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Forfatter: Erling Grindhaug	(signatur forfatter)
Fagansvarlig: Erik Skaugen Veileder(e): Rune Haugom	

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The use of alternative materials for drill pipe to extend drilling reach in shallow reservoirs

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Abstract

One of the limiting factors for extended reach and horizontal drilling is high torque and drag values. One way to reduce torque & drag is to reduce the weight of the drill pipe by exchanging the standard steel with other materials that weigh less. This technology has potential to extend drilling length and/or to be cost-effective in drilling some wells.

This thesis focuses on whether alternative materials for the drill pipe could be an alternative for shallow reservoirs such as the shallow Skrugard reservoir in the Barents sea, which is planned for development in the next few years.

The results of the simulations show that a tapered string with 1500 m of aluminum pipe gives the longest possible drillable length. If a string with just one material is to be used, a normal S-135 string will be the best alternative due to its high buckling resistance, as compared to available alternative materials

Contents

Acknowledgements

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1. Introduction

The dwindling easy accessible oil and gas reservoirs has forced the petroleum industry to develop both targets that are situated in challenging areas and that are technically difficult to drill. The high price of oil has made overcoming the challenges economical, and many prospects that were considered uneconomical in earlier decades are now prime targets for exploitation.

These often hard to reach targets, has caused the development of techniques and technology to extend drilling reach in order to access remote locations, or to drill remote targets from existing drilling facilities, or reach offshore locations from a land drilling rig.

Torque and drag (T&D) is often a limiting factor in drilling wells with long horizontal sections or high dog legs (DL). There are many technologies and techniques centered on reducing T&D, with alternative drill string materials as one of them. By using lighter materials for producing drill pipe (DP), the friction will be less in the deviated sections of the wellbore and T&D will be reduced.

This thesis simulates the use of titanium drill pipe (TDP), aluminum drill pipe (ADP), composite drill pipe (CDP) and high strength UD-165 drill pipe, as replacement for standard S-135 drill pipe (S-135 DP) in coping with the drilling challenges in the shallow Skrugard field. Also a simulation of maximum possible drilled length for each of the materials is simulated and this length is compared to S135 DP to see if any of the other materials can help to extend reach. A tapered string design with a combination of S-135 DP and ADP is also simulated to see if a tapered design could give better results than any of the other materials alone.

2. Theory

2.1 Fundamentals of Torque and drag

2.1.1 Torque

In drilling, torque is the force used to rotate the drill string around its axis. The torque is generated by the top drive and is used to overcome the frictional forces opposing rotation of the drill string and bit.

The top drive applies torque to the drill string and the torque stress in the string is then diminished along the string before reaching the bit where it is used to cut/crush rock. Long deviated or horizontal sections experience greater resistance to rotation and therefore require extra torque from the top drive in order to rotate successfully and still maintain the required torque at bit. In long wells the bore hole friction can become so great that it either surpasses the drill string or rig limitations and further drilling becomes impossible.

In drilling, torque is dependent on the coefficient of friction, and the normal force of the pipe against the wall in the bore hole.

Torque is divided into three major categories in drilling:

- The bit torque
- The torque along the wellbore
- The mechanical torque (cuttings, stabilizers, centralizers)

The frictional force between the borehole wall/casing and the pipe is the most important factor in extended reach wells (ERD) wells[(1)]. Torque is directly proportional to the radius of the rotating pipe, the friction coefficient and the normal force exerted by the wall on the pipe. The normal force is dependent on the drill string weight including buoyancy, the well length and inclination.

