is a time delayed phenomena and is normally not a problem if the open hole sections are kept open at a minimum amount of time (Holt, 2012).

3.1.2. During dynamic killing operation

Fracture at last set casing shoe of the blowing well
When the high density kill fluid is injected in the blowing well a risk of fracturing the formation near the last set casing shoe is real. The hydrostatic column and the friction created from the high rate generate a large hydrostatic pressure and may exceed the fracture gradient. It is therefore important to closely calculate the kill fluid density and rate so that a potential fracture not will occur. A fracture at the last set casing shoe may lead to an underground blowout and loss of circulation fluid.

Collapse of interception hole
A minimum flow rate must be present at the interception hole to avoid collapse. Similar to a drilling operation there must be mud flowing through the interception hole at all time to keep the minimum collapse pressure. The minimum magnitude of the flow to avoid hole collapse is assumed not an issue compared to other risks of not having mud flowing through the interception hole, like gas migration up the relief well.

Gas Migration to relief well
To avoid gas migration from the blowing well to the relief well a minimum flow rate must always be applied from the relief well. The minimum flow rate can be estimated by assuming a gas migration velocity of 1000 m/hr and calculate the flow rate through the annular area **Error! Reference source not found.** (Asheim, u.d.).

$$Q = v\ x\ (OD^2 - ID^2)\ x\ \pi\ x\ SF \tag{3.1}$$

If the annular section is 12 ¼” and the drill string is 6 ½” the minimum flow rate must be 1821 lpm when applying a safety factor (SF) of 100%. This implies that gas migration is rarely an issue in a dynamic killing process. The annular flow rate is always higher after interception.

Rig selection/Rig capacity

The rig capacity is an important restriction to single relief well drilling. A rig only has the pump capacity of delivering around 11000 lpm or a pressure equal to 690 bar (Kallhovd, 2012). An applicable rig will also have to be able to deliver the mud from the pit to the rig pumps. During the Macondo killing operation two pumps from the mud storage boat was used to transfer mud to the rig pits at 3785 lpm each. If there is a need of a higher rate an additional mud storage boat can be attached (Oskarsen, 2013). The mud storage and reserve pits of some suitable rigs can be found in appendix A.1. A minimum Mud storage of 1000 m3 is recommended (Inderberg, 2013).

High pressure pump capacity

The high pressure pump capacity is the most important restriction of a single relief well killing operation. Often high rates and pressures are needed to reestablish control of the blowing well. As already mentioned a rig has a maximum applied pump capacity. There are three important parameters that define these restrictions; The magnitude of the blowout, the friction pressure loss of the relief well and the friction loss of the blowing well.

Friction in the relief well is dependent on the final casing diameter, measured depth (MD), Inner diameter (ID) of the kill & Choke line and OD of the drill pipe and Bottomhole Assembly. All these factors contribute to an unwanted friction loss through the relief well. Friction in the blowing well is dependent on the hole diameter and the fluid shear force against the wall. When dynamically killing a blowing well the kill fluid creates friction due to its high rate. Density and viscosity will enhance the killing procedure when increased due to increased hydrostatic pressure and fluid shear force.

The wanted scenario for the high pressure pump system is to have low friction loss in the relief well and high pressure loss in the blowing well. Sensitivities on these parameters will be performed in this thesis.

Weather conditions

The weather in the North-sea is very challenging in the winter seasons. If a blowout occurs in the late fall and the dynamic killing operation are planned to be performed in the winter season challenges related to the weather will be present. A dynamic killing operation needs a six day weather window to successfully kill the well. A study done by Statoil showed that number of Wait on Weather (WOW) days in the north sea/Norwegian sea in January are 15-20 days/month(Inderberg, 2013). If a platform supplying vessel (PSV) is needed the maximum wave height can only be 3 ½ m. A killing operation in the is challenging to successfully perform in the winter season based on these studies.

Sensitivities of the most important restrictions relevant for this thesis are very important when showcasing the importance of dual relief well drilling planning. The results of these sensitivities will be presented later in this thesis.

3.2. INTRODUCING DUAL RELIEF WELLS

This section will introduce the reader of this thesis to the term dual relief well, why it must be applied and the general major challenges related to the operation. A dual relief well operation uses the same drilling and killing procedures as a single relief well, but there are some major differences related to segments of the operation. The well trajectory, pump rates, pressure losses and interception method are the modified factors compared to a single relief well operation. The dual relief well procedure will be denoted later in this study.

3.2.3. Why dual relief wells?

Blowout simulations are always performed with data based on the worst case scenario. As described earlier the blowing well's friction is the most important factor for defining the magnitude of a blowout. If a gas blowout occurs in a long 12 ¼" section and no drill string is located inside the well a dual relief well operation usually is the only option to produce the required rates (Selbekk, 2013). A blowout simulation of a 12 ¼" section gas blowout when there is no drill string in hole is provided by Add Wellflow to give a independent view of the required rates (Tab. 3.1). Even two relief wells will have to push its capacity to kill this scenario.

Operation	Kill fluid	Kill rate	Kill rate	Press	Power	Volume
	Sg	Bpm	Lpm	bar	hhp	m3
Single relief well	2,2	170	27000	N/A	N/A	N/A
Dual relief well	2,2	2x85	2x13500	520	15730	1000

Tab. 3.1 – Dynamic kill requirements 12 ¼" open hole.(Kallhovd, 2012)

3.2.4. Major challenges

There are several challenges related to a single relief well operation. A dual relief well operation enhances these challenges. Below are the major challenges that must be strictly evaluated before performing a dual relief well kill operation.

Hydraulics

The main reason for killing a well with two relief wells is the pump capacity restriction per rig. When solving this issue by using two rigs and double the pump capacity another restriction presents itself. Fracturing at the last set casing shoe of the blowing well during the dynamic killing process is a potentially huge risk. A maximum flow rate must be monitored to avoid fracturing the formation. The sum of the hydrostatic and frictional pressures in the blowing well cannot exceed the fracture gradient in the blowing well.

Larger hydraulic pressures will automatically lead to more severe challenges related to pressure handling and friction losses. This will be evaluated later in this thesis.

Interception method
The interception method of a dual relief well operation is the same as a single relief well. However the challenge becomes greater when two wells are going into the same blowing well. There are different theoretical methods of intercepting the blowing well. The two presented in this study are either by going in with both relief wells within a time span of less than four hours, the other option is to go in with one main relief well by a commingling section. A commingling section is where two wells have been brought together in one.

The main issues and restricting factors to the interception methods are magnetic disturbance of the proximity ranging tool and the borehole stability of the intercepting hole. The different methods will be discussed later in this thesis.

Survey restrictions
The survey restrictions in a dual relief well drilling operation are the same as in single relief well drilling operations. Then again disturbance from the other relief well will affect the accuracy of the proximity ranging tools and demands a strict survey procedure to avoid these increased uncertainties. The survey procedure is explained in the dual relief well model later in this thesis.

Rig and tools availability
Relief well drilling/killing Tools are part of the contingency planning of a relief well operation. When the Well control emergency response plan is created the tools that are needed is given a maximum response time. However if the blowout were to happen in a logistic challenging environment, like a dessert or in the arctic, transporting the tools to the logistic main quarter can be a challenge.

Rig availability is a major logistic concern due to uncertainties related to the correct rigs being located nearby. A relief rig has certain demands that it must fulfill. Mud storage/reserves capacity, deck space, capability of having large Kill & choke-line diameters and pump capacity are the most constraining factors needed by a relief rig. Statoil set up a list of potential relief rigs located in the north/Norwegian sea that can be found in appendix A.1.

Continuous flow through both relief wells
Both rigs must be operational after the interception is performed. If one relief rig fails the consequences may be hazardous due to the potential of a cross flow between the two wells, or the fact that there will not be sufficient flow rate to dynamically kill the well. The amount of mud loss may lead to loss control of the relief wells.

4. MODELS

All models applied for supporting the discussion of this thesis are listed in this section. Additionally, the different scenarios and introduction of the results will be explained in detail.

4.1. OLGA ABC

This section includes the governing equations from *OLGA* used to complete the simulations in this thesis. The equations are provided to give the reader insight in the mathematical model. The governing equations in OLGA are namely the conservation of mass and conservation of momentum. These equations are combined to simulate two-phased fluid behavior in a well (Bendiksen. et al, 1991).

The conservation of mass for gas, liquid and droplet are used to compute multi-phase flow in a flowing well. The equations can be expressed as follows:

$$\frac{\delta}{\delta t}\left(V_g \rho_g\right) = -\frac{1}{A}\frac{\delta}{\delta z}\left(A\, V_g \rho_g v_g\right) + \alpha_g + G_g \tag{4.1}$$

$$\frac{\delta}{\delta t}\left(V_L \rho_L\right) = -\frac{1}{A}\frac{\delta}{\delta z}\left(A\, V_L \rho_L v_L\right) - \alpha_g \frac{V_L}{V_L + V_D} - \alpha_e + \alpha_d + G_L \tag{4.2}$$

$$\frac{\delta}{\delta t}\left(V_D \rho_L\right) = -\frac{1}{A}\frac{\delta}{\delta z}\left(A\, V_D \rho_L v_D\right) - \alpha_g \frac{V_D}{V_L + V_D} + \alpha_e - \alpha_d + G_D \tag{4.3}$$

Where V is volume, ρ is density, A is area, z is coordinate direction, v is velocity, α is mass transfer between phases, G is possible mass source. Indexes g, D, e, d and L denote gas phase, droplet, entrainment rate, deposition rate and liquid, respectively

The conservation of momentum for the gas and liquid droplets phase are used to compute multi-phase flow in a flowing well. The equations can be expressed as follows:

$$\begin{aligned}\frac{\delta}{\delta t}\left(V_g \rho_g v_g\right) = &-V_g\left(\frac{\delta p}{\delta z}\right) - \frac{1}{A}\frac{\delta}{\delta z}\left(A\, V_g \rho_g v_g^2\right) - \lambda_g \frac{1}{2}\rho_g \left|v_g\right| v_g \times \frac{S_g}{4A} \\ &- \lambda_i \frac{1}{2}\rho_g \left|v_r\right| v_r \times \frac{S_i}{4A} + V_g \rho_g g\, cos(\beta) + \alpha_g v_a - F_D\end{aligned} \tag{4.4}$$

$$\begin{aligned}\frac{\delta}{\delta t}\left(V_D \rho_L v_D\right) = &-V_D\left(\frac{\delta p}{\delta z}\right) - \frac{1}{A}\frac{\delta}{\delta z}\left(A\, V_D \rho_L v_D^2\right) - V_D \rho_L g \cos(\beta) \\ &- \alpha_g \frac{V_D}{V_L + V_D} v_a + \alpha v_i - \alpha_d v_D + F_D\end{aligned} \tag{4.5}$$

Where β is the pipe inclination, S is the wetted perimeter of a phase, F is the gas/droplet drag term. Indexes g, D, e, d, i and L denote gas phase, droplet, entrainment rate, deposition rate, interface and liquid, respectively.

For simplicity the other equations are excluded in this thesis. The author encourages especially interested readers to read (Bendiksen. et al, 1991)

OLGA ABC applies the dynamic Two-fluid motor of the OLGA software to simulate a dynamic killing operation. The simulation procedure is explained in bullets below (SPT Group. et al, 2011):

- A blowout scenario is created and pre-circulation is initiated. The pre-circulation period is to initialize both the blowing and relief well. During the pre-circulation period no influx is taken and the pumps are switched off.
- When the pre-circulation period is finished the unloading period is initiated. This will develop the reference blowout in the main well. Depending on the influx from the reservoir 20 simulation-minutes is sufficient to develop a blowout.
- When the blowout is fully developed with 100% gas inside the well the dynamic killing procedure may be initiated (Fig. 4.1). The flowing bottom hole pressure is now below the reservoir pressure and has created an underbalanced situation. Flow rate and kill fluid density is assumed within the restrictions given by the rig pumps.

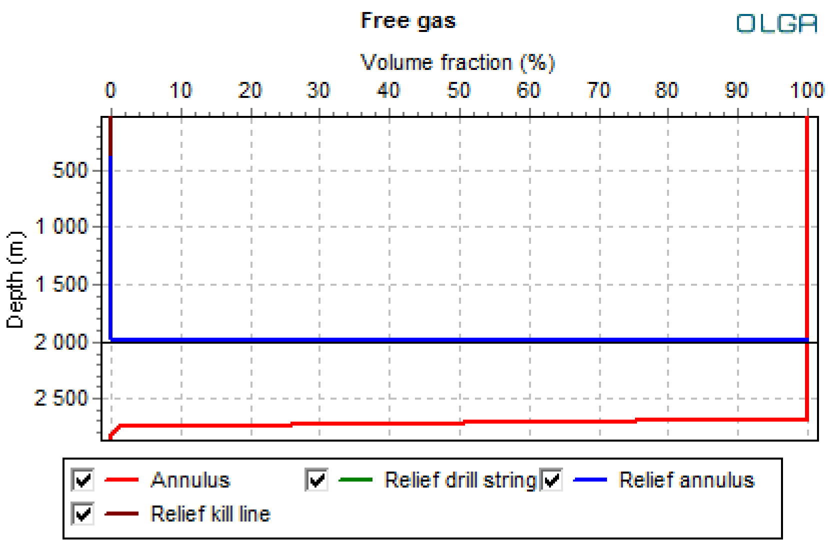
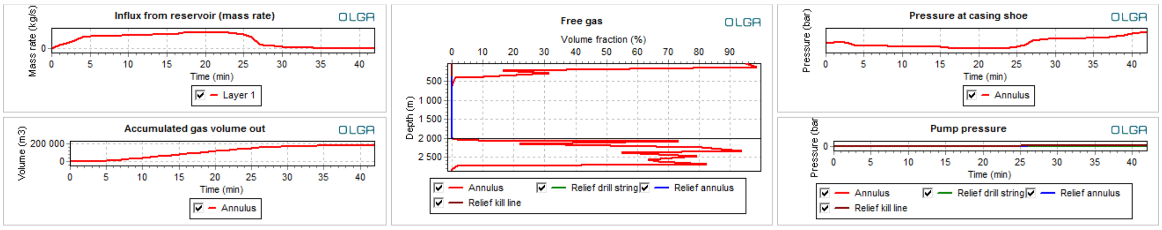
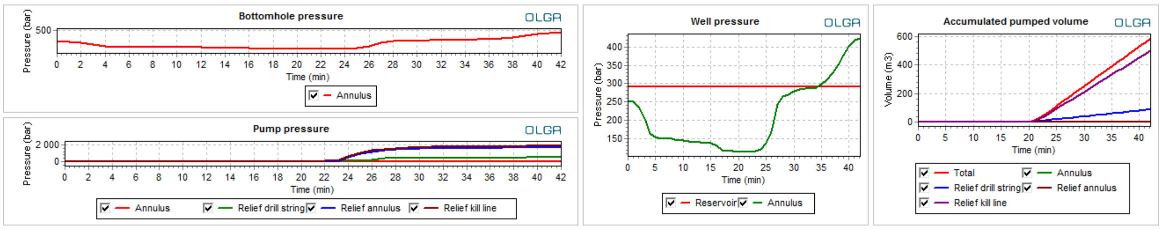


Fig. 4.1 - Free Gas as function of depth.

- The total flow rate is split between the drillpipe and the annulus of the relief well to enhance the performance. The narrower C&K-line is used to pump kill fluid down the annular space and will therefore also generate a large pressure loss.
- The Flowing bottom hole pressure, pump pressure, accumulated pump volume, Amount of free gas in the blowing well, pressure at the last set casing shoe and influx from the reservoir is monitored while pumping kill fluid through the relief well. The trends of these important blowout parameters indicate the situation of the killing operation (Fig. 4.2).



(a)



(b)

Fig. 4.2 (a-b) – Monitoring of different killing parameters of reference scenario in OLGA ABC.

- When the flowing bottom hole pressure exceeds the reservoir pressure an overbalanced situation is re-established and the influx from the reservoir stops. FIG right after FBHP = PR

- When the bottom hole pressure has attained a pressure 50-100 bar over the reservoir pressure the killing rate can be decreased to save kill fluid (Fig. 4.3). To better compare the different scenarios applied in this thesis a constant pump pressure is assumed throughout the entire killing operation.

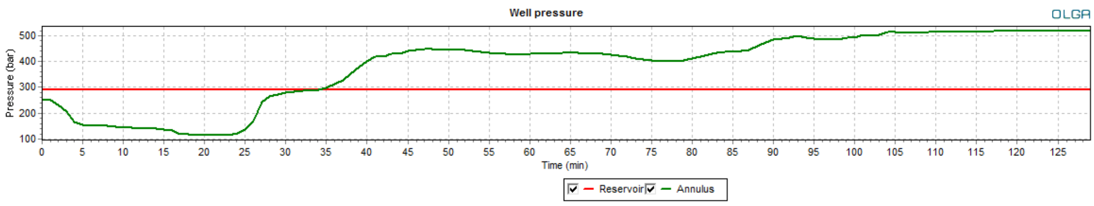


Fig. 4.3 – OLGA ABC flowing well pressure

- The circulation phase of the gas is now initiated and the gas will percolate through the heavy kill fluid and leave the flowing wellhead (Fig. 4.4).

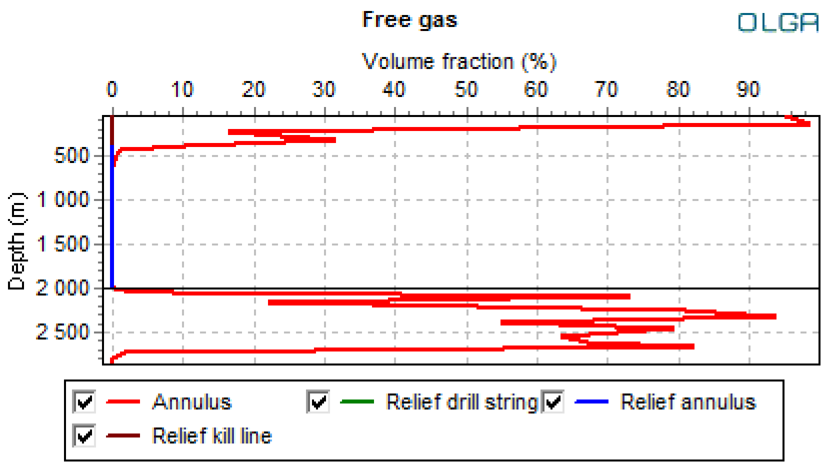


Fig. 4.4 – OLGA ABC, Free gas during the circulation phase

- The flowing wellhead will be shut-in by a wellhead stack or the BOP when all free gas is circulated out.
- Read the pump pressure, accumulated pump volume, pressure at the injection point, pressure drop in the C&K-line, Pressure drop in the drill pipe, pressure drop in the annulus and pressure at the casing shoe of the blowing well to evaluate the killing operation.

The OLGA ABC simulator will be applied as a tool for sensitivity analysis and to support the applied dual relief well killing procedure. The dynamic killing operation has assumed constant pump pressure throughout the operation. This is to better monitor the results when doing sensitivity analyses. OLGA ABC is a good tool to measure pressure losses in the C&K-line, but not user friendly when evaluating other pressure losses in the relief well.

4.2. MUD_CALC-PRESSURE LOSS: EXCEL MODEL

The Pressure loss-model is an external model(Andreasen, u.d.). The model is used to calculate the pressure drops in wells. The model is applied in this thesis to calculate the pressure losses in the dual relief well operation due to the restriction of only using a single relief well in OLGA ABC. It is also applied to support the pressure loss-model in OLGA ABC. As long as it is only one phase present in the relief well the results will be fairly equal. The model uses fluid properties and wellbore design to calculate the frictional pressure losses. The kill fluid properties taken into the calculations are density, viscosity and gel effects. Gel effects are not present in the OLGA ABC simulation. This however will not make a large difference when the flow is fully developed through most of the killing operation. The gel effect is then neglected in this study.

