Downhole **GRA**vity **S**lip **S**eparator

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Abstract

The Downhole GRAvity Slip Separator (DGRASS) is a new system for downhole separation. It is based on gravitational separation of oil and water. This paper presents the functionality of DGRASS, and a production analysis of DGRASS using data from three mature wells at the Gullfaks A oil field. Finally, it discusses how well completion can be done with DGRASS.

1 Introduction to DGRASS

DGRASS is based on gravitational separation of oil from water. What makes it so interesting is the fact that it is the production pipe itself.

A special challenge for downhole separation is the separator diameter restriction. While separator lengths of tens of meters are easy to implement, their diameter is usually restricted to below $0.3m$. A challenge is then to develop a design where the small diameter may be compensated by extended length. The piping in a well consists of sections that are $10m$ long. Three of these sections are put together, forming a total length of $30m$. DGRASS may consist of as many of these $30m$ sections as desired. Thus, DGRASS solves the extended length challenge of downhole separation [8].

Installing DGRASS may have several positive effects:

- Higher production rate due to lower well pressure increases the flow towards the well
- Increases the reservoir lifetime, as it can produce with economical benefits on high water cuts
- No gas in the water phase makes it energy saving when it pumpes the major water phase up to lower pressure
- Faster separation on the platform

Figure 1 shows a principal drawing of a simplified DGRASS separator based on three tapping points. An actual separator will contain a large number of tapping points. The tapping points are numbered sequentially from 1 to n, and are assumed to be equidistant. The total distance between the first and the last tapping point opening is L. The inner diameter of the tubing and casing are D_t and D_a, respectively. The tubing thickness is T [9].

The inclination angle for the separator and for the tapping points is as shown in figure 1. Both θ and β are defined such that zero angle means horizontal flow and $90°$ angle means vertical upward flow. Negative angle therefore means that the flow

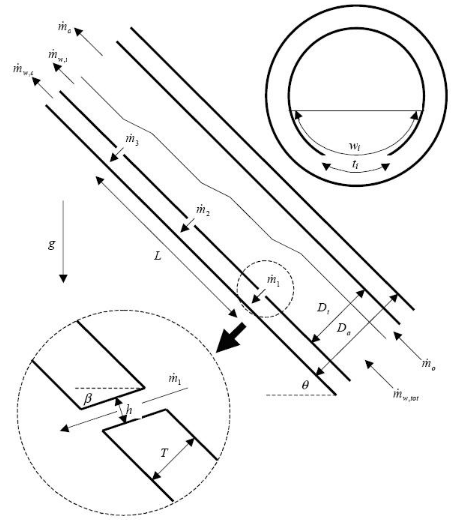

Figure 1: DGRASS principal manner of operation

through the tapping points is in the downward direction. All the tapping points are assumed to have the same inclination angle.

ABB has done previous work on DGRASS, indicating that it may be a useful method for downhole separation. However, it needs more testing before implementation. ABB identified the tapping points and design of the DGRASS as the main challenges. They also found that the flow behaviour is altered after each tapping point. This influences the flow regime and separation quality.

Post doctor Pascal Klebert and Benjamin Buorgeois at the Department of petroleum engineering and applied geophysics (IPT) at NTNU are doing research on a DGRASS system using an inclined oil/water flow with separation of the water phase. The preliminary lab results show that the separator is functioning well with an inclination up to 40°. With a watercut of 80% and an inclination of 30°, it will probably be possible to separate out over 90% of the water. The problem they face with higher inclinations are the flow regimes.

The flow regime depends on the mixture, velocity and angle. A horizontal flow will give a stratified flow regime, even with relatively high velocities. This means that there is no turbulence, and it is easy to separate with high quality. A vertical flow will give a turbulent flow regime. Results so far show that with an angle of up to 40° it will be possible to separate, even with some turbulence, as the water still seeks towards the bottom of the pipe. With angles above 40° the flow becomes highly turbulent, and a good separation is difficult to establish.

2 DGRASS production analysis

The main goal of DGRASS is to enhance oil production by lowering the bottom hole flowing pressure P_{wf}. By reducing P_{wf}, the flow from the reservoir will increase due to the increased pressure difference between the reservoir and the well. To meet the system demands top side, this reduction is made possible by dividing the mixed flow into separate flows of oil and water from the DGRASS installation and up.