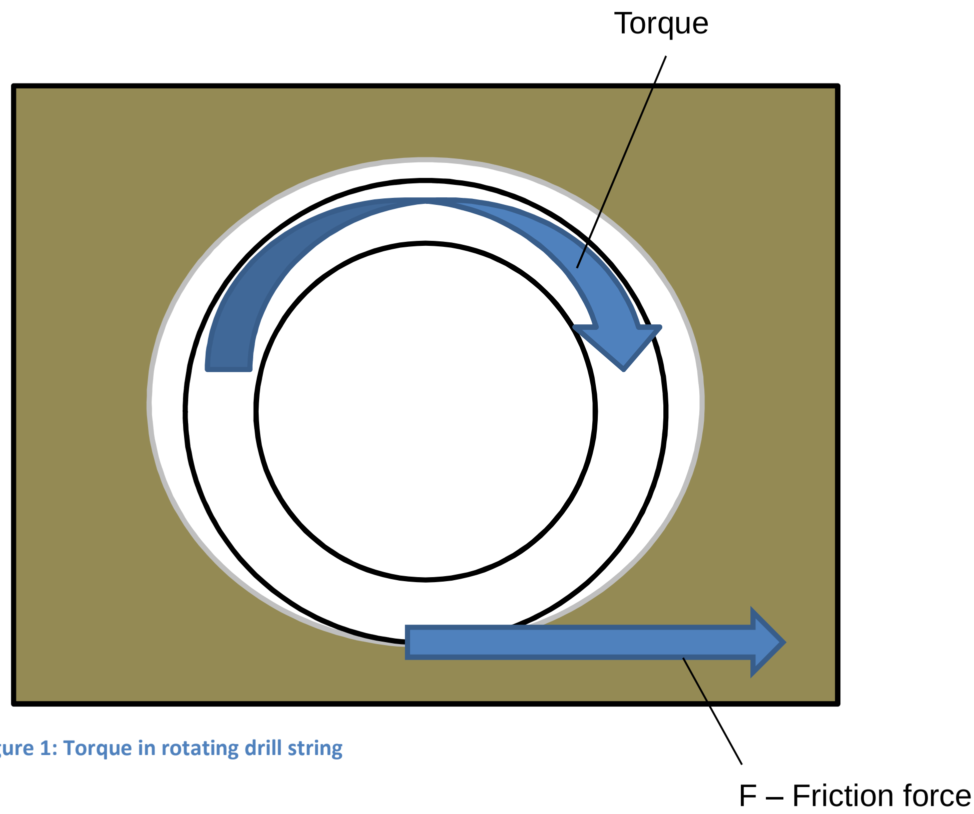

Figure 1: Torque in rotating drill string

2.1.2 Drag

Drag forces are the friction forces that oppose sliding the drill string into the hole. Drag forces depend on a series of factors. Hole inclination is important as drag forces are generally not a problem in vertical strings. This is because it is in deviated or horizontal wells that the string rests on the borehole/casing wall and where gravity and compressive forces push the drill-string against the borehole wall, while in vertical wells the string does not rest on the bore hole wall.

A lot of factors contribute to the total friction in the well. Some of the effects are possible to model, but most of these factors are accounted for by the “friction factor” which is a collection of the friction contributed from the different friction sources such as local dog legs or micro-tortuosity. This friction factor is not to be confused with the kinetic friction factor for sliding.