Calculations of pressure losses are based on the following equations:

$$\Delta P_{annulus} = 2 \times f \times v^2 \times \rho_{kill} \times g \times \frac{1}{\left(OD_{hole} - OD_{pipe}\right) \times L_{section}} \tag{4.6}$$

$$\Delta P_{pipe} = 2 \times f \times v^2 \times \rho_{kill} \times g \times \frac{1}{ID_{pipe} \times L_{section}} \tag{4.7}$$

$$v = \frac{Q}{A} \tag{4.7}$$

$$Re_{annulus} = \frac{v \times (OD_{hole} - OD_{pipe}) \times \rho}{\mu_{annulus} \times \left(\frac{2n+1}{3n}\right)^n} \tag{4.8}$$

$$Re_{pipe} = \frac{v \times ID_{pipe} \times \rho}{\mu_{PL,pipe} \times \left(\frac{2n+1}{3n}\right)^n} \tag{4.9}$$

Where ΔP is the pressure loss, f the friction factor, v the velocity, ρ the density, g the gravity, OD the outer diameter, ID the inner diameter, L the measured depth of the section, μ the viscosity, n the rheology constant and Re the Reynolds number.

The viscosity to calculate the Reynolds number and the friction factor varies down hole and is different inside the drill pipe and in the annulus. The model uses iteration to calculate the friction factor and checking if it is within the correct flow regime (Turbulent or laminar).

The reader of this thesis can check the reference input values in appendix A.5.

4.3. SENSITIVITY OF SINGLE RELIEF WELL PRESSURE LOSSES

4.3.1. Overview

This section will present what sensitivity analyses are performed to enhance a single relief well's capacity. The result of the analysis is presented later in this study.

It is never desired to apply a dual relief well operation to kill an uncontrollable blowout. Therefore it is important to do sensitivity analysis to enhance the capacity of a single relief well killing operation. The important factors when enhancing a relief well's capacity are either to decrease the pressure loss of the relief well, increase the friction of the blowing well or increase the hydrostatic column in the blowing well.

4.3.2. Pressure losses

The best scenario of a relief well killing operation is to have low friction loss in the relief well and high friction loss in the blowing well. Friction in the blowing well is created by a viscous and dense kill fluid. The friction in the relief well is mainly restricted by the diameter and length of the drill string, C&K-line and last set casing. Sensitivity analysis on each of these seven factors will be performed in the OLGA ABC simulator and the mud_calc-pressure loss model based on a reference scenario from the north-sea. The sensitivity analyses are included in Tab. 4.1.

Parameter	Notation	Reference value	Sensitivity range	Interval
Kill fluid viscosity	[cP]	60	[1 , 80)	20
Kill fluid density	[Kg/m3]	2000	[1500 , 2200]	100
C&K-line ID	[m]	0,1143	[0,0762 , 0,1143]	0,0127
C&K-line MD	[m]	400	[0 , 2000]	200/500
Annular size (OD of DP		0,1397	[0,1143 , 0,1778]	0,0127
and hole size)	[m]	0,2159	[0,1539 , 0,3114]	0,0254-0,058
Rig location (equivalent to MD of relief well)	[m]	1000	[500 , 3000]	500/1000
Open hole in relief well	[m]	20	[2 , 100]	10

Tab. 4.1 – The range and interval of the input parameters that will be performed in this study.

4.4. DUAL RELIEF WELL OPTIONS

In this section two different dual relief well options will be presented. The chosen option for this study will have a well design explained more detailed regarding survey restrictions, killing procedure and interception method. The other option is assumed equal to two single relief wells, and will be shortly explained when comparing the two options later in this thesis. The sensitivity analysis on single relief wells will also be used as a guideline for optimizing the dual relief well operation. This will be evaluated later in this study.

4.4.3. Dual relief well design

There has been performed some internal research on two different methods of dual relief well drilling operations; one by Statoil and one by Shell. None of the two different researches are available for the public. This study is based on interviews with recognized well killers and drilling engineers. By adding up knowledge about the restrictions of the survey tools, the killing procedure and interception methods the information needed to set a conclusion have been achieved. Comparing the dual relief well options, and conclude on the practicality of the drilling/killing operation will be presented later in this study.

Sum up of the applied restrictions:
Before going into details on the different dual relief well options the restrictions explained in the literature study and theory section will be summed up to make it easier for the reader of this thesis to understand the background of the decisions taken.

Rig location: The rig location is the main contributor to measured depth of the well. Minimum distance from the blowing well is 500 m and maximum is 3000 m

Survey tools: To be able to intercept the blowing well the uncertainty of the survey tools must be minimized. Therefore a well deviation of more than 60-70 degrees is rarely recommended. The intermediate casing, or second last set casing, is usually set around the section of the proximity ranging. The electrode of the active proximity ranging tool cannot be located inside the casing. The electrode is located 30-40 m above the bit. The intermediate casing will therefore have to be set 30-40 m MD before the proximity ranging section, which is located 30 m in lateral distance from the blowing well. If this procedure is not followed the 30-40 m MD must be drilled blindfolded until the electrode is outside the casing.

The proximity ranging tool needs to verify the location of the well before entering it. This is called the homing-in phase and demands the relief well to pass right by the blowing well to define the location. 10 m in horizontal distance passed the blowing well the relief well deviates with an angle of 3-8 degrees towards the blowing well.
The last set casing can be set as close as 0,5 m in lateral distance from the blowing well. It is recommended to add a safety factor of at least 100% to this distance. If setting the last casing 1,4 m in lateral distance from the blowing well and homing in at 4 degrees the setting depth will be 10 m below the last set casing shoe. While drilling the two relief wells at the same time a disturbance occurs if they are close to each other. The critical part is if one of the relief well casings is within the range of the electrode of the other active proximity ranging tool. A magnetic disturbance equal to the situation when setting the intermediate casing may be the result.

Interception method: There are three different interception methods recommended by the different well killers. The normal milling operation is either performed 10 m above or 10-20 m below the last set casing shoe of the target well. The other method is when the last casing is set parallel to the target well. Then the milling operation is performed by the help of a whipstock through both casings. The casing setting distance can be closer than 0,5 m (Oskarsen, 2013). The last method is angled perforation 10-20 m below the last set casing shoe of the target well.

The killing procedure: Kill fluid can be pumped through both the drill string and the annulus. If sufficient rate is reached only by pumping through the annulus, sea water can be pumped at low rates through the drill string to monitor the pressure environment downhole.

Other restrictions: Borehole stability is a situational restriction. If the formation is weak and unconsolidated at shallow depths the kick of point (KOP) will have to be located deeper than expected. The Interception point will also demand a greater rate and a more stable interception method to avoid collapse of the interception hole if the formation is weak. The Whipstock interception method is recommended in weak formation situations (Inderberg, 2013). Reactive shale may cause trouble during the drilling operation with stuck pipe as result. A stuck pipe scenario is a potential time consumer.

Friction loss in annulus due to small hole diameter is a decisive factor when comparing the dual relief well methods. Gas migration through the relief well occurs if the flow rate is too low from the relief wells at the interception point. This rate can easily be upheld by pumping sea water at low rates and is not seen as a problem unless a heavy loss of mud is occurring.

4.4.4. Dual relief well options

This study will focus on two dual relief well methods, and highlight the option that is assumed to be the most successful. Shell and Statoil have evaluated two different options, with a significant difference in well trajectory and interception method (Fig. 4.5).

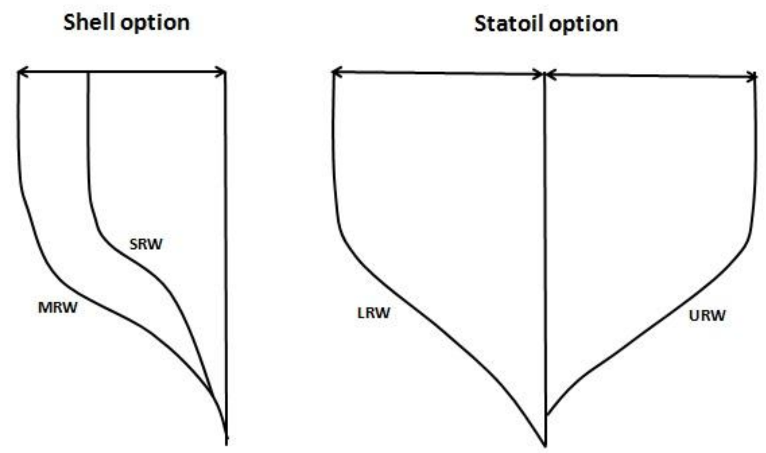


Fig. 4.5 – Dual relief wells schematics

The Shell option uses one main relief well (MRW) to intercept the blowing well. To gain the required pump rate and pressures needed to dynamically kill the blowout a supplying relief well is connected to the MRW downhole (Hagenes, 2013).

The Statoil option applies two independent single relief wells. The upper relief well (URW) intercept the blowing well first and starts pumping sea water to neutralize the pressure differences. Within a short amount of time the lower relief well (LRW) intercepts the blowing well and the dynamic killing procedure is initiated. The homing-in section is neglected in these schematics, but it does play a major role when comparing the two different options (Inderberg, 2013).

For clarification the difference between interception and intersection will be explained before going into details about the applied dual relief well option in this study.

Intersection is equal to a crossroad. Put in other terms both lines must cross each other. If a line cross another line it is called an interception. This means that all milling procedures in a relief well operation are interceptions (Inderberg, 2013).

4.4.5. Modified Shell option

The dual relief well option applied in this study is a modification of the shell method, later referred to as the modified Shell option or MSO. The option uses the same principal as the Shell method by entering the blowing well with only one relief well, and add a supplying relief well to the main relief well (Fig. 4.6).

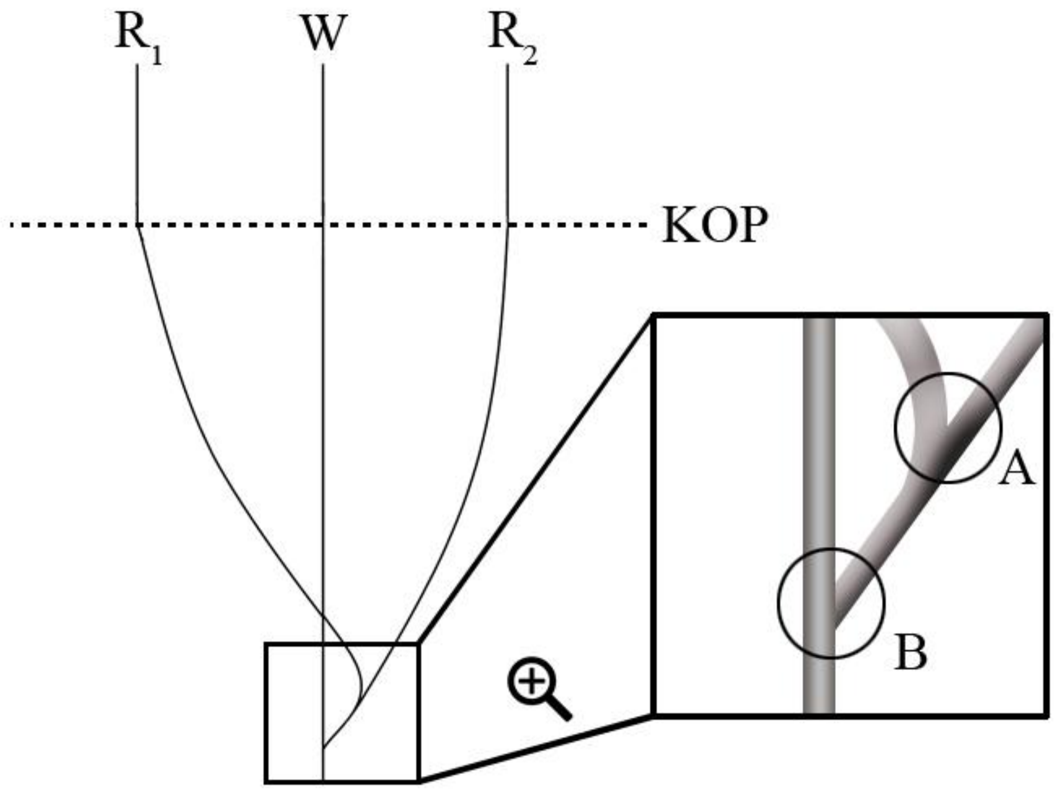


Fig. 4.6 – Detailed schematic of the homing-in section of the modified Shell option.

The reference scenario

Well trajectory and interception:

Both rig locations is set to be 1000 m in horizontal distance from the blowing wellhead. The water depth is kept at 400 m TVD from the rotary kelly bushing (RKB). The kick off point (KOP) is set at 750 m TVD. It is set at this depth to avoid issues related to unconsolidated formations. Max dogleg is assumed 5 degrees/30 m of MD. This is a quite large dogleg but is considered fair by several different sources (Pruitt. et al, 1988)[3]. Maximum angle of deviation is initially set to 60 degrees due to MWD accuracy, but this limit can be pushed up to a 70-75 degrees if necessary (Oskarsen, 2013).

The intermediate casing, 12 ¼“, of the MRW is set at 1800 m MD and 300 m lateral distance from the blowing well. It is not assumed issues related to the proximity ranging

[3] This assumption is confirmed by other independent sources.

tool. The intermediate casing of the supplying relief well is set at the same MD to simplify borehole stability issues. The drill string of the supplying relief well will be pulled back inside the last set casing shoe before intercepting the MRW. This will protect the drill string and enhance the annular area of the interception point between the relief wells. The drill string of the MRW can be pulled back a distance of maximum three stand lengths (30 m) to enhance the annulus area of the commingling section (Oskarsen, 2013). The reference scenario has assumed that the drill string is stuck in the interception point, so the drill string length is equal to the measured depth of the well.

By increasing the distance from the MRW and supplying relief well the risk of experiencing magnetic disturbance in the surveys are eliminated until they are located within the proximity ranging tool area. To completely avoid the magnetic disturbance of the proximity ranging survey the MRW is drilled and cased ready to intercept the blowing well before the supplying relief well intercepts the MRW. The distance between the interception point and the well is 39,5 m TVD above and 4,9 m in lateral distance from the interception point of the blowing well. The commingling section length is then 39,8 m MD. The relative attack angle is 17,5 degrees towards the MRW.

To keep consistency in the sensitivity analysis the main interception point is set 10 m below the last set casing shoe of the blowing well at 2010 m TVD (Fig. 4.7). This is the most normal procedure of intercepting a blowing well (Oskarsen, 2013).

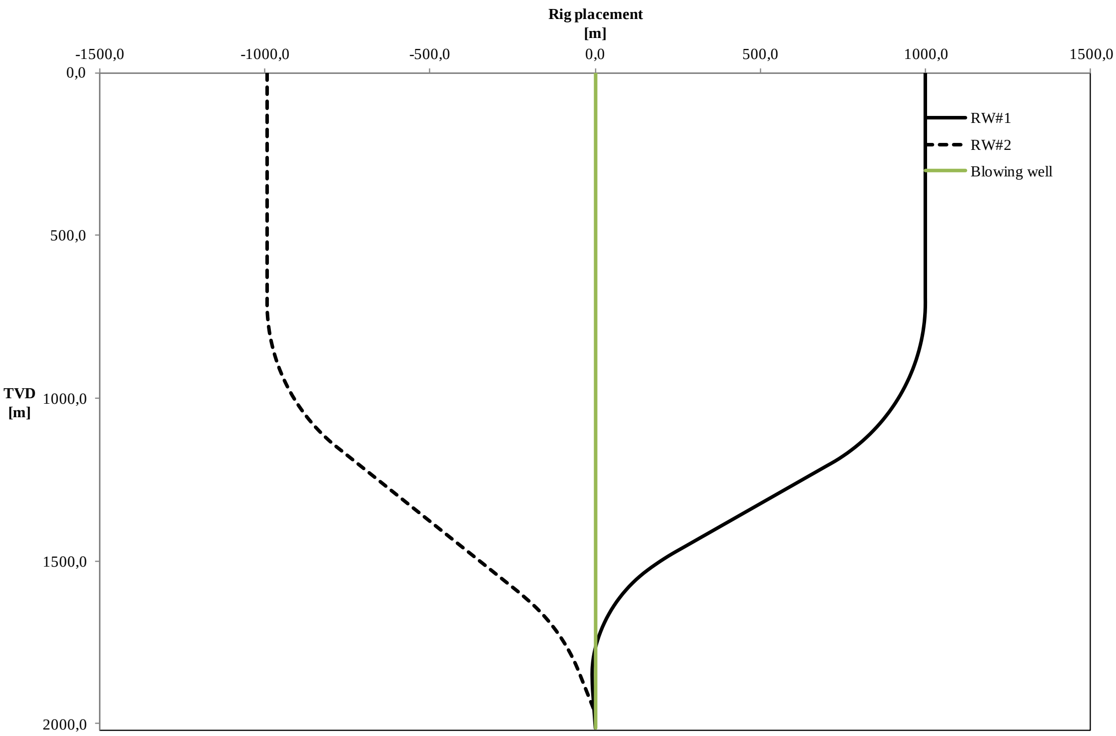


Fig. 4.7 – Exact well trajectory of the modified Shell option.

The killing operation:
The MRW will be supplied with the needed rate and pressures from the supplying relief well. All kill fluid will come from the annulus of both relief wells to keep friction losses at a minimum. The pressure down hole will be monitored either by a PWD or if sufficient

pump rate is given from the annuluses the drill pipe of the MRW can measure the ECD at the interception point. Different scenarios of the reference scenario will be calculated and discussed later in this study.

4.5. REFERENCE SCENARIO

This section will present the reference scenario data, assumptions and emphasize the important parameters, which may be an uncertainty around this report. The blowing well is a real scenario in the north-sea provided by GDF Suez E&P Norway. The relief well designs are created based on the restrictions related to both a single relief well and a dual relief well drilling operation.

4.5.6. The blowing well (vertical)

The reference scenario reservoir parameter values are given by GDF Suez (Tab. 4.2). The gas productivity index is very high, but approved by experts due to the 0% water cut (Oskarsen, 2013). It is applied in a linear influx model, and not the more realistic Forcheimer model. This is done to simplify the influx, which is not important in this study. For a closer explanation and comparison of the inflow models, please see appendix A.2.

Reservoir data		**Layer 1**
Top reservoir (TVD)	m	2592
Reservoir pressure (day 0)	bar	290
Reservoir pressure (day 50)	bar	261
Reservoir temperature	C^o	102
Reservoir thickness	m	100
Net/Gross ratio	-	0,6
Net pay	m	162
Horizontal permeability	mD	500
Mechanical skin factor	$1/MSm^3/d$	3
Turbulent skin factor	$1/MSm^3/d$	3,5
Gas productivity Index	m3/bar/d	200000*
Water cut	%	0

Tab. 4.2 – Reference scenario reservoir parameters.

The initial planned well design was a long horizontal well through a gas reservoir (Fig. 4.8). A fictive blowout is simulated when experiencing a loss of hydrostatic pressure when drilling through the reservoir formation at 2692 m TVD. The 12 ¼” casing shoe is set at 2000 m TVD instead of the given 1800 m TVD to give a more realistic open hole section.

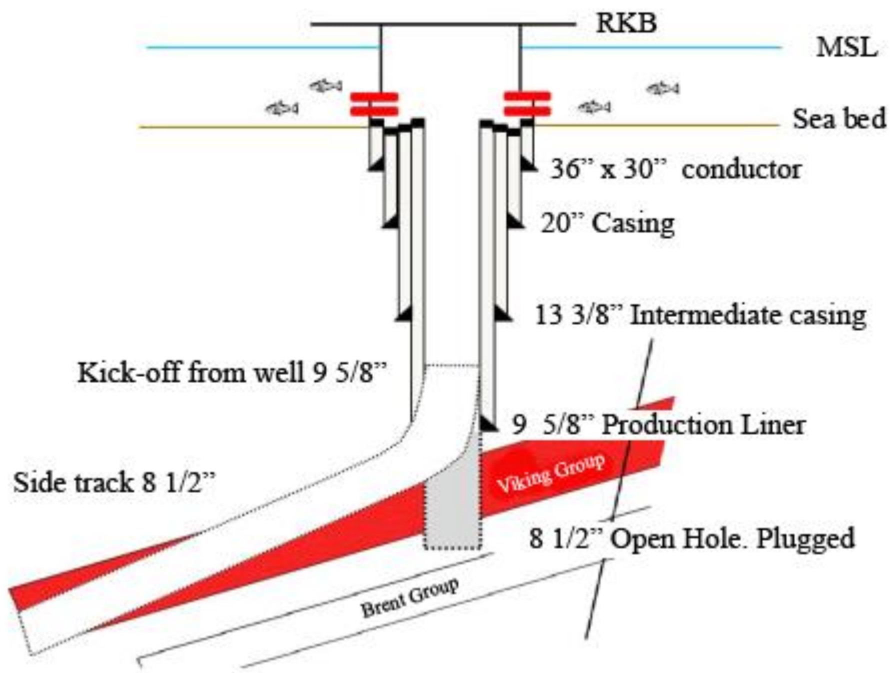


Fig. 4.8 – Schematic of originally planned well

More details about the input variables applied in the reference scenario can be found in appendix A.4.