We created a spreadsheet which allows you to determine pressure, fluid, well and tubing data as well as the desired DGRASS depth. All calculations are made under the assumption of one phase, non compressive flow. The pressure is calculated in three different tubes, and the flow in each tube is considered single phase. From the reservoir and up to the DGRASS installation the liquid is mixed. From the separator and up we consider two separate tubes; one contains oil and the other contains water.

The spreadsheet is designed around the built-in solver function in Microsoft Excel, changing the depths and other variables to estimate a depth where implementation of DGRASS yields the highest oil production. The user has to assume a P_{wf} where the calculations can start, and a maximum allowed calculated P_{wf} value.

2.1 Equations used in the analysis

The spreadsheet is built around some basic equations. The assumption of one phase, non-compressive flow is applied through the whole spreadsheet using the equations in table 1.

Name	Equation
Productivity index [3]	$Q = J * (P_r - P_{wf})$
Reynolds number [6]	$R_e = \frac{\rho D u}{\mu}$
Haalands equation [6]	$f_m = (\frac{1}{(-1.8log(\frac{6.9}{R_e}+(\frac{e}{3.7D})^{1.11})})^2$
Pressure loss due to friction [3]	$\Delta P_f = \frac{1}{2} f_m * \rho * u^2 * \frac{h}{D}$
Pressure loss due to hydrostatical head [3]	$\Delta P_h = \rho g h$

Table 1: Production analysis equations

The pressure at the DGRASS installation is calculated separately for each tube as shown in table 2. Herein, the different pressure losses are calculated with their respective material properties, true vertical depth (TVD), measured depth (MD) and percentage of water. The different depths are described in figure 2.

Tube	Equation
Tube A	$P_{dgrass} = P_{wf} - (\Delta P_f + \Delta P_h)$
Tube B	$P_{grass} = P_{soil} + (\Delta P_f + \Delta P_h)$
Tube C	$P_{grass} = P_{swater} + (\Delta P_f + \Delta P_h)$
Reference tube	$P_{wf} = P_{sep} + (\Delta P_f + \Delta P_h)$

Table 2: Equations for the different tubes

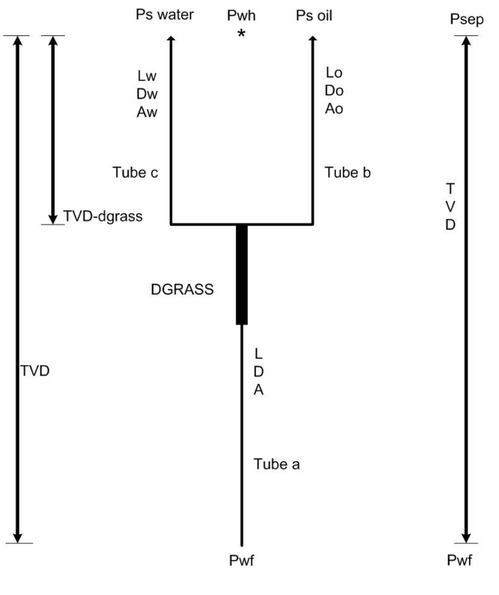

Figure 2: Production analysis model

2.2 Implementation depth in Gullfaks wells

By applying real well data from Statoil as input, an analysis with regards to placement depth versus production results has been performed. A selection of the best range of depth in which to implement DGRASS is chosen for each well. The range of depth is then calculated in the production analysis spreadsheet. The main production data for the three wells is presented in table 3. During all evaluations casing diameter, giving the equivalent annulus diameter, has been assumed equal throughout the whole well.