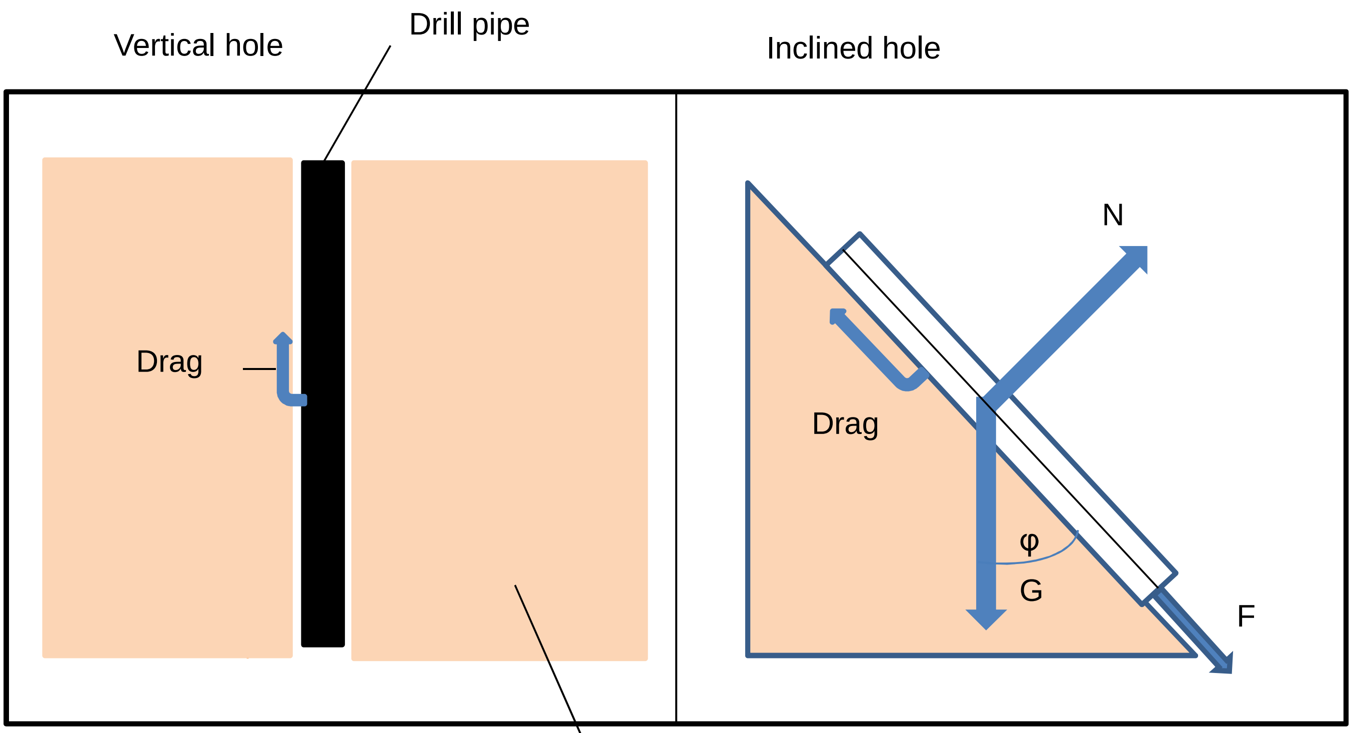

Figure 2: Illustration of drag in vertical and inclined hole

Torque and drag both depend on factors like inclination, length and friction in the well and high torque and drag normally occur together.

Factors that give torque and drag in drilling operations:

- Wellbore related problems – Such as swelling clay and tight hole. The wellbore can also collapse.
- Differential sticking – When the pressure is larger in the well than the pore pressure in the formation, the drill string can be drawn toward the bore hole wall and be pulled into the mud filter cake.
- Hole curvature – The well bore curvature is important for torque and drag as combined with drill string stiffness it contributes substantially to well bore friction. High dogleg combined with stiff drill string will give large torque and drag forces.
- Mud type - Lubrication reduces the friction factor between the drill string and the bore hole wall, leading to a reduction in torque. Lubricants can be added to water based mud (WBM) to add to the WBM lubricating effect, but generally oil based mud (OBM) is always superior in this area. Added lubricants can also have other unwanted effects such as interaction with the

formation, and thereby reducing inflow performance. Other mud parameters such as viscosity, also has a lot of influence on T&D

- Tortuosity – Tortuosity is divided into "micro-tortuosity" which is well bore spiraling and tortuosity due to differences in dogleg severity over a short area. Both are difficult to measure as they will not be shown in measurement while drilling (MWD) readings, as the MWD tool measures tool inclination and direction of the drift and not the wellbore itself[5].
- Key seating – Is the effect where the drill pipe digs a channel in the formation rock in a curve. The larger pieces of the drill string then gets stuck in that channel when they move past the same area
- Tension/compression of the drill string also plays a part, as a compressed string will be forced harder into the bore hole wall than a non-compressed one, and a string in tension will be pulled to the high wall of the wellbore in dog leg sections[3].
- Hole cleaning – Cuttings accumulation can give rise to increased mechanical friction
- Formation properties – Different formation lithology give rise to different friction coefficients for kinetic sliding of the drill string against the bore hole wall. Among other things this depends on the coarseness of the formation and the lubricating effect between formation and drillstring.
- Drill string weight – Directly influences normal force and therefore friction
- Differing diameters along the string – Varying diameters along the string as is the case with tool joints and the bottom hole assembly (BHA), may give rise to extra drag
- Mud weight – Higher mud weight gives higher buoyancy for the drill string reducing T&D, but might lead to other problems such as reduced hole cleaning, lower ROP or high ECD

In In addition to these factors drag is greatly reduced by rotating the string compared to slide drilling. When sliding the drillstring the friction force will be oriented along the drill string axis opposing forward motion. Rotating the drill string will not decrease the friction force, but will change the direction of the friction force, from along the string axis to almost perpendicular to the axis, as rotational speed increases.