Wellbore design of the blowing well

The last set casing shoe, 12 ¼ ”, is located at 2000 m TVD and the open hole section is down to 2692 m TVD. It is assumed no drill string in hole (Fig. 4.9).

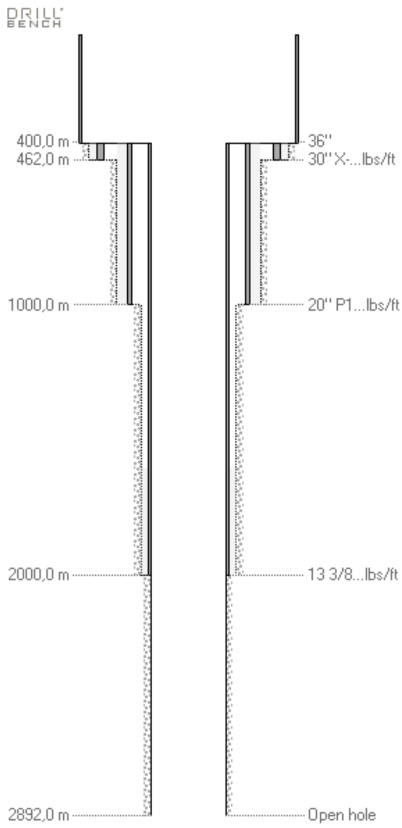


Fig. 4.9 - Wellbore schematic: Blowing well

Dynamic kill operation

The dynamic kill parameters needed to kill the reference scenario with one relief well are pumping 14000 lpm of kill fluid through the annulus and 3000 lpm of sea water through the drill pipe. These rates are found by using the OLGA ABC blowout simulator. A regular single relief well cannot achieve these rates due to pump capacity restrictions. Hence, two relief wells must be applied. It is possible to lower the kill rate by increasing the density. Sensitivities on these parameters will be performed later in this study.

Kill fluid properties:
The rheology used is given by Statoil. It is the same fluid that Statoil used in their research on dual relief wells (Fig. 4.10) (Inderberg, 2013).

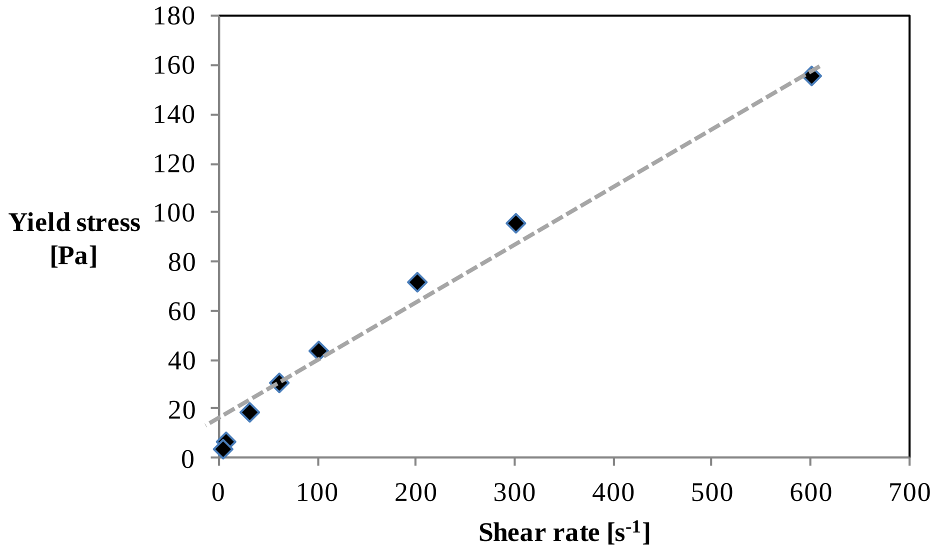


Fig. 4.10- Rheology from a Statoil relief well used in a killing operation. Dashed line illustrates the Bingham approximation used for simplicity.

This rheology gives the kill fluid a plastic viscosity of 60 cP and yield point of 17,3 Pa calculated from the mud_calc-pressure loss model. It is assumed a Bingham fluid because of the normal behavior of a pressurized water based fluid (Skalle, 2013).

4.5.7. Relief wells

The reference dual relief well design is based on the modified Shell option. A main relief well will start 1000 m North of the blowing well and intercept it 10 m below the last set casing shoe. This operation will be supplemented by a supplying relief well. The supplying relief well intercepts the main relief well as deep as possible to minimize the commingling section length. The interception depth to the blowing well is 2010 m.

Main relief well

The MRW looks like a single relief well. The purpose of this is to act as the intercepting relief well or referred to as the main relief well. When doing simulations in OLGA ABC only a single relief well can be applied. Therefore the pressure drops will have to be evaluated before concluding with a result.

Wellbore design: The MRW intercepts the blowing well just below the last set casing shoe at 2010 m TVD or 2250 m MD. The last set casing shoe, 9 5/8“ is 20 m TVD above the interception point.

The string is a 5“ drill pipe with a 150 meter long 6 ½ “ OD drill collar (DC) and 50 meter long 6 ½ “ OD bottom hole assembly (BHA) both having an ID of 3 ¾” (Divins. et al, u.d.). During the killing operation the Drill string is located just above the last set casing shoe of the relief well (Fig. 4.11).

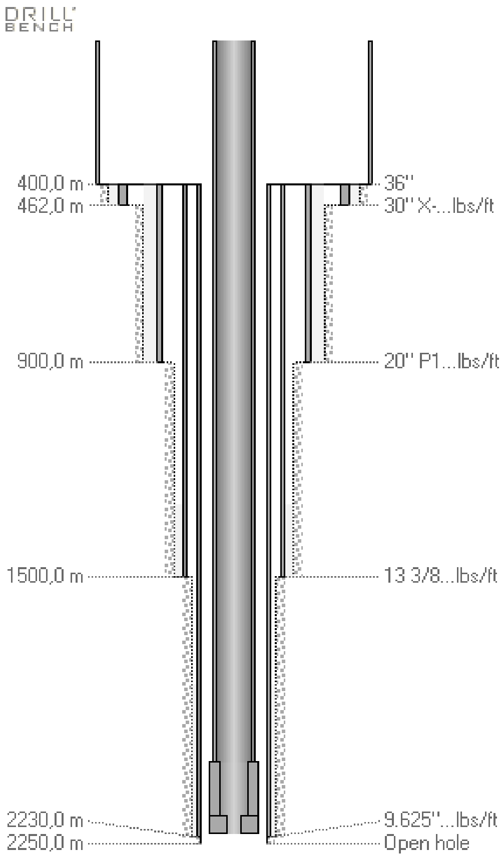


Fig. 4.11 - Wellbore Schematic: Main relief well

Supplying relief well
The Supplying relief well will provide with the additional flow rate needed to kill the reference scenario blowout.

Wellbore design: The interception point is at 1969,5 m TVD and 995,1 m lateral distance from the relief rig wellhead. The string has the same dimensions as the MRW and is located just above the internal last set casing shoe (Fig. 4.12)

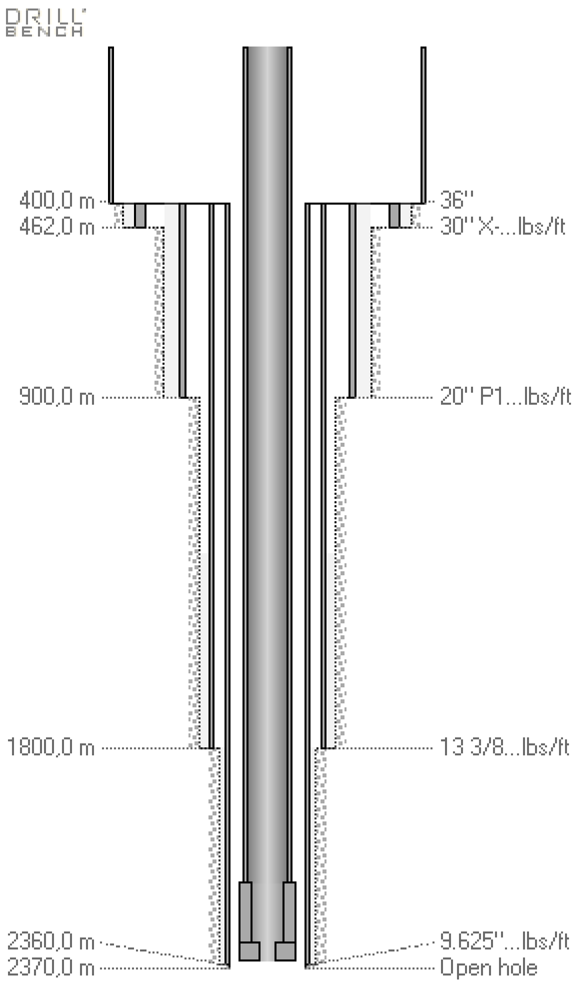


Fig. 4.12 - Wellbore schematic: Supplying relief well.

4.6. SENSITIVITY ANALYSIS OF DUAL RELIEF WELL OPERATION

All trends of single relief well sensitivity analysis can be applied in the evaluation of the dual relief well operation, but there are some specific parameters that must be evaluated especially for dual relief well drilling. This section showcase these parameters and the models applied to carry out a sensitivity analysis. The importance of doing these sensitivities is to better compare the dual relief well methods and conclude on the practicality of the operation.

4.6.8. Well trajectory: Relief rig placement

The rig location of the two relief wells can vary a lot, but is usually around 500-1000 m in lateral distance from the blowing wellhead. Depending on water depth, water streams and wind forecast the location of the relief rigs can be as far away as 3000 m in lateral distance from the blowing wellhead. New regulations tell that Shallow water depths (<300 meter) demands a lateral distance of as much as 3000 m. Minimum distance for deeper water depths (>300 meter) are 500 m (Inderberg, 2013) The rig location creates large variations in MD of the well and this change the friction loss of the kill fluid. The rig location will also change the deviation of the well and increase the uncertainty of the MWD tool. A high dogleg will lead to borehole stability issues compared to low doglegs.

For this study an excel document has been made for sketching different scenarios of relief rig placement. The model uses simple trigonometric equations and the built-in excel tool, “solver”, to approach the fixed interception point by changing the dogleg. The “solver”-tool has some restrictions related to it. If adding too many constrains it will eventually crash the document, due to the poor motor of excel. It is however a great way to approach the desired inclinations needed. The reference scenario excel document can be found in appendix A.6 for the reader to take a closer look at the model.

The well trajectory data will be applied in the mud_calc-pressure loss model to evaluate the magnitude of the pressure losses in the relief wells. The reference scenario will also be applied in OLGA ABC to simulate the killing operation of the blowout.

4.6.9. Hydraulic pressure losses in the commingling section

When comparing the OLGA ABC simulations and the mud_calc-pressure loss results, the pressure losses of the commingling section can be predicted. It is assumed in the reference scenario that this section is 39 m MD long. There will be performed sensitivities on the length and hole size of this section due to lack of past studies. The chosen killing procedure of pumping kill fluid through both the annulus and the drill pipe make other simulation programs not suited for this study. HYSYS and the original OLGA software have both been applied without giving any reasonable results due to the pumping of fluid through both the annulus and DP. They have therefore not been included in this thesis.

An important assumption in the commingling section is the assumption of developed flow where the two flow rates meet in the start of the commingling section. The assumption is justified by the fact of high pressure losses and high flow rates throughout the annular sections and neglects the pressure loss caused by the undeveloped flow at the start of this segment. For future studies is it recommended to empirically verify this assumption.

5. RESULTS

The results of this study are divided into two sections. One is about enhancing a single relief well's capacity to avoid having to drill a dual relief well and the other is to enhance and evaluate the dual relief well drilling/killing operation. These results will together with the literature and theory about relief well drilling/killing be discussed to draw conclusions around the practicality of dual relief well operations.

5.1. ENHANCEMENT OF SINGLE RELIEF WELL'S CAPACITY

5.1.1. Overview

Drilling a dual relief well is never wanted due to the high time and cost consumption. The capacity of a single relief well is pushed to manage a blowout before adding more kill fluid from another relief rig. The results in this section will help this study to establish trends and then enhance the capacity of both single and dual relief well operations. The same reference blowout scenario parameters have been applied for all sensitivity analysis. This section will present the results of sensitivities done on the important parameters for a single relief well.

The parameters evaluated are:

- Choke- & Kill-line diameter and length
- Drillpipe outer diameter and hole size
- Wellbore length
- Open Hole section length
- Fluid properties, viscosity and density

5.1.2. Reference pressure losses

When applying the reference blowout scenario in a single relief well killing operation the annular pressure losses compared to a dual relief well operation is higher (Fig. 5.1). It is assumed a killing rate of 14000 lpm through the annulus at kill fluid density 2,0 sg and 3000 lpm of sea water through the drill pipe for pressure monitoring.

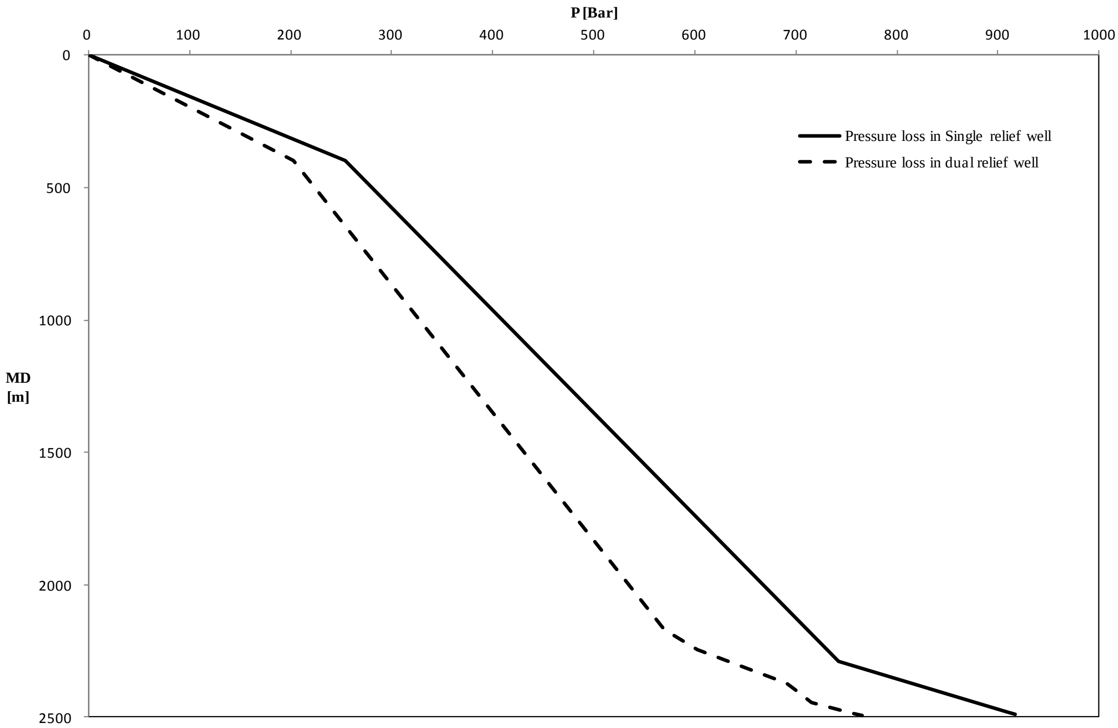
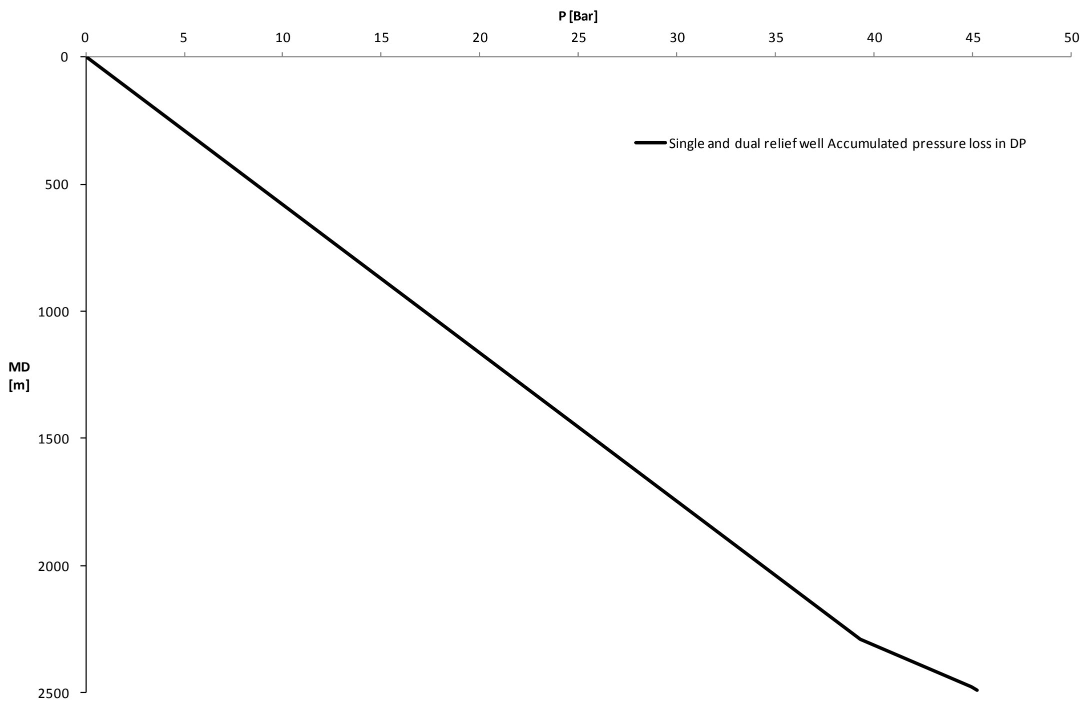


Fig. 5.1– Pressure losses in a single and dual relief well assumed the reference scenario parameters.

The annular pressure loss is 152 bar lower in the dual relief well killing operation. This is due to the increased fluid friction generated from twice the fluid rates used in the single relief well. Also noted is the commingling section of the Dual relief well killing operation. The two flow rates from each rig commingle and create the largest pressure loss gradient. Sensitivities are performed and will be presented in this chapter.

The pressure losses in the drillpipe are assumed the same in both operations due to assumed similar ID of both the DP and BHA when intercepting the blowing well. This is a fair assumption given the killing procedure recommended by the industry (Oskarsen, 2013).



5.2 - Pressure loss in drill pipe in a single and dual relief well drilling operation

When doing a single relief well operation with the required rates and density the pump pressures needed is given in Fig.5.3.The difference between the two upper lines is the pressure drop from the C&K-line. The lowest line is the required pump rate for the DP.

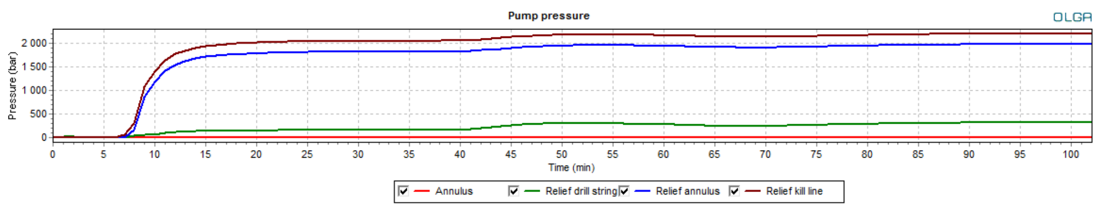


Fig.5.3 - Pump pressure vs. time in a single relief well killing operation

According to the OLGA ABC simulations the pump pressure needed through the C&K-line is 2197 bar. From this a pressure drop of 225 Bar will be generated through the C&K-line. Due to limitations on reading of pressure losses in the OLGA ABC simulator pressure losses will primarily be calculated by the mud_calc-pressure loss model. This model generates a pressure loss of 255 bar through the C&K-line when applying 4 ½”-lines. The main differences in these two models are the rheology parameters of the mud_calc-pressure loss model. The OLGA ABC simulator does not allow input of specific rheology parameters. The C&K-line sensitivity analysis will be applied by both models to better support the combined conclusions later in this study.