Well	Productivity index	Reservoir pressure	Water cut
A-8R2	$0.00038 \frac{m^3}{s*bar}$	$274.96 bar$	80.5%
A-16A	$0.00046 \frac{m^3}{s*bar}$	$299.92 bar$	75.9%
A-23	$0.00417 \frac{m^3}{s*bar}$	$299.92 bar$	85.5%

Table 3: Main production data for the Gullfaks A wells

The analysis strongly indicates that implementation of DGRASS is highly profitable in the three candidate wells A-8R2, A-16A and A-23. Gained oil production may be viewed in figures 3, 4 and 5. A comparison of flow rates of oil and water, with and without implementation of DGRASS is displayed in figure 6. The ratio between the oil and water production remains unchanged with and without DGRASS, but the increased production is significant. A shared tendency is that the gained oil production grows as the implementation depths go deeper . This is due to the fact that splitting the fluid flow at the deepest possible depth yields the largest pressure loss.

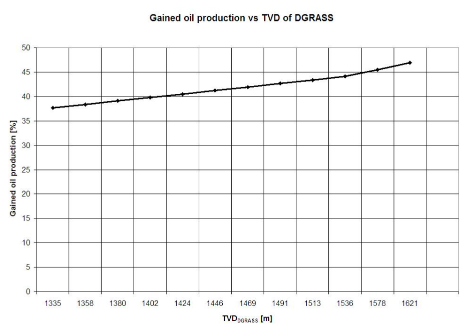

Figure 3: Gained oil production from implementation of DGRASS in well A-8R2

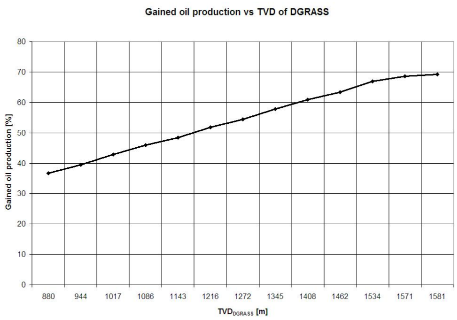

Figure 4: Gained oil production from implementation of DGRASS in well A-16A

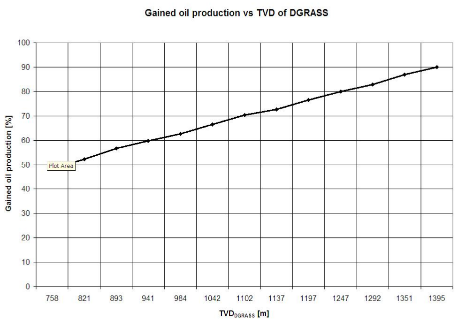

Figure 5: Gained oil production from implementation of DGRASS in well A-23

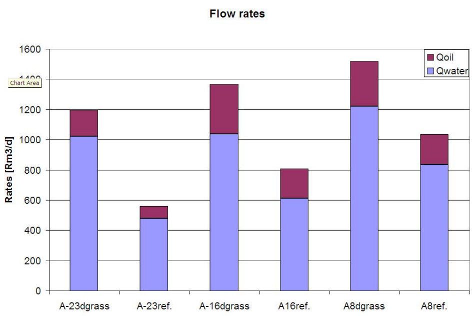

Figure 6: Flow rates of oil and water, with and without implementation of DGRASS

2.3 Annulus diameter impact on produced oil

To perform evaluation of annulus diameter impact on produced oil, the least profitable well A-8R2 is chosen. Fixing DGRASS to the most beneficial depth and then varying annulus diameter gives information about the annulus diameter dependency. Varying the diameter between 0.06 and 0.10 meters yields the results presented in figures 7, 8, and 9.