The rotational speed of the string easily reach values of over 100 times the speed of forward motion, but the reduction in axial friction seems to hit a limit around 90-95% of the total friction force in actual drilling[46].

2.1.3 Friction

Contact friction is a result of the frictional forces generated when the surfaces of two bodies are in direct contact with each other. It is divided into Static and kinetic friction. Static friction occurs when there is no movement between the two bodies, and is the force necessary to initiate movement from rest between the two. Static friction is often larger than kinetic friction(5).

Kinetic friction is the friction between two contacting bodies in movement relative to each other. Kinetic friction is independent of contact area, is proportional to the normal contact force, and is always directly opposite the direction of movement(5).

Both static and kinetic friction is important in drilling, but for torque and drag simulations the kinetic friction is modeled. Both modes of friction increases with well length and deviation

A friction coefficient is used to describe the ratio between normal force and friction force, so that normal force multiplied with the friction factor gives the friction force.

$$F_F = \mu * N$$

$F_F = friction\ force$

$\mu = Friction\ coefficient$

$N = normal\ force\ (a\ force\ perpendicular\ to\ the\ contact\ area)$

The friction factor is essential in torque and drag simulations as it is a key parameter that can positively or negatively impact torque and drag values.

2.1.4 Yield strength

The yield strength of a material to be used in the drill pipe is very important, as it is the theoretical limit to the stress one can apply to the drill pipe without plastically deforming the pipe, and depends on both the material/alloy used and tempering of that material/alloy. A tensile stress-strain diagram, as shown in figure 2, is used for engineers to determine specific material properties, including yield strength and ultimate tensile strength(6).

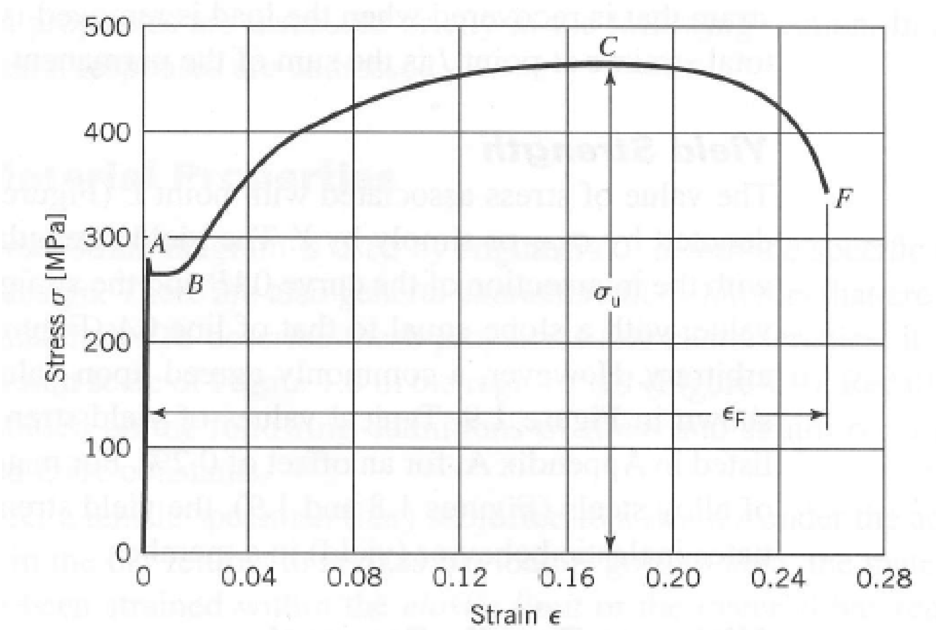

Figure 3: Engineering stress-strain diagram for tension specimen of structural steel[6]