5.1.3. Choke- & Kill-line

To be able to pump kill fluid through the annulus in an offshore relief well killing operation the C&K-lines must be used to transport high rate pump fluid down hole. This pump operation leads to a heavy pressure loss due to the small diameter of the C&K-lines. The length of the C&K-lines is also a great contributor of pressure losses, and is dependable on the water depth.

Pressure losses in the different C&K-line diameters against water depth found in the mud_calc-Pressure loss model is given in Fig.5.4.

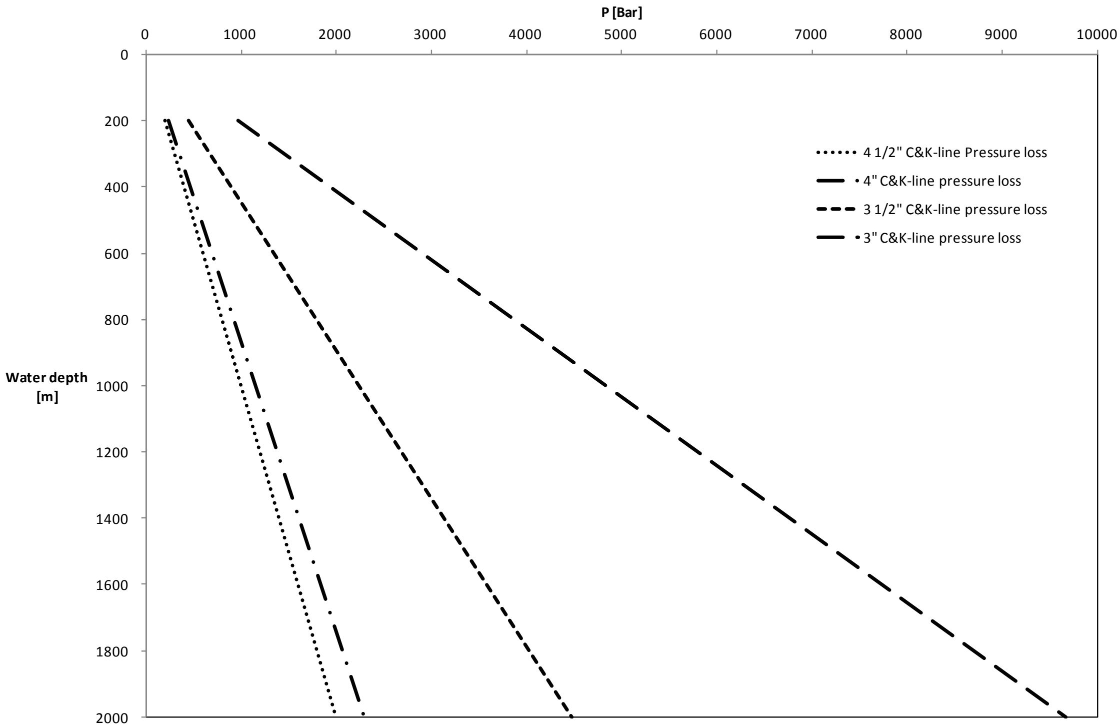


Fig.5.4 - Pressure loss sensitivity analysis when varying the Choke- & kill-line from 4 ½" to 3".

The pressure losses are very high when the C&K-line ID is less than 4". If decreasing the diameter less than 4" the pressure drops will be very severe and not recommended to be used in a relief well operation.

The OLGA ABC simulator gave the following results compared to the mud_calc-pressure loss model (Fig.5.5).

Model	ID = 4 1/2" Pressure loss [Bar]	ID = 4" Pressure loss [Bar]	ID = 3 1/2" Pressure loss [Bar]	ID = 3" Pressure loss [Bar]
OLGA ABC	225	405	783	1692
Mud_calc-Pressure loss	255	459	895	1934
Ratio between models **[%]**	88,2	88,2	87,5	87,5

Fig.5.5 - Choke- & kill-line Comparison of OLGA ABC and the mud_calc-pressure loss model

The pressure loss comparison rate between the two models at the reference water depth is consistent and close to 88% for all diameters.

5.1.4. Length of open hole section

The open hole section will have a different friction factor than the cased hole. It is difficult to predict the friction factor of an OH. Therefore a sensitivity analysis is applied in both models to support the values.

The open hole length is initially assumed being 10 m with a pressure loss of around 9 bar. A comparison of both models is performed to justify the pressure loss values (Fig.5.6). The Pressure loss uses the same friction factor as inside the casing, while the OLGA ABC values gives a slightly lower pressure loss.

OH length **[m]**	Pressure loss (mud_calc) **[bar]**	Pressure loss (OLGA ABC) **[bar]**
1	0,9	1
10	8,8	9
30	26,3	23
50	43,8	35
100	87,5	67

Fig.5.6 – Pressure losses in the open hole section. OLGA ABC and the Mud_calc-pressure loss model.

The open hole section has a neglected contribution to the total pressure loss system when compared to the cased hole section. The Mud_calc-pressure loss model does not calculate specifically for open hole sections. The OLGA ABC increases the friction factor in the open hole section, but it is still lower than the mud_calc-pressure loss values. As a conclusion, OLGA ABC generates lower pressure losses.

5.1.5. Annulus area

Two parameters are analyzed when evaluating the annulus area. One is the OD of the DP the other is the hole size. A large drill pipe diameter means a smaller annulus area. How will the diameter of the drill pipe affect the pressure losses of the pumped kill fluid in both the annulus and drill pipe. The drill string has been earlier defined as a 5 ½“ OD in the DP with a 150 m long 6 ½ “ OD in the DC section and 50 meter long 6 ½“ OD in the BHA. The DP sizes analyzed are regular dimensions applied in a normal drilling procedure (Fig.5.7).

OD [in]	ID [in]
3,5	2,764
4	3,34
4,5	3,958
5	4,276
5,5	4,778
6,625	5,965

Fig.5.7 - Normal Drillpipe diameter dimensions

The annulus area will also vary dependent on the last set casing ID. Normal casing designs evaluated in this study are listed in table Fig.5.8.

Casing size [in]	Hole size [in]
7	6,059
9,625	8,5
10,75	9,604
11,75	10,772
13,375	12,259

Fig.5.8 - Last set casing dimensions applied in the sensitivity analysis on annular area

When varying increasing the hole size and decreasing OD of the DP the pressure losses will be minimized (Tab.5.1). The DP dimensions marked with grey is assumed practical applicable in a dynamic killing operation. A OD of the DP less than 5” is not recommended due to the high pressure environment downhole (Oskarsen, 2013).

DP Specification		Pressure loss			
		Hole size = 8,500"		Hole size = 9,604"	
OD pipe [in]	ID pipe [in]	Internal [bar]	Annulus [bar]	Internal [bar]	Annulus [bar]
3,500	2,764	529,8	644,8	529,8	409,4
4,000	3,340	233,3	700,9	233,3	430,6
4,500	3,958	115,1	784,8	115,1	454,9
5,000	4,276	87,8	917,0	87,8	496,1
5,500	4,778	56,4	1140,5	56,4	557,3
6,625	5,965	28,1	2804,2	28,1	868,0

Tab.5.1 – Hole size sensitivity where (Pressure loss left) is for 8,500” hole size and (pressure loss right) is for 9,604” hole size.

5.1.6. Wellbore length

Friction loss is naturally dependent on the measured depth of the wellbore. The well trajectories of the different rig locations will be applied as examples of different wellbore lengths. These trajectories are modeled by the author the same way as the reference relief well trajectory. The pressure losses are combined with TVD to better compare the sensitivities. Pressure loss in annulus will increase when the rig is placed at a long distance from the blowing wellhead (Fig. 5.9).

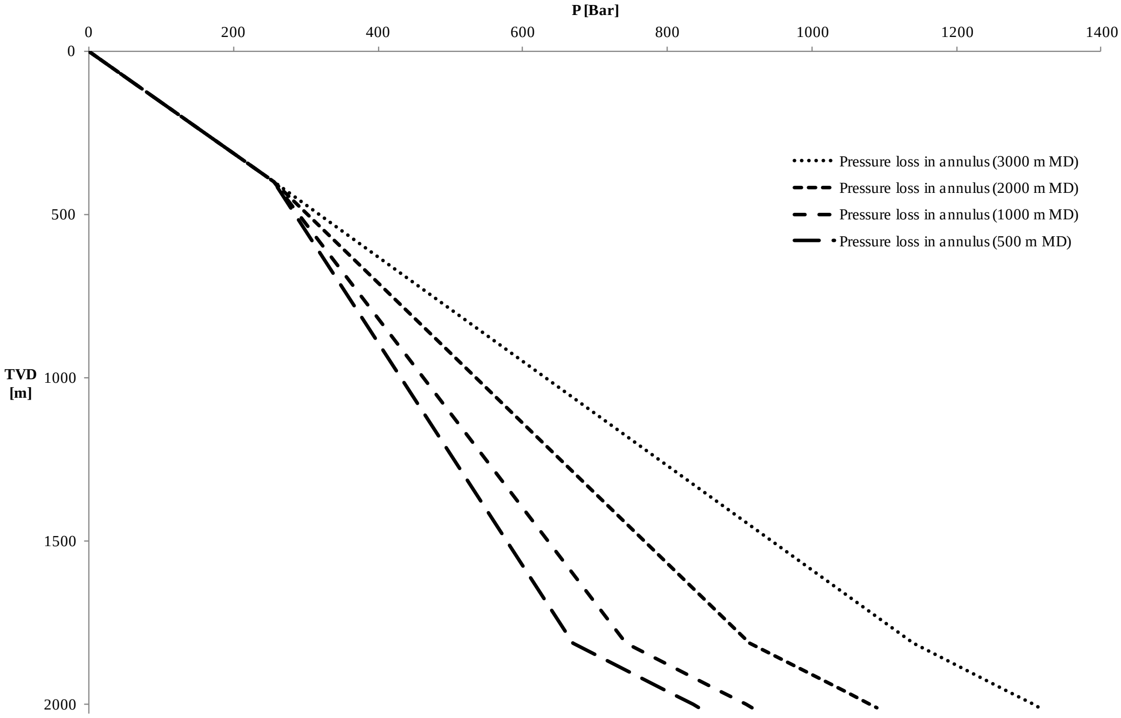


Fig. 5.9 - Pressure loss in annulus compared to TVD.

The pressure loss in DP has a similar trend as in the annulus, but the values are not that significant (Fig. 5.10).

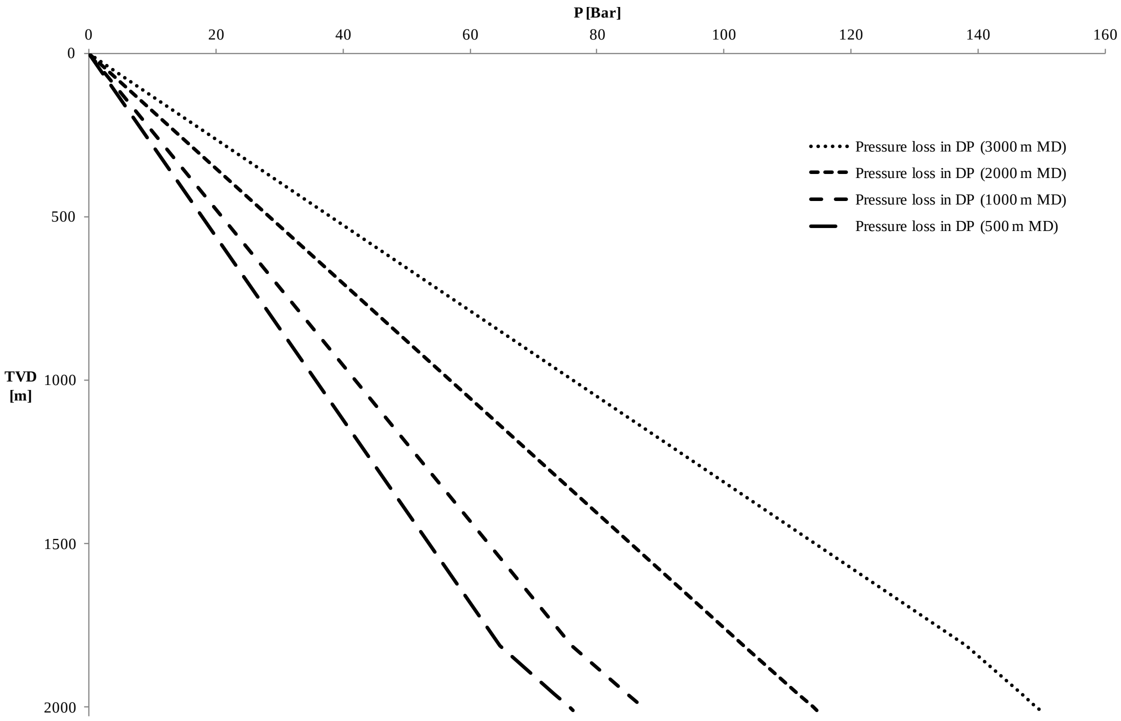


Fig. 5.10 - Pressure loss in DP compared to TVD.

5.1.7. Fluid properties

Density and viscosity of a fluid varies the shear force against the wellbore wall and by that induce friction. The effects of this additional friction will be showcased in this section by use of both OLGA ABC and the mud_calc-pressure loss model. The sensitivity analysis is only performed on the annulus kill fluid due to the killing procedure of only pumping low rate salt water through the drill pipe.

The pressure loss when changing the viscosity shows a large difference between 80 cP and 1 cP (Fig. 5.11). The sensitivity span is quite large and is not very applicable in the discussion of this study. It is applied to showcase the effect of viscosity changes in a larger scale.

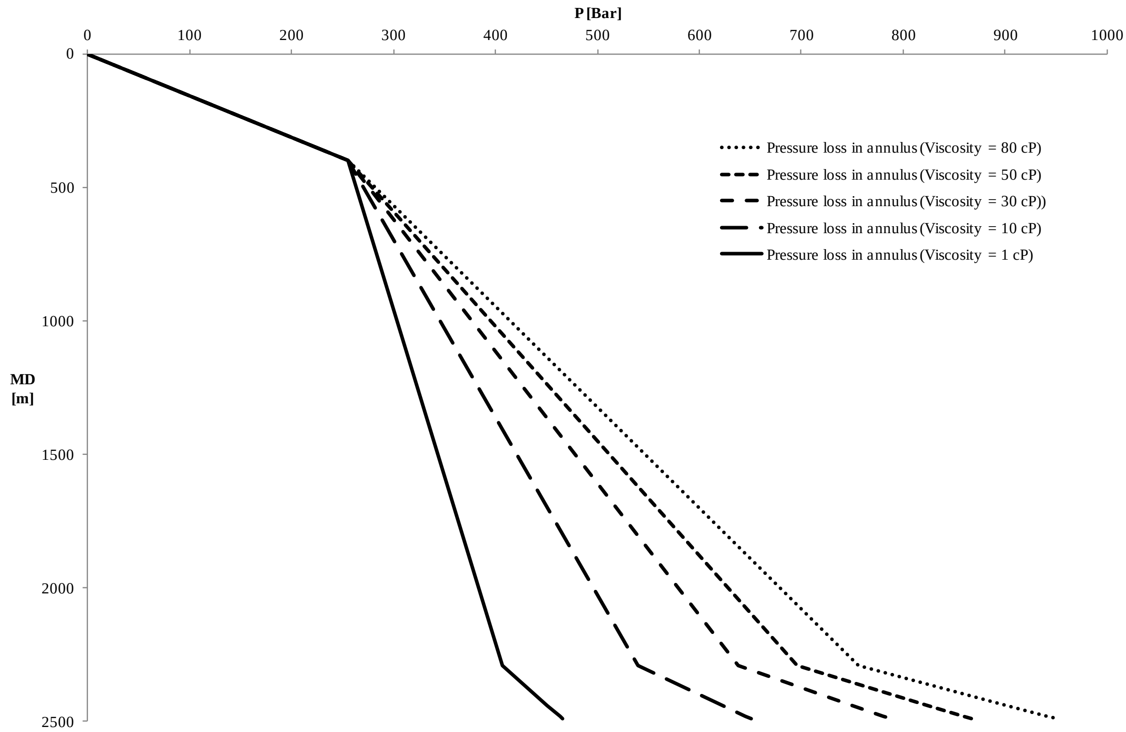


Fig. 5.11 - Pressure loss in annulus due to viscosity changes

The pressure loss sensitivity performed on kill fluid density is not very decisive (Fig. 5.12). There need to be a large difference before making an impact on the killing operation.

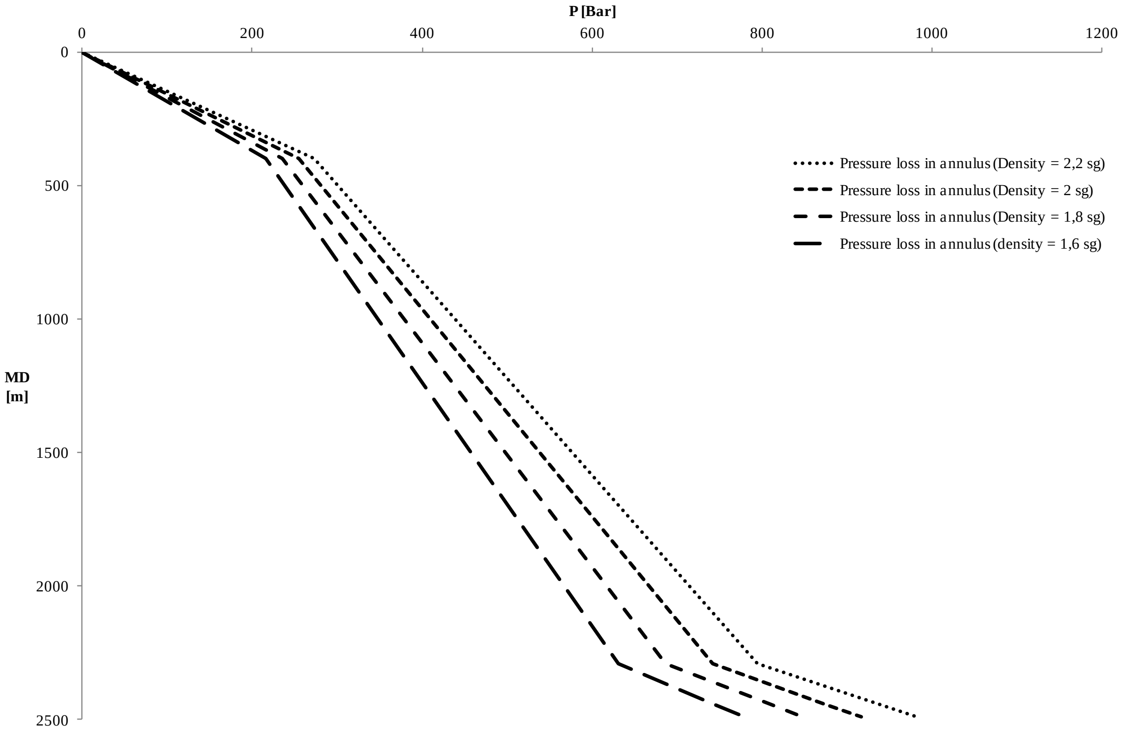


Fig. 5.12 - Pressure loss in annulus due to density changes.

The pressure loss of the DP is not of great significance and therefore irrelevant for this analysis. When applying the different values of density and viscosity in the OLGA ABC simulation software the required kill rates changes (Fig. 5.13-Fig. 5.14).