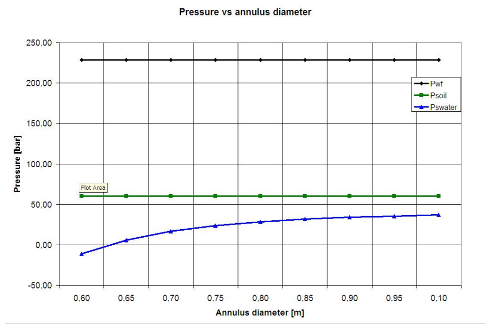

Figure 7: Pressures at different annulus diameters for well A-8R2

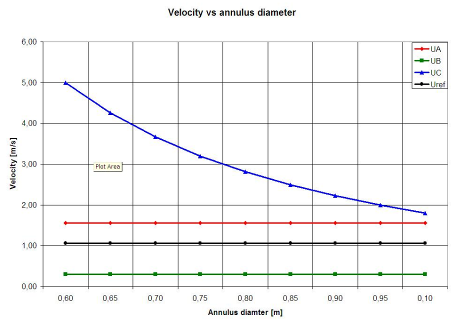

Figure 8: Flow velocities at different annulus diameters for well A-8R2

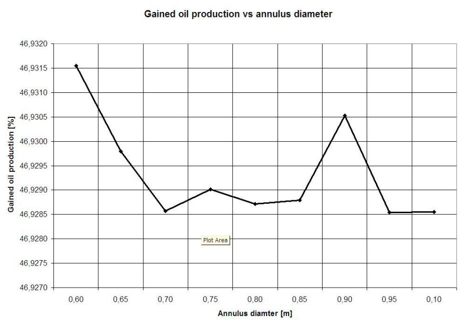

Figure 9: Gained oil production at different annulus diameters for well A-8R2

Annulus diameter has a large effect on water separator pressure. Smaller annulus diameter yields lower possible pressure of water separator. In fact, if the diameter is too small, vacuum is created. However, annulus diameter has no significant impact on gained oil production.

2.4 Water cut impact on produced oil

Water cut impact is evaluated by viewing the amount of produced oil at different water cuts for the least profitable well, A-8R2. DGRASS remains fixed to the most beneficial depth and then the water cut is changed from 0 to 100%. The gained oil production displayed in figure 10 is as expected highest at the highest water cut.

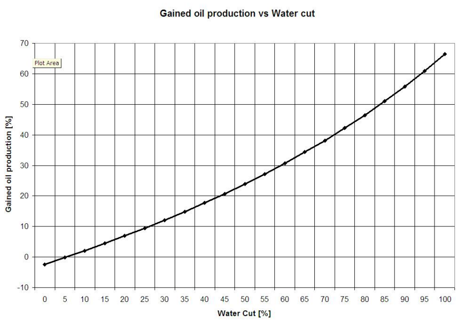

Figure 10: Gained oil production versus water cut in well A-8R2

3 Well completion with DGRASS

For mature wells, additional new completion with DGRASS will be limited. The existing production tubing will be taken out and a production tubing with modifications for the DGRASS separator will be installed. The production flow will then be started. Since the technical data for the separator (technical drawing, part list, and dimensions) is confidential, we will not go into these details here. We will do the completion in more general terms, based on the already existing completion schematics.

One of the benefits with DGRASS is that it gives higher capacity than present technologies for downhole oil/water separation, while still keeping the separation device simple and easy to install. The installation can be done during workover, which is usually planned one year ahead for each well. This is an advantage since the production then does not have to be stopped more than it would have been anyway. DGRASS cannot be installed in a horizontal or vertical part of the well; it has to have an inclination.

The separator can be installed somewhere between the production packer and the DownHole Safety Valve (DHSV)[1], but there is a lower authorized Measured Depth (MD) that is a bound on where the separator can be inserted. This is where the coupling $5in$ casing to the $7in$ casing is. The DGRASS separator can be as long as possible, as long as the conditions are right. However, the tapping points in the separator do not have to be placed in the same pipe. There can be several parts with draining holes connected together. This is because the length of what can be inserted in the well in one time limit the lengths of the parts. The limiting length is about $45m$, which is the maximum length that they can lift in vertical position and then insert in the drilled hole [5]. Since the well trajectory inclination can change with $1° - 2°$ in the places where DGRASS is suitable, this makes it possible to adapt the separators to each well.

If it would turn out, after installation, that this separation method does not work as good as expected, the separator can be removed and the production can continue as before. Alternatively, the tapping points may be closed and the DGRASS separator may be used as ordinary production tubing.

In figure 11 you get a general view of where DGRASS will be put and how the oil and water are brought separately to the separators at the platform.

Figure 12 show a schematic drawing of the main equipment that has to be in the well, but the proportions are not real.

There may also be need for modifications on the

[1] A downhole safety valve is a device that isolates wellbore pressure and fluids in the event of an emergency or catastrophic failure of surface equipment [7].