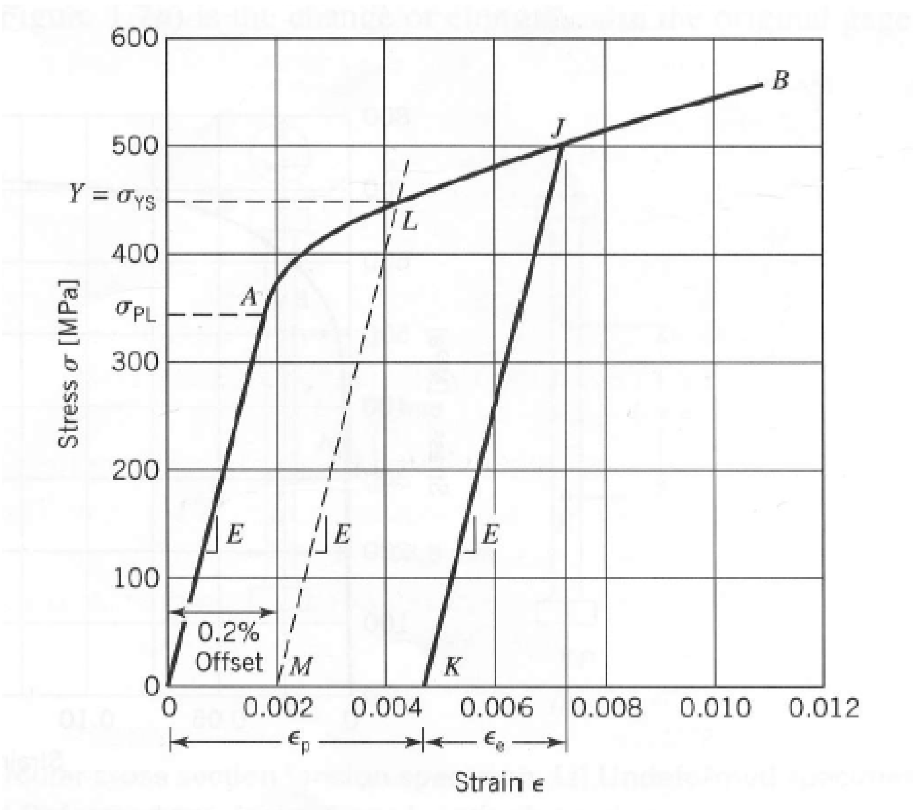

Figure 4: Stress-strain diagram for tension specimen of alloy steel with an expanded strain scale[6]

The yield strength (YS) is empirically determined, but for alloys like high strength steels and the aluminum used in drill pipe, the yield strength is not easy to determine as the transition from elastic to inelastic deformation is gradual. In this case a offset yield limit, often of 0.2% of the strain, is used as the yield limit (point L in figure 3)[6].

2.1.5 Weight

The weight of the drill pipe is extremely important for torque and drag. The weight depends on the material density of the pipe and pipe wall thickness. To calculate mass of a pipe this equation is used:

$$M = \rho_{pipe} V$$

$M = Mass\ of\ pipe$

$\rho_{pipe} = density\ of\ pipe$

$V = volume\ of\ pipe\ material$

Nominal weight in lbs/ft is often used in tables and is calculated from this equation:

$$m = \rho\pi(r_o^2 - r_i^2)$$

Weight including tooljoints:

$$M = \rho_{pipe}\pi\left(r_o^2 - r_i^2\right)\left(L_{pipe} - L_{tj}\right) + M_M + M_F$$

$r_o = pipe\ outer\ radius$

$r_i = pipe\ inner\ radius$

$L_{tj} = Length\ of\ tool\ joint$

$L_{pipe} = Length\ of\ pipe$

$M_M = mass\ of\ male\ tool\ joint$

$M_F = mass\ of\ female\ tool\ joint$

Pipe weight is used to calculate the bore hole wall normal force (N) on the pipe

$$N = Mgsin\alpha$$

$g = gravity\ constant$

$\alpha = borehole\ inclination$

The normal force is then used to calculate friction force by multiplying it with the friction factor

$$R = \mu N$$

$R = friction\ force$

$\mu = friction\ factor$

The friction force is the major constituent of drag and torque. Any reduction of friction force will therefore give a direct reduction in torque and drag forces. Materials like aluminum and titanium have lower density than steel, and the normal force will be smaller for these materials than the alternative steel equivalent.

If the total weight of the drill string is reduced smaller tensile loads will be experienced by the tubulars near the surface, and smaller compressional forces in the tubulars at the bottom. The trip time can be reduced with as much as 25% as a result of the weight reduction, if the hoisting power is the limiting factor, and not for example reservoir pressure sensitivity(7).