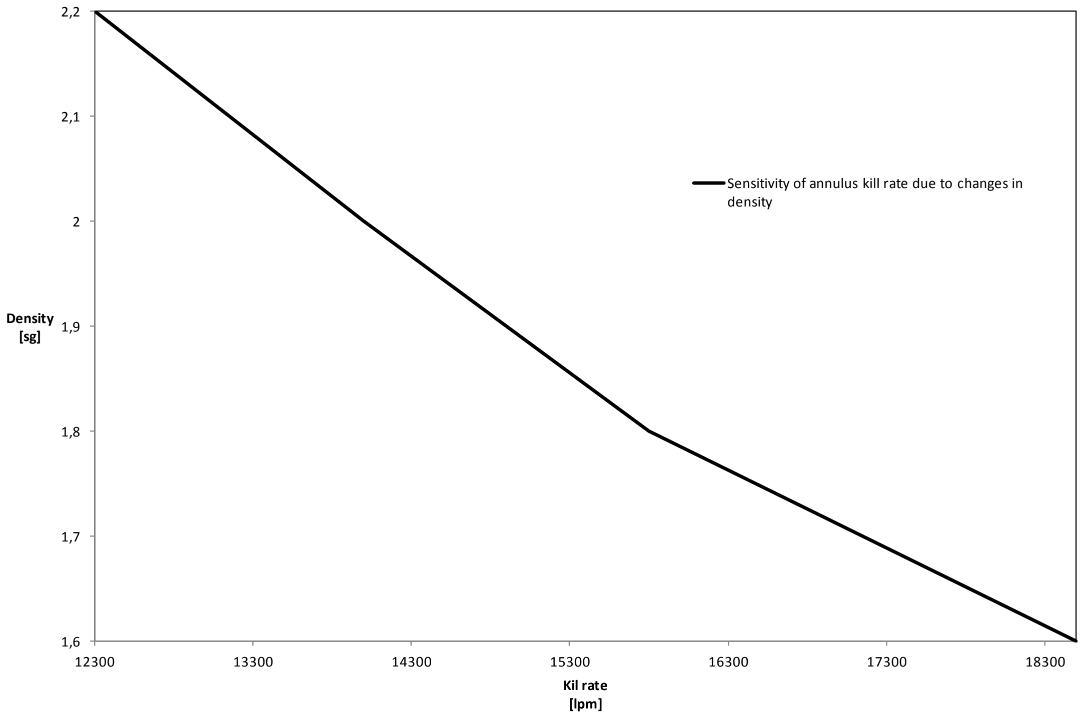


Fig. 5.13 – OLGA ABC simulations on sensitivity of annulus kill rate due to changes in density.

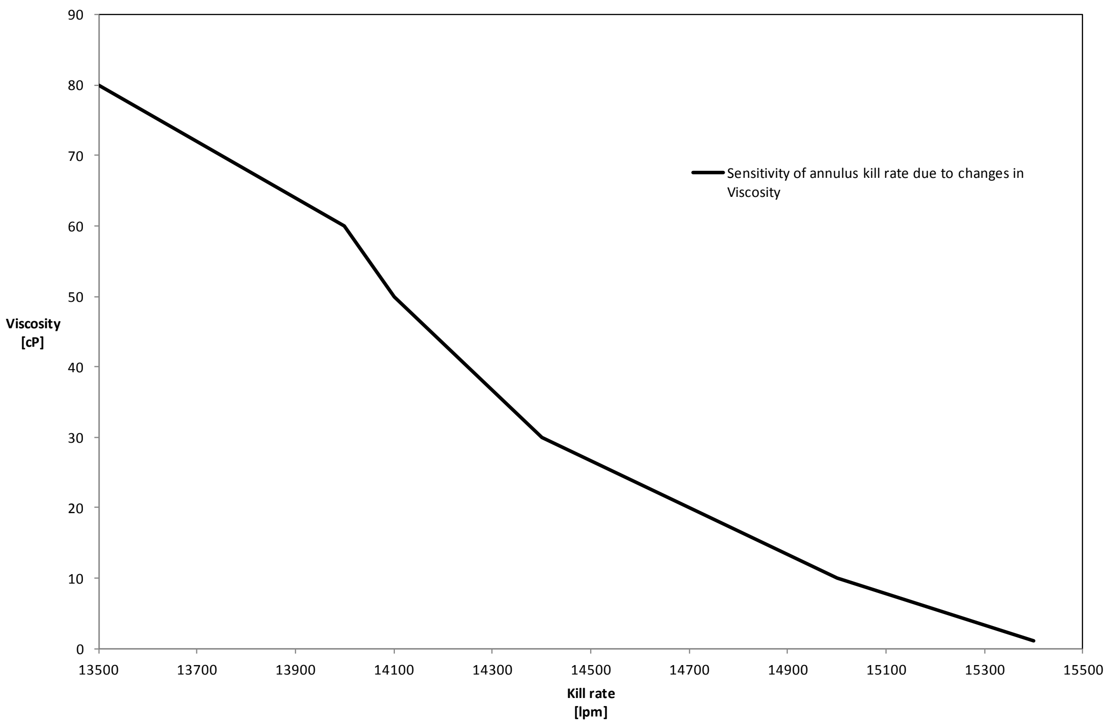


Fig. 5.1.9 – OLGA ABC simulation on sensitivity of annulus kill rate due to changes in viscosity.

5.1.8. Maximization of parameters in a single relief well operation

This section will maximize all parameters to check the capacity of a single relief well. The result and practicality will be discussed later in this study.

The last 200 m of drill string includes a BHA. This section will be minimized to the same ID as the DP and an OD of 6 ½".

The minimum pressure losses from enhancing the parameters evaluated in this sensitivity analysis will decrease the pressure loss by 827 bar (Fig. 5.14). However it will severely increase the pressure loss in the DP due to the decrease of ID. This is not assumed an issue due to the low flow rate initially planned to flow through the DP. The pressure gradient in the enhanced single relief well is very steep due to the large annulus area. The rig placement is not enhanced due to restrictions in regulations of minimum distance from the blowing well. This is not a parameter that can be varied as wanted and has been assumed constant at a 1000 m. In this scenario the pump pressure restriction is not an issue. As shown in the graph a total pressure loss of only 313 bar is experienced through the annulus area. The pump rate needed is still a bit high. OLGA ABC gave showed the need of 12000 lpm through the annulus and 3000 lpm of sea water through the DP to monitor the pressure environment.

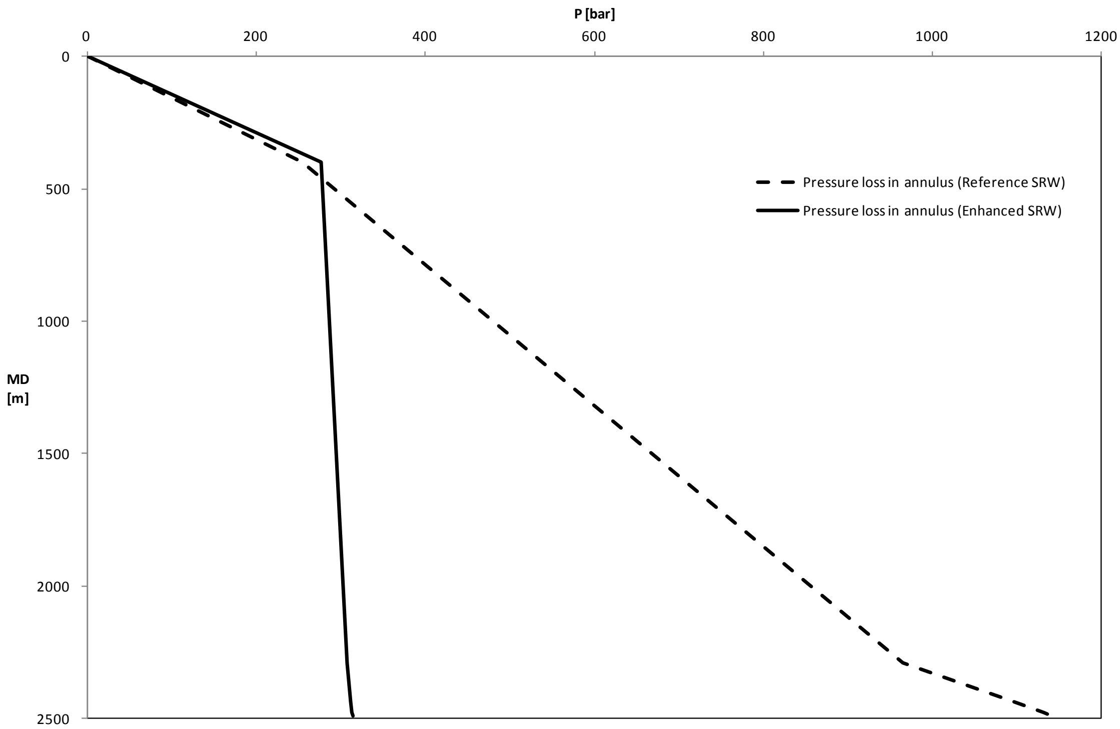


Fig. 5.14 - Maximization of drilling parameters. Input values for density, viscosity, C&K-line ID, OD of DP, rig placement and length of open hole section were 2.2 sg, 80 cP, 4.5 inch, 3.5 inches, 1000 m and 1m respectively.

5.2. DUAL RELIEF WELL DRILLING SENSITIVITY

This section will provide with results supporting the dual relief well option chosen in this study. Sensitivities will be performed on the parameters specifically important for dual relief well operations to support the choice of well design and interception method. The pressure loss in the commingling section is the constraining factor about the Modified Shell method and will be tested in this section and discussed later in this study.

5.2.9. The commingling section

Performing a dual relief well operation contains minimum all the restrictions of a single relief well operation. The main difference and biggest uncertainty is the commingling section, where the two relief wells meet and commingle into one well before intercepting the blowing well 30-50 m MD below. Parameters important for the pressure loss in the commingling section are:

- Hole size
- ID and OD of BHA

Both these parameters are factors that decide the annular space. Sensitivity analysis will be performed on these parameters in the mud_calc-pressure loss model to better evaluate the dual relief method in the discussion. OLGA ABC cannot be applied in this sensitivity due to the restrictions of behaving like a single relief well. The commingling section will only affect the pressure loss in the relief well, and by that decrease the capacity of the dual relief well (MSO). The killing rate will still be the same as in the reference scenario, but it will be need of greater pump pressures.

Hole size:
For the MSO to perform at its best the annular space will have to be maximized. The smallest hole section practically set in a dual relief well operation is a 7” liner with a 6 ½” open hole section. The reference scenario is a 9 5/8” casing and 8 ½” open hole section. The largest hole possible at the reference depth (2010 meter TVD) is 13 3/8” casing and a 12 ¼” open hole section.

BHA specifications:
The outer diameter of the Bottom Hole Assembly will affect the flow rate more than the inner diameter due to a much higher flow rate through the annulus than through the drill pipe. The ID of the BHA is under all circumstances maximized to be practical and will not be of specific importance when evaluating the pressure loss of the commingling section.

The two most relevant hole sizes and BHA specifics are displayed in this study (Fig. 5.15). Pressure losses to the right is a 10 ¾” last casing, while the pressure losses to the left is a 9 5/8” casing.

BHA specification		Pressure loss			
OD pipe [in]	ID pipe [in]	Internal [bar]	Annulus [bar]	Internal [bar]	Annulus [bar]
7	4,5	1,5	93,8	1,5	17,5
6,50	3,75	3,5	43,8	3,5	11,2
6	3,25	6,6	24,6	6,6	7,7
5,50	2,75	13,9	15,5	13,9	5,6
5	2,25	34,3	10,6	34,3	4,3

Fig. 5.15 – The pressure losses to the right is a 10 ¾" last casing, while the pressure losses to the left is a 9 5/8" casing

5.2.10. Well trajectory

The well trajectory of different rig placements have been modeled to measure the pressure losses related to wellbore length. The pressure losses are evaluated in the mud_calc-pressure loss model. The conclusion of this sensitivity analysis is predictable. If the wellbore section is long a larger friction loss will be suffered against the casing wall. By evaluating the magnitude of these pressure losses the practicality of a long dual relief well can be evaluated.

The closest distance a relief rig can be a blowing well offshore is 500 meter. The maximum lateral distance can be 3000 m away from the blowing wellhead. The reference scenario is 1000 m in lateral distance from the blowing wellhead. For simplicity and consistency in the model it is assumed that both relief wells are located the same lateral distance from the blowing well in opposite directions (Fig. 5.16).

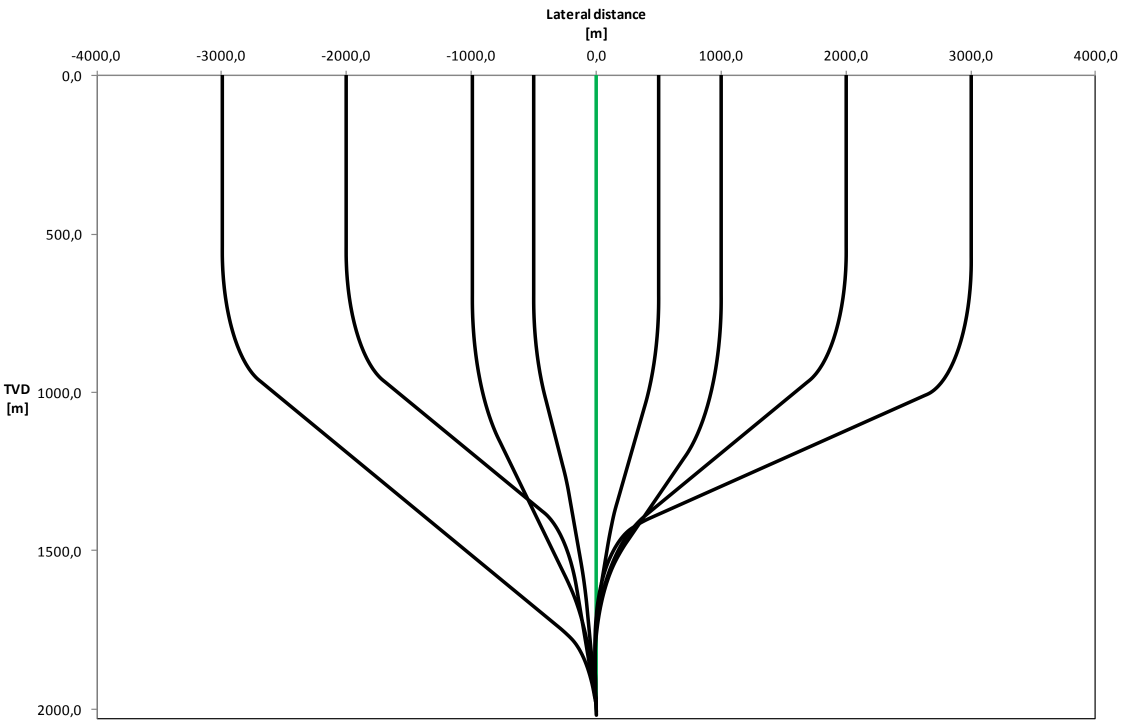


Fig. 5.16 – Schematic of well trajectories for different rig placements.

Due to the much higher flow rate through the annulus sensitivities on the pressure loss in the DP is not presented. The pressure losses in the annulus on different rig placements are given in Fig. 5.17. The pressure loss increases significantly for increasing measured depth of the wellbore. The potential of saved pressure loss when drilling with the smallest wellbore length is almost 300 bar. The well trajectory is not only restricted to the well pressure. The other parameters are discussed together with the theory established from a single relief well killing operation later in this study.

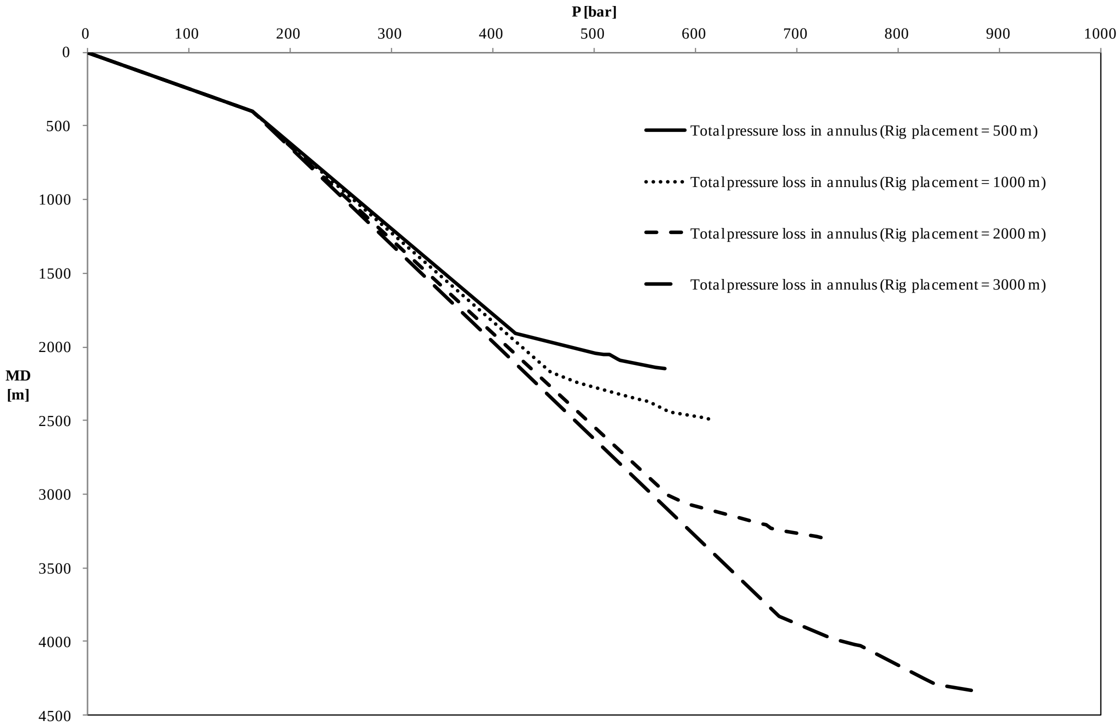


Fig. 5.17 - Pressure losses in the annulus for different rig placements.

6. DISCUSSION

6.1. OVERVIEW

A blowout is referred to as an uncontrollable flowing of reservoir influx. When this is experienced the ranking listed in the flowchart is followed (Fig. 6.1).

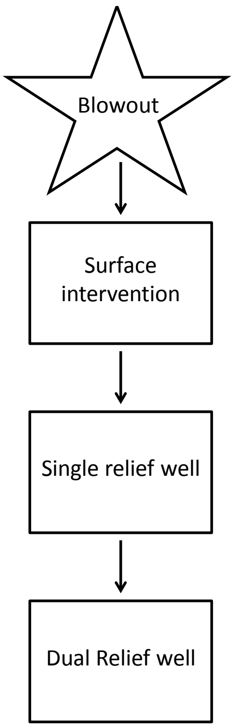


Fig. 6.1 - Flow chart of operational procedures when blowout occurs.

If surface intervention tools are not capable of regaining control of the blowing wellhead a relief well drilling operation is initiated. If a single relief well is not able to produce the required rates needed to kill the blowing well a dual relief well operation must be initiated. The restrictions of a single relief well are rarely exceeded in a real blowout scenario, but it has recently been required by Norwegian regulators (PTIL) that all design of casing programs needing two or more relief wells is rejected for drilling.

As shown in this study a blowout scenario is at its worst when the hole is large and the open hole section is long. If the well hits a deep gas pocket when having set a shallow 13 3/8” casing shoe a potential very large blowout may occur. A scenario like this is the worst to kill in a dynamic killing operation from a relief well. If the blowing well does not have a drill string down hole the killing operation is rarely able to be performed by a single relief well. This is the motivation of doing research on dual relief well operations.

By discussing the results of this study and compare it to the theory and technology applied on single relief wells a conclusion can be made about the feasibility of drilling a dual relief well and successful kill a high rate blowing well. Before concluding a study has been performed on enhancing a single relief well operation. If a single relief well can kill higher rates than initially assumed dual relief well operations may be eliminated. The sensitivities applied on single relief well operations are also transferable to the evaluation of a dual relief well operation and may be of help in the discussion of the dual relief well procedure.