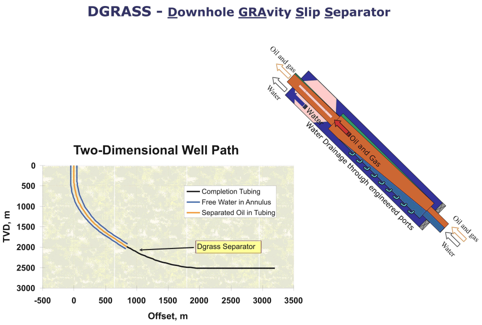

Figure 11: DGRASS sketch with well trajectory

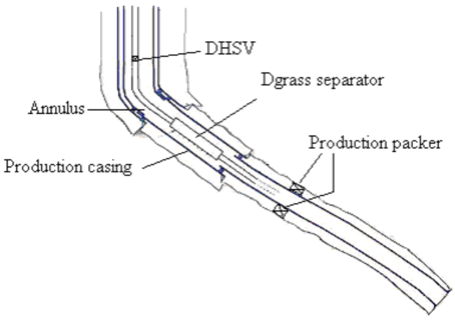

Figure 12: Main equipment in a well with DGRASS

platform. With DGRASS the separated water and oil will go to separate low and high pressure separators at the platform deck, so there may be need for another separator.

3.1 Operating DGRASS

The drainage of DGRASS will be controlled by an operator on the platform. His goal will be to find the different drainage rates which suites the different flow regimes in the separator best. This is done by adjusting the back pressure (surface controlled). Since the flow rates for all the holes not will be the same, an appropriate back pressure, assuring maximum water drainage from each tapping point, will have to be found. Taking into account that the layer of water will become smaller and smaller for each hole. The flow regimes will differ depending on the angle of inclination, water cut and flow rate inside the separator. Additional adjustments of the tapping points and optional shut-down of DGRASS, if found useless, can be performed by valves at each tapping point. The valves will be controlled by actuators operated either by a hydraulic, electrical or combined system. This depends on how the existing completion and control systems in the candidate well are designed. Valve control is preferably performed by utilizing extra capacity in existing control systems.

3.2 Flow of oil and water

The efficiency of the separator depends on several factors. To get the best possible separation, the DGRASS has to be fitted to each single well. What should be taken into consideration is emulsion[2] in the flow and improved coalescence[3] before the DGRASS separation. The reason for this is that we want to drain out as few as possible of the droplets to achieve efficient separation, and emulsion works against this.

There are several possible solutions to this problem. One possibility is to add emulsion breakers[4] to the oil/water, but these generally contain components of varying toxicity and collapsibility and have to be special made for each type of crude oil [2]. To reduce the need for emulsion breakers we can adjust the construction better, so the turbulence is reduced. The flow velocity, the well trajectory inclination and the "entrance" conditions affect turbulence. The inclination angle is set, but the flow velocity and DGRASS can be adapted to decrease turbulence.

The flow velocity will also affect the efficiency. To get a high fraction of the water drained out the flow velocity has to be low.

What is wanted is a flow that gives a high fraction of the water drained out. A flow pattern map[5] for a flow with angle of 45° shows what kind of

[2]Emulsion is a mixture of a fluid as undissolved droplets in another fluid, in this case oil in water.

[3]Coalescence constists of crashing droplets to make bigger droplets so they can be separated more easily.

[4]Emulsion breakers are chemicals designed for separating oil-in-water and water-in-oil emulsions in industrial process and waste streams [1]

[5]A flow pattern map shows what flow regimes we will get in the tube for different amounts of water and oil for a given inclination angle

flow regime we will get with the different oil/water contents, at this angle [5].

Figure 13 shows the flow map for an inclination angle of 45°. Figure 14 gives an explaining picture for each of the different flows.