6.2. ENHANCEMENT OF SINGLE RELIEF WELLS

This section will discuss the enhancement of a single relief well with the restrictions defined in the literature, and sensitivity studies performed by the OLGA ABC simulator and the mud_calc-pressure loss model. The main restriction of a single relief well due to restrictions of the drilling rig is maximum pump capacity of 11000 lpm and 690 bar. The goal of these sensitivity analyses is to get within these pump restrictions by applying reasonable adjustments to a normal relief well operation. The conclusions drawn in this section is also applied in the description of the dual relief well procedure.

The parameters evaluated in this study are:

- Choke- & Kill-line diameter and length
- Drill pipe outer diameter
- Wellbore length
- Open Hole section length
- Fluid properties, viscosity and density

6.2.1. Choke- & Kill-line

The C&K-line diameter is a restrictive parameter for many rigs operating on the Norwegian shelf. There are only a few rigs able to operate with the largest possible C&K-line diameter, and they need to be within reasonable transport distance from the blowing well.

The maximum C&K-line diameter is 4 ½” while the minimum in this study is 3”. When combining different diameters within this span together with the length of the lines an overview of the pressure losses can be showcased. The graphics results in a conclusion that it is needed a 4 ½” C&K-line diameter in depths deeper than 200 meter. At the reference water depth of 400 meter the difference in pressure loss between a 4” and a 4 ½” inner diameter is 180 bar. This difference becomes even more severe when the water depth increases.

The maximized and realistic ID of the C&K-line is set to be 4 ½”.

To check the reliability of the pressure loss model applied a similar sensitivity was performed in OLGA ABC. This showed results equal to 88% of the values generated in the mud_calc-pressure loss model. The trends of both models are therefore correct but the behavior of the mud may be different in the two models. The mud_calc-pressure loss model uses the rheology given by Statoil while OLGA ABC uses a rheology from the mud library of the OLGA database. An Msc study performed by Ingrid Haugen in 2011 supports these trends, but gave lower pressure losses than both my studies(Haugen, 2011). The main reason for this difference is the lower flow rate applied (11000 lpm compared to 14000 lpm).

6.2.2. Annulus area

The drill pipe OD is the restrictive parameter when maximizing the annular space. The sensitivities performed on drill pipe OD are not applicable according to the experienced well killers (Oskarsen, 2013). To drill in the challenging environments of a relief well minimum outer diameter of the BHA is 6 ½” and the DP 5”. The OD of the DP is normally set to 5 ½” in most relief well operations due to the high pressure environment down hole. The results of this study gave quite severe pressure loss differences when changing the OD of the DP. By combining the information given in the literature a 5” OD of the DP will give a pressure loss of 917 bar and a OD of 5 ½” will lose 1140 bar due to friction in the well. If possible a 5” DP is preferred but it is not recommended in most situations.

The hole size gave very large differences. The normal hole size when intercepting the blowing well is 8 ½”. This will lead to the same pressure losses as given above and is a fair assumption when maximizing the capacity. There is however possibilities to increase the hole size even further if the formation is strong enough and there is no risk of shale issues related to the large hole size. If only increasing the last set casing from 9 5/8” to 10 ¾” a pressure loss of 557 bar is experienced when using a 5 ½” DP and 6 ½” BHA. If applying this casing design the pump pressure will be within the restricted value.

The maximized and realistic DP specifications and hole size is set to a 5 ½” DP and 6 ½” BHA in a 10 ¾” hole.

The calculations done on the annular area is performed in the mud_calc-pressure loss model and is considered precise due to the fluid parameters applied. The Assumption of single phase water based fluid in the relief well simplifies the fluid behavior and makes the model more reliable.

6.2.3. Wellbore length

The wellbore length is equivalent to the placement of the relief rig. The rig can be either 500 m away or 3000 m in lateral distance of the blowing wellhead. Rig placement affects the wellbore length of the relief well and produces a lot of friction. The rig is usually set at the minimum distance allowed depending on water streams, wind and potential of shallow gas. Usually this distance is 1000 m away from the blowing wellhead. By applying this literature all sensitivities on wellbore length is not applicable when minimizing the pressure loss. Then again a precise evaluation of the pressure loss compared to the measured depth of the wellbore may give the driller permission to drill closer to the well if the situation allows it.

Rig placement enhancement based on the calculations performed in this thesis implies that pressure losses in a well at a lateral distance of 1000 m is close to the losses in arig placement 500 m away from the blowing wellhead. The homing in phase of the relief well is a sensitive operation and demands a smooth transition to enhance the proximity ranging tool’s uncertainty. This can be difficult when drilling from a rig 500 m away due to larger doglegs needed when aiming for the blowing well. Real relief well operations are usually regulated by law to be drilled at a minimum distance of 1000 m from the blowing wellhead. The enhanced and realistic rig placement based on the results of this study is set to be 1000 m lateral of the blowing wellhead.

6.2.4. Fluid properties

Density and viscosity has an important role in the dynamic killing process. Both fluid properties increase the pressure losses when being maximized. However, the maximizing of fluid properties also contributes to a higher friction in the blowing well and enhances the killing operation. When comparing the simulations of the OLGA ABC and results of the mud_calc-pressure loss model maximizing the fluid properties, viscosity and density enhances the killing operation.

Common knowledge amongst well killers is that increased density enhances the killing operation due to larger friction created in the blowing well. According to the mud_calc-pressure loss model the friction increases with turbulence and velocity. This implies that an increase in density will enhance the killing procedure. An increase in viscosity of the kill fluid will also according to the same model increase the friction. The effect of viscosity changes is not as obvious as an increase in density, but it will slow down the blowing gas from percolating through the kill fluid and by that increase the fluid friction. Fluid friction is usually neglected compared to the friction on the wellbore, but it will give a noticeable contribution when being exposed to high rates (Asheim, n.d.)

The pressure losses are calculated in the mud_calc-pressure loss model and the kill rates are found from simulations in OLGA ABC. The pressure losses gained from the OLGA ABC simulations are as shown in the C&K-line calculations lower than the mud_calc-pressure loss. Evaluation of the results is that the models are to be trusted due to the constant equality of the two models based on the C&K-line comparison.

The realistic maximization of density is kept at 2,0 sg. This is due to the potential of fracturing the formation at the last set casing shoe of the blowing well. The realistic maximization of viscosity is also kept at 60 cP due to a low enhancement of the kill rate. By increasing the viscosity the increased pressure loss will decrease the pressure capacity of the pump and is therefore kept at the initial value.

6.2.5. Maximum enhancement of parameters in a single relief well operation

In the presentation of the results there was showcased a minimized pressure loss graph. These calculations was done without any sort of restrictions on the outer diameter of the DP, hole size, wellbore length, fluid properties and open hole length. By applying the restrictions given in the literature study of this thesis and combine it with the results a more realistic enhancement of a single relief well can be established and justified.

Comparison of pressure loss for reference case and enhanced single relief well simulated with OLGA ABC is presented in Fig. 6.2.

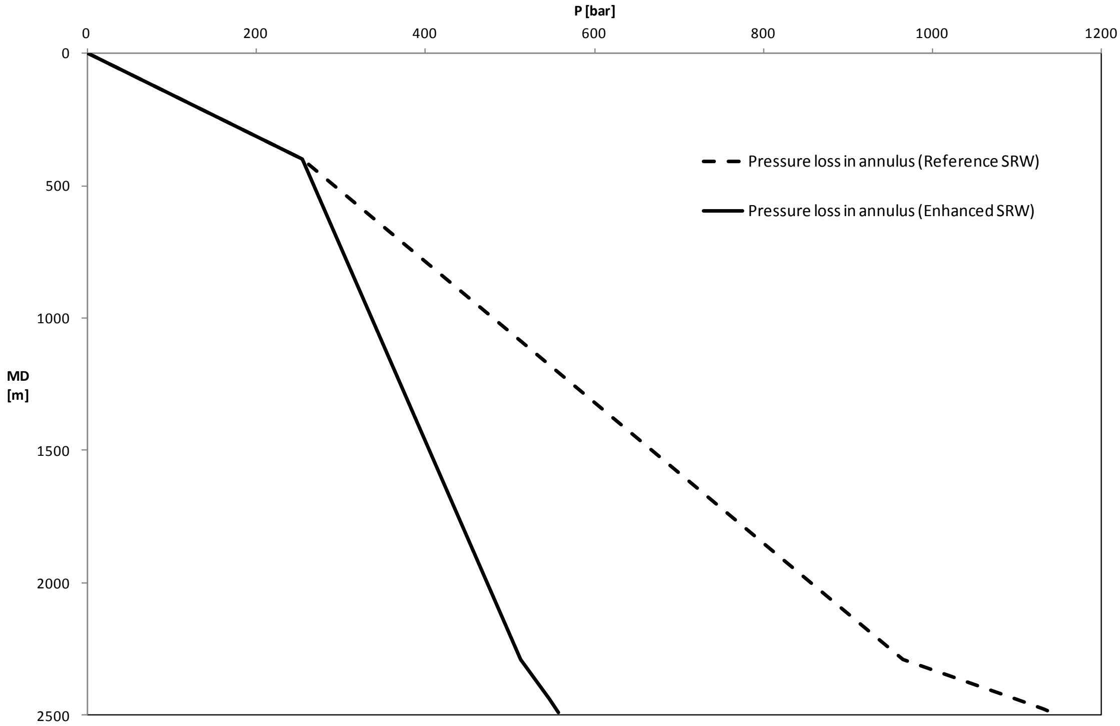


Fig. 6.2 - Pressure loss in reference case (solid line) and pressure loss in enhanced single relief well (dashed line). Input drilling values for the enhanced single relief well were 60 cP, 2,0 sg, 4.5 inches, 5.5 inches, 9.604 inches, 1000 m and 20 m for kill fluid viscosity, kill fluid density, C&K Line ID, annular OD of DP, hole size, rig displacement, OH in relief well respectively.

The only difference from the reference scenario and the enhanced SRW is the hole size. As Fig. 6.2 shows the pressure loss is halved by only increasing the hole size by 1,1 inch. The conclusion of this enhancement implies that if there are guarantees of sufficient formation strength able to handle a 9,604” hole it is recommended. When using this hole size the pump pressure is within range, but the pump rate is still the same as the reference scenario, 14000 lpm. There is however a couple of issues related to this hole size. It is a unconventional casing design. Tripping a 10 ¾” casing through the 12 ¼” hole may be troublesome. There may be need of a larger unconventional intermediate casing as well and this is now a logistic issue.

When evaluating the practical enhancement of a single relief well and combining it with the guidance of the well killers it is obvious that there will still have to be performed a dual relief well operation on the reference scenario applied in this study. If the acquired flow rate shall be lowered the sensitive parameters are viscosity and density. The sensitivity studies done on single relief wells are applicable to the evaluation when combining the different dual relief well operations. Quantified restrictions have been found and together with the literature study a precise discussion can be made on the dual relief well killing procedure.

6.3. PRACTICALITY OF A DUAL RELIEF WELL

This section will describe the entire dual relief well drilling and killing procedure by using the restrictions from both the literature and sensitivity analysis study. During the review of the procedure overall comparisons will be made between the different dual relief well options introduced earlier. The main focus will be between the Statoil and Modified Shell option.

6.3.1. Dual relief well procedure

When using all literature and sensitivities given in this study a procedure for a dual relief well can be predicted and evaluated. The main focus will be on the procedures directly or indirectly related to the pressure loss in the relief well section and friction losses in the blowing well. Before starting the drilling process planning and evaluation of the rig specifications must be performed.

Rig specifications

Rig placement:
The first thing to evaluate before starting a dual relief well drilling operation is where to place the rig compared to the blowing wellhead. The fact that there are two rigs being placed based on the restrictions of shallow gas, under water currents, wind and water depth makes it a bigger challenge to minimize the lateral distance from the blowing well and then having to increase the MD of the wells. The sensitivity analyses done on the rig placement of the single relief wells indicate large pressure losses when the well's measured depth is increased. Before intercepting the blowing well an increased time consumption is suffered and uncertainties of the survey tools are increased due to the steeper deviation in the relief wells.

Rig capacity:
If the blowout magnitude is the same as the reference scenario the two relief rigs does not have to be maximized as in a single relief well operation. Having the kill fluid volume pits and reserve pits twice the size of the estimate needed is sufficient to make sure that the operation will be successful (Oskarsen, 2013). The reference scenario needs of kill fluid (This is difficult to predict in OLGA ABC) (Fig.6.3). During the killing procedure a PSV is always on-site in case of large fluid loss situations or miscalculations in an off-bottom killing operation. This is to work as a a reserve for the reserve mud pit.

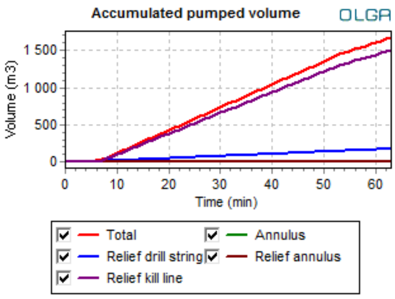


Fig.6.3 - Accumulated pumped kill fluid volume

A necessary measure is to maximize the pump capacity on each rig. The pump capacity of a dual relief well is doubled compared to a single relief well. This is off course given that there are available rigs nearby. The doubled pump capacity implies that a blowout twice the magnitude of the limit of a SRW can be killed.

The C&K-line is as shown in this study a heavy contributor of pressure losses. By using two relief wells instead of one the flow rate will be less than in a single relief well killing operation. The magnitude of pressure loss in the C&K-line is still quite severe if applying an ID of less than 4 ½”. It is concluded with the need of a rig that can handle a 4 ½” ID in the C&K-line(Inderberg, 2013). The MD of the lines cannot be enhanced like other parameters given that it starts at the rig and ends below the BOP on bottom of the sea. It is therefore assumed the same length as the water depth.

Drilling procedure

The drilling operation restricts the amount of pressure loss during the killing operation. It is therefore important to design the well with small MD and large last set casing dimension. When performing a relief well killing operation time consumption during the drilling operation is very important. The casing design is therefore designed not to experience any trouble with borehole stability issues and this often lead to smaller casing dimensions at the bottom of the relief well.

The dual relief well drilling procedure based on the restrictions given in this study is explained in detail below. It is assumed the reference scenario.

- When the first rig arrives the spudding operation is initiated for the main relief well (MRW). The second rig will initiate the supplying relief well drilling operation as soon as possible. Dynamic positioning is preferred due to potential of crossing anchors of the relief wells(Inderberg, 2013). The two relief rigs are positioned at a safe distance between each other and away from the blowing well. Assumed in this study is a 1000 m radius clearance, and both wells are drilled fairly simultaneously (Fig. 6.4).

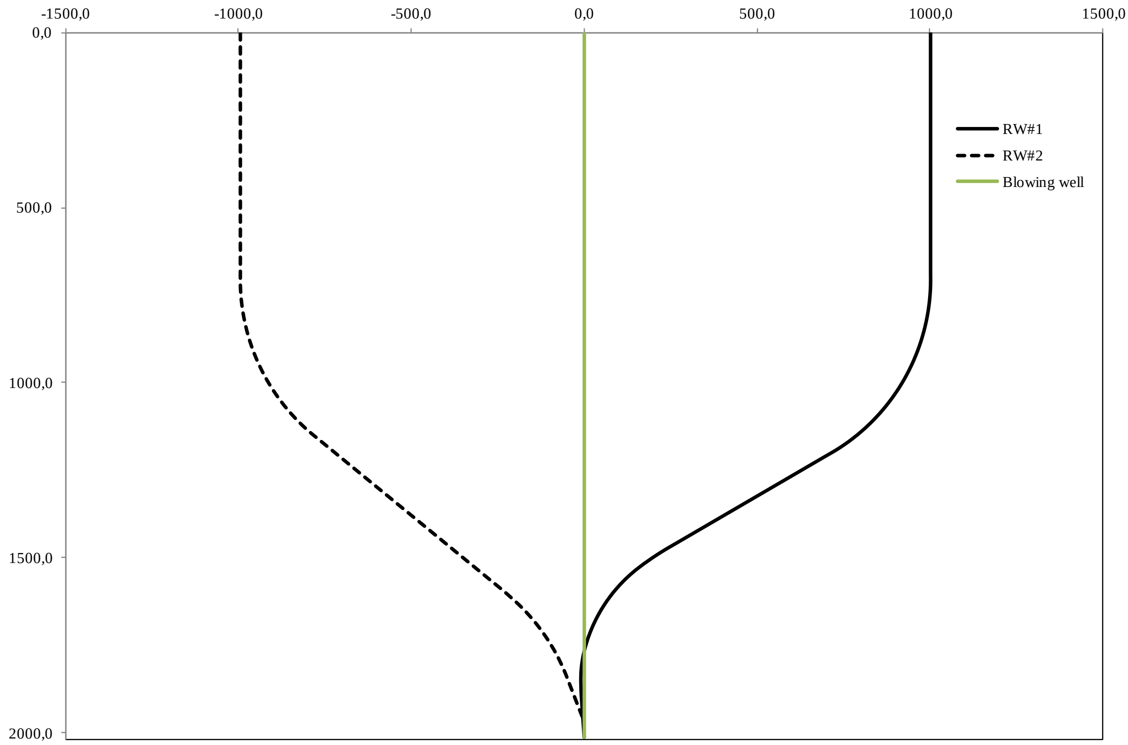


Fig. 6.4 - Modified Shell Option Well Trajectory.

- The drilling procedure of both relief wells are assumed fairly equal until reaching the proximity ranging phase. It is planned that the MRW reaches the blowing well before the supplying relief well.
- Assuming an average North Sea formation and the drilling of the Saga blowout in 1988 the kick of point (KOP) is initiated at 750 m TVD from the RKB (Leraand. et al, 1992). Usually the KOP is below the surface casing, but there is normal directional drilling technology available that can initiate the KOP at much shallower depth (Markle. et al, 1987).
- The Dogleg is set to 3 degrees/30 m from 750 m MD to 1320 m MD. This is a normal dogleg and it builds up to a deviation of 60 degrees.
- While Drilling at 60 degrees the MWD tool is keeping track of the position from the blowing well and utilizes the directional tool to keep the deviation constant. The MWD has a uncertainty larger than a proximity ranging tool, but it is assumed to be precise in terms of keeping track of the well path.
- During the constant inclination section a small azimuth change is applied to make sure that the blowing well is not hit when marking it later in the drilling process.
- The MWD section I preferred to end at least 50 m MD after the intermediate casing shoe, 13 3/8”. This is due to start of the proximity ranging phase and disturbance of the magnetic field in the proximity ranging tool. The intermediate casing is set at 1800 m MD or 1450 m TVD due to fear of hitting the same reservoir as the blowing well. This is far before the proximity ranging tool phase that is initiated at 2150 m MD or 1770 m TVD of the MRW.
- The first real challenge of drilling a relief well occurs about 30 m of lateral distance from the blowing well. The proximity ranging process involves a lot of Logging tools tripping in and out. Vectormagnetics™ are usually the survey

contractor used when drilling relief wells. The proximity tools are very accurate, but demands many runs before the blowing well is locked-in position.

- The MRW is drilled 10 m past the blowing well while performing several surveys when passing the blowing well at a different azimuth. This phase is performed in every relief well operations drilled today (Oskarsen, 2013).
- The homing-in phase is a low deviation and time consuming operation. It starts 10 m lateral from the blowing well and has an attack angle of 4 degrees from 2340 m MD or 1865 m TVD to 2490 m MD or 2014,6 m TVD. The homing-in phase of the drilling operation is the most time consuming and difficult part of the relief well drilling. While approaching the interception point, which is located 10 m below the last set casing shoe, the supplying relief well is being cased and put "on-hold" only meters away from the MRW at 1970 m TVD or 2370 m MD.
- When only 1 m of lateral distance from the blowing well a 9 5/8" casing is set in the MRW. This will make an OH-section of 10 m MD. When the casing is set the supplying relief well can use proximity ranging tools to precisely detect the MRW. The Supplying relief well will due to potential magnetic disturbance of the survey tools not intercept the MRW until right before the MRW has the position of the blowing well locked-in.
- The last interception phase is precisely predicted by the proximity ranging tools and can be drilled blindfolded. The normal procedure is to apply the ranging tool, Wellspot at Bit (WSAB). Due to the disturbance from the last set casing shoe of the MRW the normal active ranging tool, Wellspot™ cannot be applied (Oskarsen, 2013).
- When the MRW is 1 m MD from the blowing well the milling process is initiated between the supplying relief well and the MRW. (Oskarsen, 2013)[4].