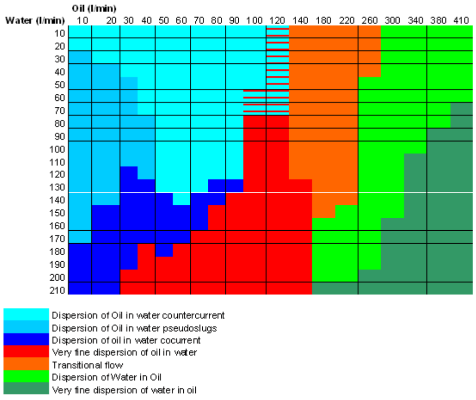

Figure 13: Flow map for a 45-degree inclination angle

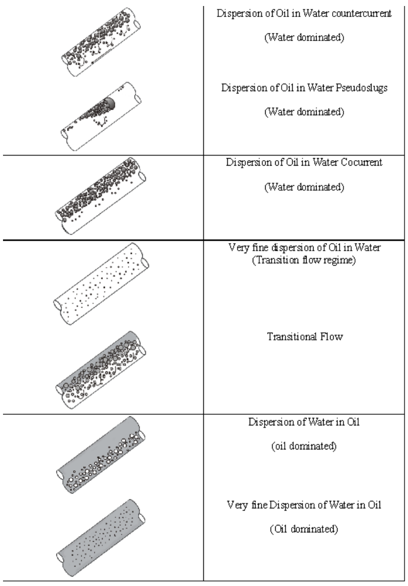

Figure 14: Explanation of different flowregimes

A definition of the angles is shown in figure 15. In the three well candidates the water cut is 75.9−85.5 %. That would be in the blue area, which is the type of flow regime that we desire. When making

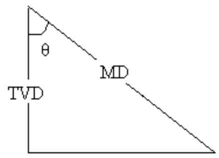

Figure 15: Definition of the angles used in the completion

the map for 30° and 60° the internal boundaries for the blue region will be changed, but for the red and green ones they will not. Thus, it is expected that inclinations at 30°, 45° and 60° will not change a lot at this flow pattern. This needs confirmation in a lab experiment. This is good for our candidates, which have an average inclination angle of about 35°, 47° and 53°.

3.3 Results

We have used existing completion schematics for the three wells at Gullfaks A, data from those wells, and data from the production analysis to find out where it could be possible to insert a DGRASS separator and what outcome this will give [4]. We have also plotted the two-dimensional well trajectory, and marked with green dots, between which is the part of the well that is suited for the DGRASS separator. The upper limit is the DHSV. This valve is placed so high up in the wells that the angle at this point, in well A-8R2, A-16A, and A-23, is respectively 0.4°, 11.1° and 15.1°. These angles are too small for the DGRASS separators; we will have to move further down in the wells until the angles are at least 30°.

The numbers used here are taken from the calculations with $P_{soil} = 60 bar$, since this gave the best results. At all the wells the best place to put the separator is at the bottom of the possible area.

3.3.1 Gullfaks A-8R2

This well is the shortest in MD (Measured Depth) and TVD (True Vertical Depth). The lower authorized MD is 1718.90m, and the TVD is 1621.03m.

At the relevant part of the well we have:

- Inclination angle: $31.6° - 36.7°$, only a small part has $31° - 34°$ before mainly about $35° - 36°$
- TVD: From about 1335m to about 1621m
- Length: About $1718m - 1367m = 351m$, but for the part where the inclination angle is most stable the length is $1718m - 1421m = 297m$

The well trajectory for well A-8 is shown in figure 16.

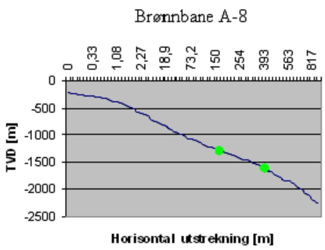

Figure 16: The well trajectory for Gullfaks A-8

From the production analysis we found that placing the separator at a TVD of about 1620m and MD of about 1718m would give:

- P_{swater}: 28.25bar
- Calculated outflow: $0.0034\frac{m^3}{s}$
- U_a (flow velocity into the separator): $1.553\frac{m}{s}$
- Gained oil production: about 47%
- Diameter, D: 0.12m

3.3.2 Gullfaks A-16A

This well has the longest TVD. The lower authorized MD is 1925.03m, and the TVD is 1582.14m.

The relevant part to insert the separator in has the following values:

- Inclination angle: $36.1° - 47.5°$
- TVD: $880m - 1581m$
- Length: $1924m - 916m = 1008m$

There is also a part further up that has an inclination angle above 30°, but the angle varies very much here, so since the part where it is more stable is so long, it is not necessary to use that part.

The well trajectory for well A-16A is shown in figure 17.