Interception process

- The supplying relief well intercept the MRW at 1970 m TVD and the relative attack angle of 17,5 degrees. The attack angle is assumed in the well trajectory created for this study. The main reason for choosing this attack angle is primarily to enter the MRW most efficiently, but with a relatively low deviation.
- The interception method is assumed a normal milling operation through the casing of the MRW. Another potential method considered using is the whipstock procedure. If the formation is weak this may be a more stable method to enhance the borehole stability from the OH-section.
- When the MRW and supplying relief well has commingled the supplying relief well drillstring is pulled back behind the last set casing shoe. There is a constant flow of mud being pumped through the string to keep the interception hole from collapsing. The C&K-line of the supplying relief well is made ready to pump kill fluid through the annulus.
- The interception process into the blowing well is initiated as soon as the supplying relief well is under control and ready to pump fluid through the annular space. The drillstring of the MRW is switched to the milling string with a BHA and DC outer diameter of 6 ½" and DP outer diameter of 5 ½". When the MRW experience contact with the blowing well, fluid is being pumped through both the MRW and supplying relief well annular spaces to avoid loss of the hydrostatic columns and create the sufficient kill rate.

[4] Statement also confirmed by (Inderberg, 2013)

Killing operation

- The kill fluid rates are 7000 lpm through both the MRW and supplying relief well's annulus while 3000 lpm of sea water is being pumped through the DP of the MRW. Fluid is pumped through the drillstring to monitor the pressure environment downhole. Sea water is applied due to the easy access and unlimited resources.
- The pressure loss in the MSO is quite similar to two single relief wells. The main difference is the 50 m MD commingling section. This section have twice the rates of a single relief well and creates a pressure loss of 44 bar compared to 2 x 14 bar in two single relief well. Given that the pressure loss is almost twice as large in the 50 m MD commingling section implies that the annular space must be maximized in the MSO. However if the reference scenario of 8 ½" hole and 6 ½" BHA is applied the pressure loss is negligible compared to the total pressure loss. It is not recommended by any of the well killers interviewed in this study to have a BHA OD less than 6 ½" and a DP OD less than 5 ½".
- The commingling section can be compared to a multilateral well. There is done much research on monitoring production from two different reservoirs and commingled into one pipe. There will be a pressure-while drilling (PWD) tool in the BHA of the supplying relief well to monitor the pressure environment at the interception point of the commingling section additionally to the low rated sea water through the drillpipe. This is mainly to make sure that no cross flow between the two relief wells will occur(Zhakarov. et al, 2007).
- The commingling section also has a 10 m MD OH section. The section is evaluated as negligible due to the very short length. It is not assumed a decisive factor when designing the well.
- A great concern when using high rates to kill a blowing well is risk of formation fracture at the last set casing shoe. The LOT tests preformed when drilling the blowing well must be carefully evaluated to avoid exceeding the fracture gradient. This is done by adjusting the pump pressure as soon as the flowing bottom hole pressure has exceeded the reservoir pressure and stopped the influx.
- When regained control of the influx from the reservoir the gas is percolated out through the blowing wellhead and the well shut in when the amount of free gas is equal to zero. Shutting in the wellhead with a capping stack is a normal procedure when being able to approach the wellhead with the tools.
- Plugging the blowing well and relief wells with a cement plug is the usual way of abandoning the site.

6.3.2. Evaluation of a dual relief well

The procedure of the MSO dual relief well has showcased the practicality and possibility of a dual relief well to be performed based on the knowledge of single relief well drilling/killing and calculations performed on relevant parameters. A dual relief well is very much feasible, but demands planning and evaluation of the formation to be able to successfully perform the operation within a reasonable amount of time. Borehole stability issues like swelling shale, hole cleaning and key seating are issues that can jeopardize the entire operation(Holt, 2012). The proximity ranging and homing-in phase is also a large time consumer. All these combined can make the dual relief well operation not suitable to kill a well and other killing methods should be applied. However if a well blows with the magnitude equal to the reference scenario, there is not much choice apart from drilling two relief wells with the technology of today.

Discuss the dual relief well options

The MSO and Statoil option is the two dual relief well methods available today. If a blowout occurred today, a method must be chosen. The two methods both have positive and negative side effects related to different situations. The two methods will be combined based on survey restrictions, interception method, relief well pressure losses, killing reliability, interception method and pump capacity.

The survey procedures are equal during the MWD phase. When approaching the proximity ranging phase the Statoil option will experience some challenges unknown to the MSO. The Statoil method has one upper relief well (URW) and one lower relief well (LRW). The URW set the last casing first while the LRW is on-hold above the casing depth. The LRW then set the casing at a lateral distance further away than 40-50 m below the last set casing shoe due to risk of disturbance of the magnetic field from the last set casing of the URW. The two relief wells then have to intercept the blowing well within a short time span. When the upper relief well intercept the blowing well it immediately starts to pump sea water to avoid getting influx inside the annulus. If one of the rigs experience problems a potential hazard may occur to the relief wells especially if the process of pumping kill fluid has been initiated, and there is a risk of using all reserves. The survey procedure of the MSO is a much more simple process due to the fact that the relief wells do not have to be drilled simultaneously at close distance when approaching the blowing well. This makes the MSO a more efficient option according to the interception- and proximity ranging tool phase.

The capacity of the options is the same, but the pressure loss differences increases the pump pressures needed when applying the MSO. The only difference in pressure losses between the two options are the commingling section and by evaluating the sensitivities performed in this study the increased pressure loss from this section is of a very small scale and did not affect the killing operation (Fig. 6.5).

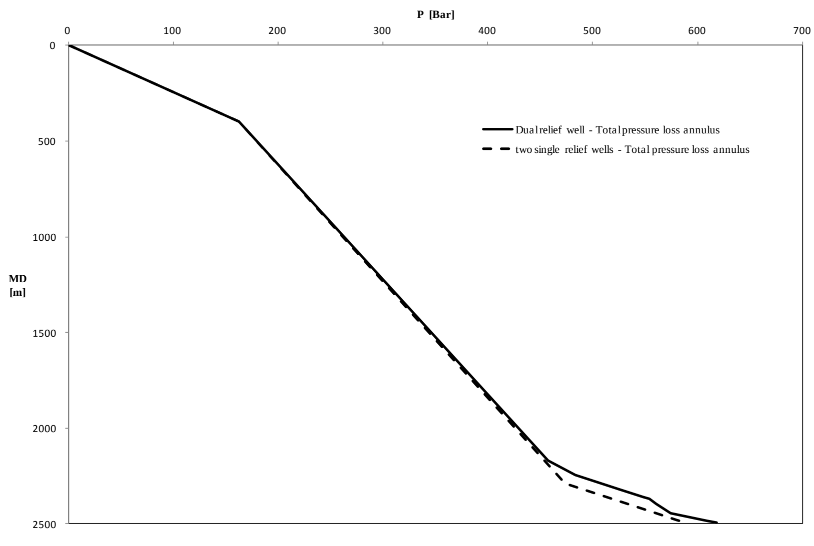


Fig. 6.5 -Total pressure loss in annulus of MSO and two single relief wells.

The two options are both very challenging to perform and heavy planning will have to be performed in both situations. By combining the capacity of the options there is not much of a difference, so the decisive phase when choosing a dual relief well option is based on the experience from the crew performing the operation. Both options are still theoretical but evaluated and planned with experience present today.

The proximity ranging phase, including the interception, is seen as the most challenging and time consuming part of a dual relief well operation. Intercepting with one well instead of two is concluded as the most comfortable and gives the highest success rate based on the experience of the interviewed well killers and operators. Intercepting with one well does not demand the strict communication between the relief rigs as when intercepting with two wells.

7. FUTURE WORK

The author encourages future studies to include fluid behavior in the commingling section. The OLGA ABC simulator cannot handle two relief wells killing a blowing well, hence the results of the dual relief well killing operation is not accurate in this study. Assuming the commingling section not creating large pressure losses and cross flow challenges will have to be clarified by experiments or more applicable simulation software. Additionally the borehole stability challenges during both the drilling and killing operation has only been taken into account when performing sensitivity analysis on indirectly dependent variables. Borehole stability variables that in future work must be evaluated are temperature, shale effects, hole cleaning, collapse and fracture gradient. At last the amount of tripping operations is a key factor of time consumption. Future study on enhanced survey tools, both LWD and MWD can decrease the time used to drill the relief wells.

8. CONCLUSION

Pressure losses and kill rate changes on relief wells have been studied and tested to evaluate a dual relief well drilling operation. A pressure loss model has been applied to compare the pressure losses of both single and dual relief well options and the killing operation have been simulated by use of OLGA ABC. All results have been used to evaluate the practicality of the dual relief well option, Modified Shell option. The following conclusions have been drawn from the results:

- By increasing the last set casing diameter by 1,1” the pressure losses of a single relief well operation is almost halved compared to the reference scenario. The pump rate required is the same as the reference scenario due to no change of killing parameters like density and viscosity. This concludes that a single relief well is not *practically* able to kill the reference scenario blowout.
- The Choke & Kill-line must be 4 ½” ID to avoid large pressure losses when pumping high rate kill fluid to the annulus.
- The pressure loss of the open hole section is not a restricting factor when drilling a relief well. The potential hazard is if the formation is weak and borehole stability issues occur.
- The fluid properties applied are maximized based on the fracture gradient in the blowing well. A density above 2,0 sg is not to recommend when killing the reference blowout. The viscosity is not an important parameter when enhancing the killing operation. The viscosity will only play a major role in decreasing the friction loss in the relief wells.
- The commingling section of the dual relief well evaluated in this thesis will, according to this study and the models applied, give a negligible pressure loss compared to two single relief wells.
- The survey and interception operations of the modified shell option are easier to handle than the Statoil option. Due to the simplicity procedure of drilling the two wells into each other before intercepting the blowing well the modified Shell option is preferred as the safest drilling option according to this study.
- The killing operation is fairly the same for both dual relief well options after it has been initiated. The pump capacity is the same.

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APPENDIX

In this section additional information, plots and models have been included to provide the reader insight in the simulations carried out in this study.

#1
Relief rigs capacity.

#2
Second order reservoir pressure loss.

#3
Leak off test applied in this thesis.

#4
OLGA ABC simulation input values

#5
Mud_calc-pressure loss: Excel model overview

#6
Well trajectory model: reference scenario

A.1 RIG CAPACITIES

	Active pits	Reserve pits	Storage tanks	Total
Rig	**m^3**	**m^3**	**m^3**	**m^3**
Spitsbergen	254	545	930	1730
Barents	254	545	930	1730
Hercules	272	430	1837	2539
Phoenix	400	510	964	1874
Atlantic	1043	763	918	2724

Fig A.1 - Rig capacities collected from offshore.no

A.2 SECOND ORDER PRESSURE LOSS

The difference between linear and Forcheimer inflow performance from the reservoir to the blowing well is illustrated in the graph below. This is again directly dependable on the IPR (Asheim, H. 2011)

$$p_w = p_R - \frac{1}{J} q_o - F q_o^{\ 2}$$

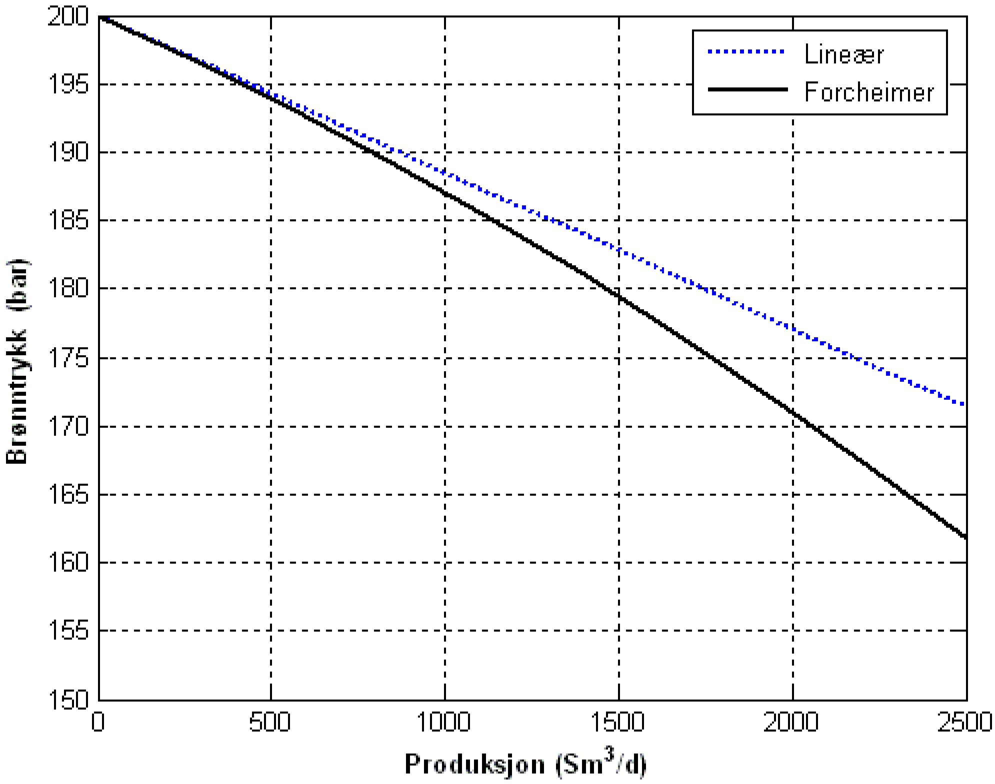


Fig A.2 - Illustration of forcheimer's equation vs linear production.

A.3 LEAK OFF TEST

A leak off test (denoted LOT) is a test done to estimate the fracture gradient at a specific point in the well. The test is always performed at the last set casing shoes to estimate the fracture pressure at the most critical point of the well. If light weighted fluid percolates up the open hole section a pressure increase will be experienced when the light weighted fluid is compressed. In a killing situation large rates may increase the hydrostatic pressure to a critical level, and experience fracture at the last set casing shoe or below.

The LOT is performed when the well is shut in. Fluid is being pumped up the annulus at high rates to gain the graph sketched (Fig A.3).

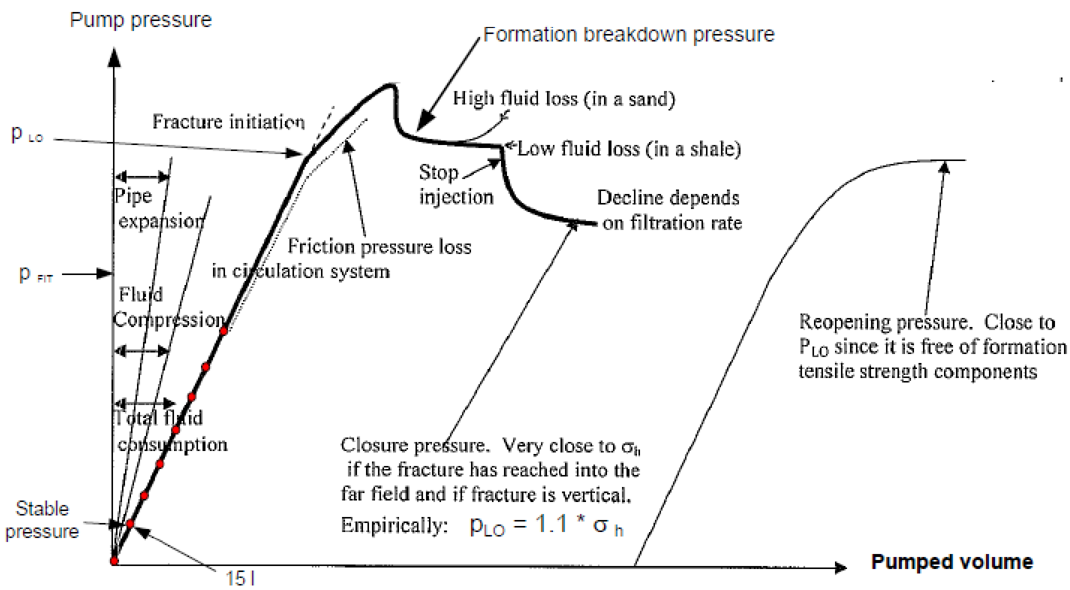


Fig A.3 - Schematic of a traditional Leak Off Test(Skalle, 2011).

This study has assumed different fracture gradients, with reservations that the kill fluid does not exceed an unrealistic density. The LOT below is taken from a similar environment as the blowout case in this study. It is therefore reasonable to use these values in the main well.

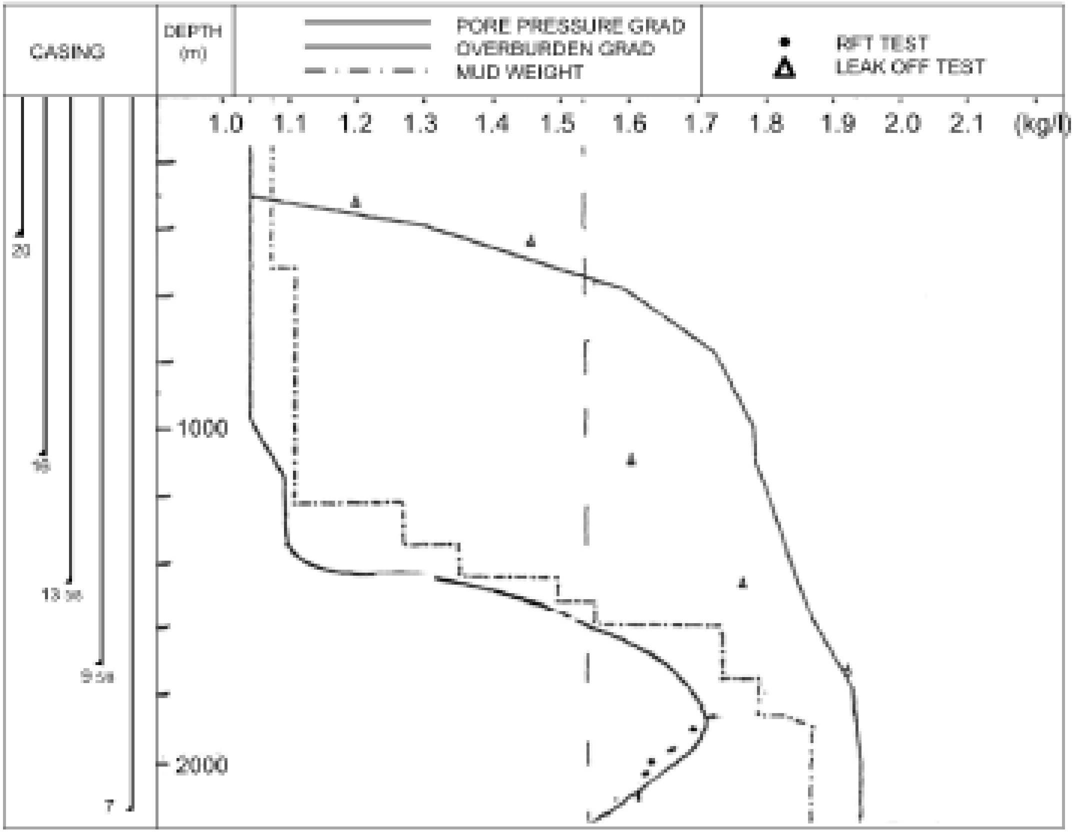


Fig A.4 - Illustration of casing design based on pore pressure (Skalle, 2011)

A.4 OLGA INPUT PARAMETRES

Here are the input parameters used in the OLGA simulation.