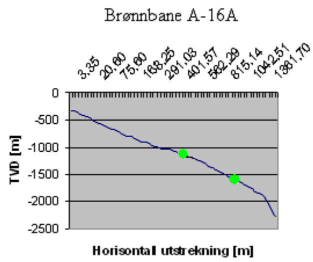

Figure 17: The well trajectory for Gullfaks A-16A

From the production analysis we found that placing the separator at a TVD of 1581m and MD of 1924m would give:

- P_{swater}: 30.96bar
- Calculated outflow: $0.0038\frac{m^3}{s}$
- U_a (flow velocity into the separator): $1.398\frac{m}{s}$
- Gained oil production: about 69%
- Diameter, D: 0.12m

3.3.3 Gullfaks A-23

This well has the longest MD. The lower authorized MD is about 2508m, and the TVD is 1731m.

The relevant part to insert the separator in has the following values:

- Inclination angle: 51.3° - 59.8°
- TVD: From about $758m$ to about $1731m$
- Length: $2509m - 785m = 1724m$

The well trajectory for well A-23 is shown in figure 18.

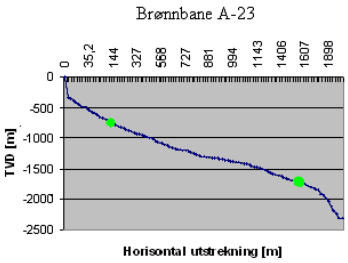

Figure 18: The well trajectory for Gullfaks A-23

From the production analysis we found that placing the separator at a TVD of $1731m$ and MD of $2509m$ would give:

- P_{swater}: $26.18bar$
- Calculated outflow: $0.0020\frac{m^3}{s}$
- U_a (flow velocity into the separator): $1.224\frac{m}{s}$
- Gained oil production: 114%
- Diameter, D: $0.12m$

As we see from these figures and data there is more then enough space to place the DGRASS separator, in relation to the inclination angle and the length of the well part. In the production analysis the length of the separator has not been taken into account. Thus, we will not consider how long the separator in each well should be, and what the results will be then. Still, it is desirable to have it long, to get as much as possible separated.

We get the best effect of the DGRASS separator when it is placed as close to the reservoir as possible. This matches the theory of having a separator pressure as close to the reservoir pressure as possible gives the best separation. The water and oil will blend more and more before separation the further away from the reservoir the DGRASS separator is.

From a completion point of view the DGRASS separator is a good alternative. It can be implemented in already existing wells during workover and if it turns out to be a failure it is possible to go back to the old separation method.

4 Conclusion

Our production analysis performed on the three Gullfaks wells A-8R2, A-16A and A-23 concludes that implementation of the DGRASS system will give significant gained oil production figuring between 40% and 90% for these three wells. Installation of the DGRASS system in the deepest part of the evaluated well bore yields maximum oil recovery. Our analysis shows that depth is the main factor influencing gained oil production with DGRASS. Water cut is also of importance. Annulus diameter has no significant effect on gained oil production, but is however important regarding top side modifications necessary to implement the DGRASS system.

The DGRASS system is brilliant in its simplicity and may have a very promising future. The lifetime of old wells can be significantly prolonged by few installation efforts. Based on our results we highly recommend a field trial of this novel technology.

References

[1] Inc. Applied Specialties. Emulsion breakers. http://www.appliedspecialties.com, 2005.

[2] Sintef Petroleumsforskning AS. Emulsion explanation. http://www.sintef.no/content/page1_1985.aspx, 2005.

[3] L.P. Dake. *Fundamentals of reservoir engineering*.

[4] Michael Golan. Well trajectory data.

[5] Pascal Klebert. Conversations between post doctor klebert and the project group, 2005.

[6] Okiishi Munson, Young. *Fundamentals of fluid dynamics.*

[7] Schlumberger. Schlumberger oilfield glossary. http://www.glossary.oilfield.slb.com.

[8] ABB Corporate Research Svein Håheim. Oil/water slip in inclined pipes and application to downhole separation. ABB research.

[9] Ivar Balk Svein Håheim, ABB Offshore Systems and Rune Killie. Experimental study of inclined oil/water flow with separation. ABB research.