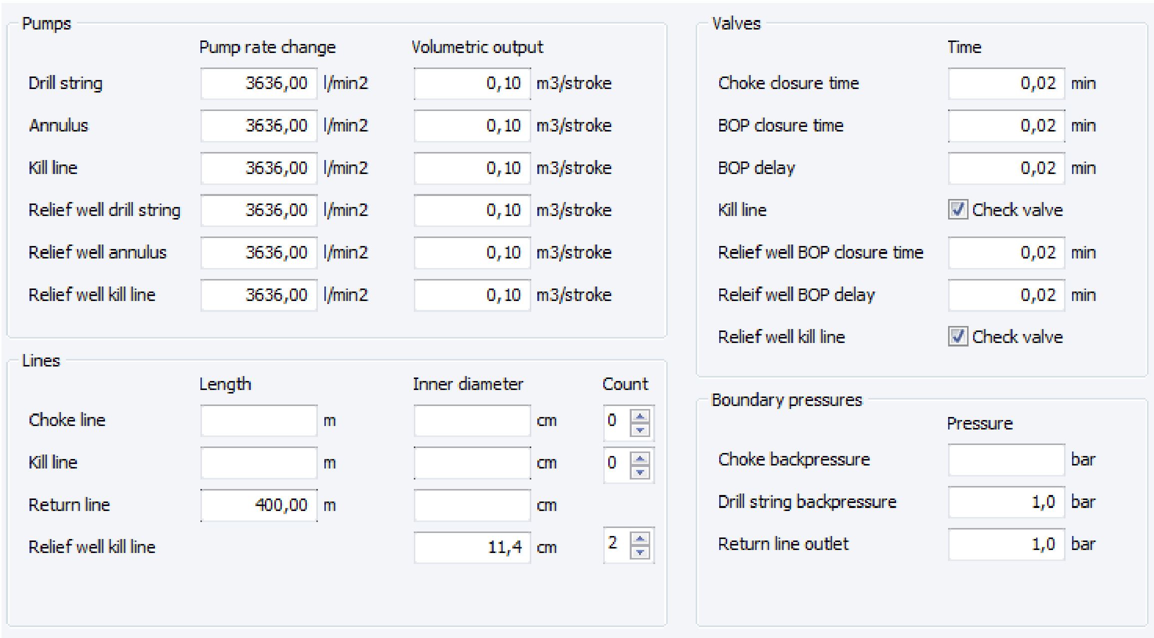


Fig A.5 - Surface equipment input

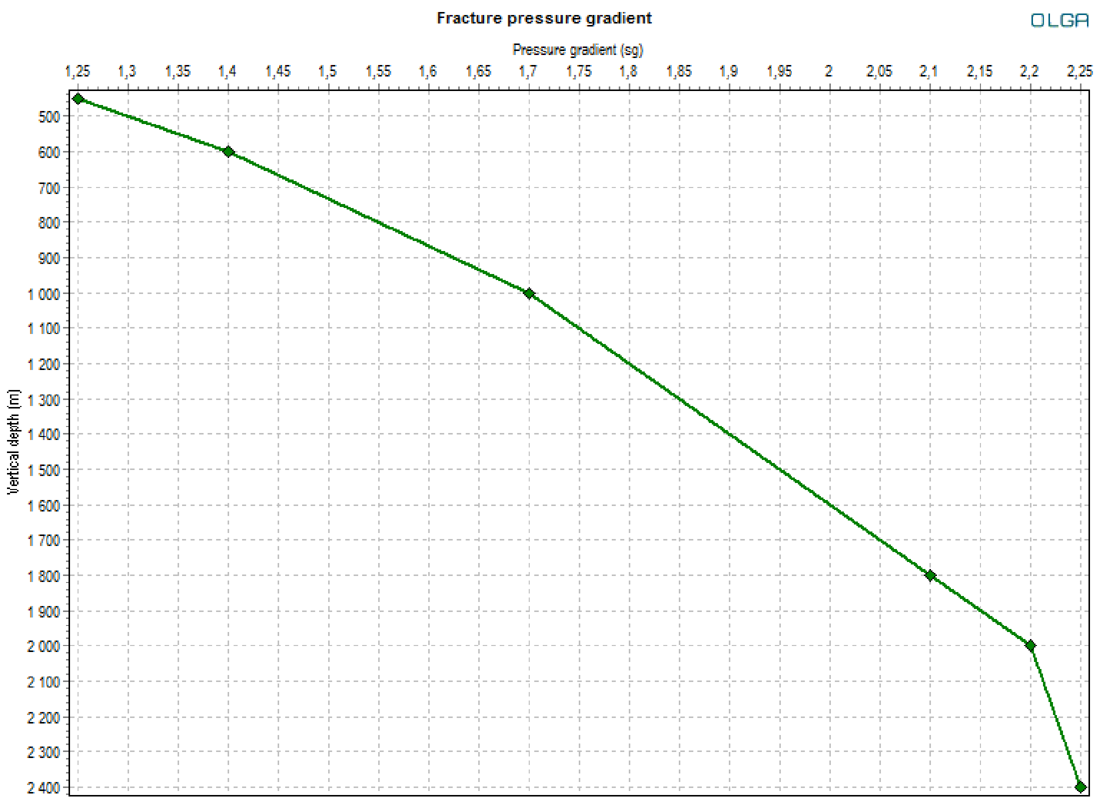


Fig A.5 – Fracture pressure gradient

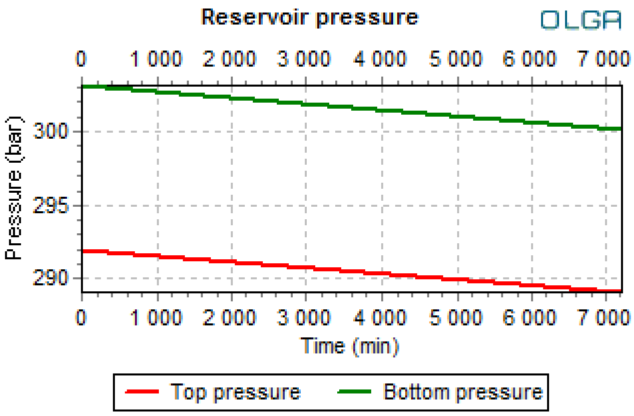


Fig A.6 - Reservoir pressure decay

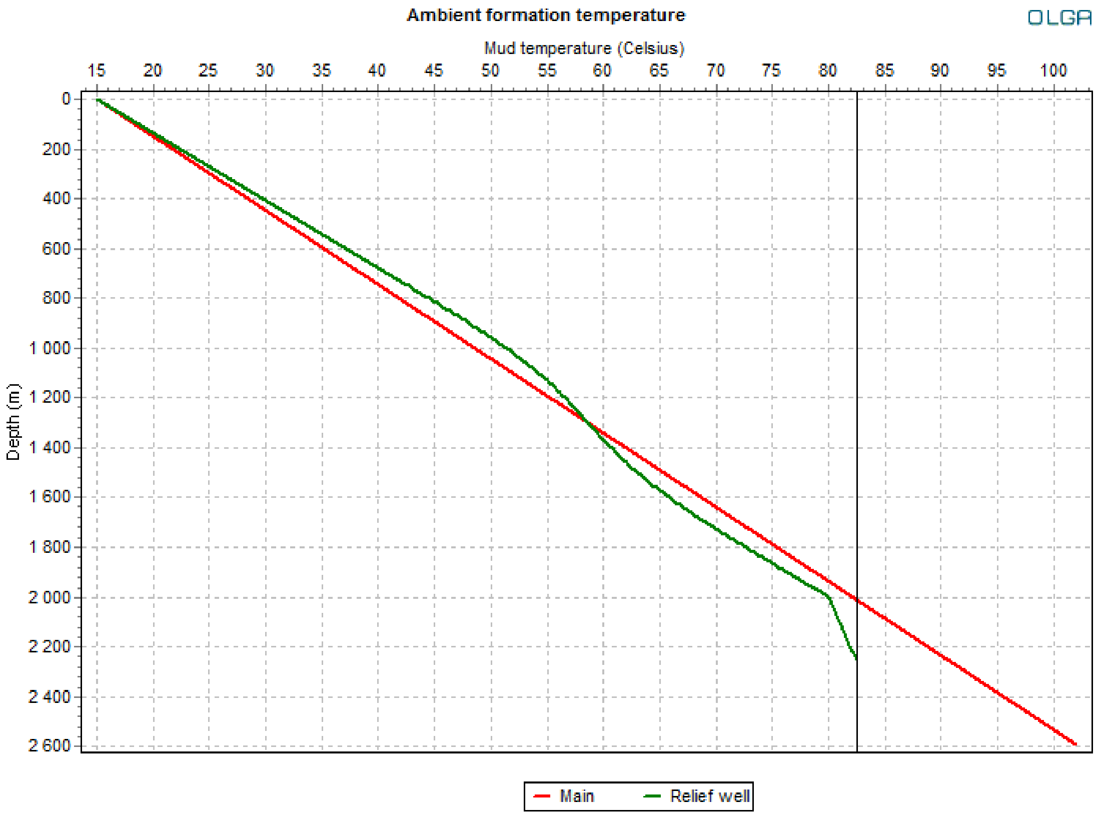


Fig A.7 – Ambient formation temperature

A.5 MUD_CALC-PRESSURE LOSS: EXCEL MODEL

M U D C A L C

Bosque B-5

PRESSURE DROP AND ECD CALCULATIONS

Versjon 0.0

		8,5	HOLE
	Water+RKB	400	m

SECTION:	From: (MD)	To: (MD)	To: (TVD)	Length: (m)	OD Hole: (in)	OD PIPE: (in)	ID PIPE: (in)
C&K-line - 4 1/2"	0	400	400	400	-	5,50	4,50
CSG - 5 1/2"DP	0	2290	1815	2290	8,50	5,00	4,24
csg - 6 1/2"DC	2290	2440	1960	150	8,50	6,50	3,75
csg - 6 1/2"BHA	2440	2480	2000	40	8,50	6,50	3,75
OH - 6 1/2" BHA	2480	2490	2010	10	8,50	6,50	3,75

	Fann: (rpm)	An vel: (m/s)	Visc: (cP)	Cuttings: (mm)	Regime	Pres. Drop Internal:	Annulus:	
C&K-line - 4 1/2"	-	-	-	-	TURBULENT	-	254,7	bar
CSG - 5 1/2"DP	772,5	9,75	72	384	TURBULENT	76,1	487,3	bar
csg - 6 1/2"DC	2129,2	15,35	53	482	TURBULENT	8,6	131,3	bar
csg - 6 1/2"BHA	2129,2	15,35	53	482	TURBULENT	2,3	35,0	bar
OH - 6 1/2" BHA	2129,2	15,35	53	482	TURBULENT	0,6	8,8	bar
ANGLE @ BHA:	4	Deg		**TOTAL PRESSURE-DROP**		87,6	662,4	bar

READINGS

FANN REOMETER:				BIT-DATA:	
R	600	:	156	No Nozzles #1:	1
R	300	:	96	Size X/32":	104
R	200	:	72		
R	100	:	44		
R	60	:	31		
R	30	:	19		
R	6	:	7		
R	3	:	4		

Gel :	0	Pa
PV:	60	cP
YP:	17,3	Pa

annulus Mudweight :	2,00	SG
DP Mudweight	1,01	SG
Annular Pumpe rate :	14000	l/min
DP pumpe rate:	3000	l/min
Liner Size :	6	in
Pumpestrokes :	883	s/min
Diameter open hole :	8,5	in

Fig A.8 – Mud_calc-pressure loss: Pressure loss:

A.6 WELL TRAJECTORY MODEL: REFERENCE SCENARIO

Well trajectory of main relief well: *Reference scenario*

TVD Reference RTE/MSL: 40.00 m

Depth Reference is the Rotary Table

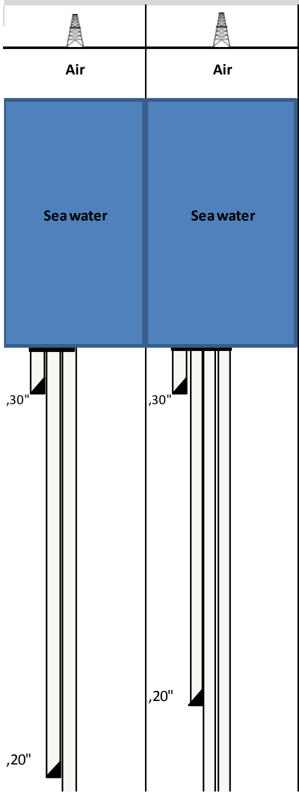
Last set casing TVD is equal in both relief wells. This because of the potential of an eqaul formation strength.

$TD_{Last\ set\ casing}$	2000,0	m
$TD_{Interception}$	2010,0	m

Initial Rig #1 placement	852,7	m
Distance between BO and int point	**-10,0**	m
Rig #1 placement	**1000**	m
Interseption point	1000,0	m
Interseption point solver	73,8	-
Interception TVD	2010,0	m

Blowing well design | **Relief well #1 design**

m



MD	SECTION	INC.	AZIM.	TVD		N/S	HD	DOGLEG	TURN ANGLE
m	#	deg	deg	m		m	m	deg/30m	deg/30m
0,0		0,0	0,0	0,0		0,0	0,0	0	0
0,0	1	0,0	0,0	0,0	2010,0	0,0	0,0	0	0
30,0	1	0,0	0,0	30,0	1980,0	0,0	0,0	0	0
60,0	2	0,0	0,0	60,0	1950,0	0,0	0,0	0	0
90,0	2	0,0	0,0	90,0	1920,0	0,0	0,0	0	0
120,0	2	0,0	0,0	120,0	1890,0	0,0	0,0	0	0
150,0	2	0,0	0,0	150,0	1860,0	0,0	0,0	0	0
180,0	2	0,0	0,0	180,0	1830,0	0,0	0,0	0	0
210,0	2	0,0	0,0	210,0	1800,0	0,0	0,0	0	0
240,0	2	0,0	0,0	240,0	1770,0	0,0	0,0	0	0
270,0	2	0,0	0,0	270,0	1740,0	0,0	0,0	0	0
300,0	2	0,0	0,0	300,0	1710,0	0,0	0,0	0	0
330,0	2	0,0	0,0	330,0	1680,0	0,0	0,0	0	0
360,0	2	0,0	0,0	360,0	1650,0	0,0	0,0	0	0
390,0	2	0,0	0,0	390,0	1620,0	0,0	0,0	0	0
420,0	3	0,0	0,0	420,0	1590,0	0,0	0,0	0	0
450,0	3	0,0	0,0	450,0	1560,0	0,0	0,0	0	0
480,0	3	0,0	0,0	480,0	1530,0	0,0	0,0	0	0
510,0	3	0,0	0,0	510,0	1500,0	0,0	0,0	0	0
540,0	3	0,0	0,0	540,0	1470,0	0,0	0,0	0	0
570,0	3	0,0	0,0	570,0	1440,0	0,0	0,0	0	0
600,0	3	0,0	0,0	600,0	1410,0	0,0	0,0	0	0
630,0	3	0,0	0,0	630,0	1380,0	0,0	0,0	0	0
660,0	3	0,0	0,0	660,0	1350,0	0,0	0,0	0	0
690,0	3	0,0	0,0	690,0	1320,0	0,0	0,0	0	0
720,0	3	0,0	0,0	720,0	1290,0	0,0	0,0	0	0
750,0	4	3,0	0,0	750,0	1260,0	0,0	1,6	3	0
780,0	4	6,0	0,0	779,8	1230,2	0,0	4,7	3	0
810,0	4	9,0	0,0	809,4	1200,6	0,0	9,4	3	0
840,0	4	12,0	0,0	838,8	1171,2	0,0	15,6	3	0
870,0	4	15,0	0,0	867,7	1142,3	0,0	23,4	3	0
900,0	4	18,0	0,0	896,3	1113,7	0,0	32,7	3	0
930,0	4	21,0	0,0	924,3	1085,7	0,0	43,4	3	0
960,0	4	24,0	0,0	951,7	1058,3	0,0	55,6	3	0
990,0	4	27,0	0,0	978,4	1031,6	0,0	69,2	3	0
1020,0	4	30,0	0,0	1004,4	1005,6	0,0	84,2	3	0

Fig A.9 – Well trajectory model: reference scenario (1/2)

Initial Rig #2 placement	-852,7 m
Rig #2 placement	**-1000** m
Interseption point	-990,0 m
Interseption point solver	143,6 -
MD distance from blowing well interception point	30,0 m
Interception TVD	1980,0 m

Relief well #2 design	MD	SECTION	INC.	AZIM.	TVD	N/S	HD	DOGLEG	TURN ANGLE
	m	#	deg	deg	m	m	m	deg/30m	deg/30m
	0,0		0,0	0,0	0,0	0,0	0,0	0	0
Air	0,0	1	0,0	0,0	0,0	0,0	0,0	0	0
	30,0	1	0,0	0,0	30,0	0,0	0,0	0	0
	60,0	2	0,0	0,0	60,0	0,0	0,0	0	0
	90,0	2	0,0	0,0	90,0	0,0	0,0	0	0
	120,0	2	0,0	0,0	120,0	0,0	0,0	0	0
	150,0	2	0,0	0,0	150,0	0,0	0,0	0	0
	180,0	2	0,0	0,0	180,0	0,0	0,0	0	0
Sea water	210,0	2	0,0	0,0	210,0	0,0	0,0	0	0
	240,0	2	0,0	0,0	240,0	0,0	0,0	0	0
	270,0	2	0,0	0,0	270,0	0,0	0,0	0	0
	300,0	2	0,0	0,0	300,0	0,0	0,0	0	0
	330,0	2	0,0	0,0	330,0	0,0	0,0	0	0
	360,0	2	0,0	0,0	360,0	0,0	0,0	0	0
	390,0	2	0,0	0,0	390,0	0,0	0,0	0	0
	420,0	3	0,0	0,0	420,0	0,0	0,0	0	0
	450,0	3	0,0	0,0	450,0	0,0	0,0	0	0
,30"	480,0	3	0,0	0,0	480,0	0,0	0,0	0	0
	510,0	3	0,0	0,0	510,0	0,0	0,0	0	0
	540,0	3	0,0	0,0	540,0	0,0	0,0	0	0
	570,0	3	0,0	0,0	570,0	0,0	0,0	0	0
	600,0	3	0,0	0,0	600,0	0,0	0,0	0	0
	630,0	3	0,0	0,0	630,0	0,0	0,0	0	0
	660,0	3	0,0	0,0	660,0	0,0	0,0	0	0
	690,0	3	0,0	0,0	690,0	0,0	0,0	0	0
	720,0	3	0,0	0,0	720,0	0,0	0,0	0	0
	750,0	4	-3,0	0,0	750,0	0,0	-1,6	-3	0
	780,0	4	-6,0	0,0	779,8	0,0	-4,7	-3	0
	810,0	4	-9,0	0,0	809,4	0,0	-9,4	-3	0
	840,0	4	-12,0	0,0	838,8	0,0	-15,6	-3	0
	870,0	4	-15,0	0,0	867,7	0,0	-23,4	-3	0
,20"	900,0	4	-18,0	0,0	896,3	0,0	-32,7	-3	0
	930,0	4	-21,0	0,0	924,3	0,0	-43,4	-3	0
	960,0	4	-24,0	0,0	951,7	0,0	-55,6	-3	0
	990,0	4	-27,0	0,0	978,4	0,0	-69,2	-3	0
	1020,0	4	-30,0	0,0	1004,4	0,0	-84,2	-3	0
	1050,0	4	-33,0	0,0	1029,6	0,0	-100,6	-3	0
	1080,0	4	-36,0	0,0	1053,8	0,0	-118,2	-3	0
	1110,0	4	-39,0	0,0	1077,1	0,0	-137,1	-3	0
	1140,0	4	-42,0	0,0	1099,4	0,0	-157,2	-3	0
	1170,0	4	-45,0	0,0	1120,7	0,0	-178,4	-3	0
	1200,0	4	-48,0	0,0	1140,7	0,0	-200,7	-3	0
	1230,0	5	-51,0	0,0	1159,6	0,0	-224,0	-3	0
	1260,0	5	-51,0	0,0	1178,5	0,0	-247,3	0	0
	1290,0	5	-51,0	0,0	1197,4	0,0	-270,6	0	0
	1320,0	5	-51,0	0,0	1216,2	0,0	-293,9	0	0

Fig A.10 – Well trajectory model: reference scenario (2/2)