2.1.6 Buoyancy

Archimedes of Syracuse discovered that the buoyancy of a body equals the weight of the displaced fluid in which it floats, in his work “on floating bodies” (ca. 220 B.C)(8). For drill pipes the buoyancy equals the weight of the mud that the drill pipe displaces.

The submerged weight of a wellbore tubular can be obtained by multiplying the weight in air with a buoyancy factor(9):

$$\beta = \frac{Suspended\ weight\ in\ mud}{Weight\ in\ air}$$

$$\beta = 1 - \frac{\rho_{fluid}}{\rho_{pipe}}$$

$\beta = buoyancy\ factor$

$\rho_{fluid} = density\ of\ the\ fluid\ the\ pipe\ is\ submerged\ in$

This equation is only valid if the mud inside and outside the drill pipe has the same density. This is not always the case, and for operations that involve different density fluid inside and outside the wellbore tubular, such as cementing operations and displacement of mud, this formula must be used[9]:

$$\beta = 1 - \frac{\rho_{mo} r_o^2 - \rho_{mi} r_i^2}{\rho_{pipe}(r_o^2 - r_i^2)}$$

$\rho_{mo} = density\ of\ mud\ outside\ pipe$

$\rho_{mi} = density\ of\ mud\ inside\ pipe$

Using a mud with high density will give more buoyancy than using a less dense mud, and therefore influence torque and drag simulations. The opposite is true for the drill string, using a less dense material will reduce torque and drag.

2.1.7 Strength to weight ratio

The strength to weight ratio describes a materials yield strength compared to its submerged weight, and represents the ultimate length of drillstring that can be suspended in a liquid-filled vertical well without exceeding the yield strength of the material.

Strength to weight ratio is a measure of pipe yield strength compared to submerged weight:

$$STWR = \frac{YS}{m_{submerged}}$$

$STWR = strength\ to\ weight\ ratio$

$YS = yield\ strength$

$m_{submerged} = submerged\ weight\ of\ one\ joint$

2.1.8 Wellbore trajectory

The wellbore trajectory can vary in all three dimensions.

The angle between vertical and the wellbore trajectory is called the inclination and varies from 0 degrees in a vertical hole to more than 90 degrees for highly deviated wells.

The azimuth is the angle between the reference points, usually a grid or true north, and a tangent to the wellbore projected to a horizontal plane, starting from North at 0 degrees and moving clockwise.

The petroleum industry originally drilled almost exclusively vertical wells, but over the years inclining wells have become standard. The methods for measuring inclination and azimuth have seen radical improvements from those early vertical wells, and today the MWD tool with its collection of tri-axially oriented accelerometers and tri-axially orientated magnetometers gives precise directional information[(5)].

The magnetometers measure the components of the earth's magnetic field, while the accelerometers measure the components of the earth's gravitational field. The vector components of the two instrument packages together determine wellbore direction and azimuth[5)]. In addition measured depth is obtained from the drillers tally, and total vertical depth (TVD) is then calculated.

Dog leg (DL) is the difference in inclination and azimuth between two survey points, and dog leg severity (DLS) is an expression used to describe changes in azimuth/inclination per 30 meters.

In the Barents Sea the magnetic field is more unstable than further south and also experiences distortions from the atmosphere where solar radiation initiates currents and induces magnetic interference. This magnetic variation has to be calibrated for, which is why a seabed magnetic observatory would be important for drilling in the Barents sea[(10)].

The wellbore trajectory is a critical factor in torque and drag, as it influences friction through a number of factors like tortuosity, hole curvature, key seating and dog leg severity.

2.1.9 Cuttings transport

In drilling, cuttings generated from the bit have to be removed. This is done by circulating drilling mud from surface, through the drill pipe and out through the nozzles in the drill bit and back up with the cuttings in suspension. If the cuttings removal process is inadequate, which is often the case in inclined or horizontal wells, the cuttings will settle along the low side of the well bore due to gravity.

Mud rheology is essential to effectively remove cuttings. Mud has to be designed to be viscous enough to be able to agitate the cuttings and keep them in solution, but if designed to be too viscous effects like low rate of penetration (ROP) and high equivalent circulating density (ECD) could be a result. Mud also has to form gel in static conditions so that the cuttings does not fall out of suspension before circulation is restarted.

Good hole cleaning depends on a number of factors, the most important of them are(11):

- Well bore inclination is one of the main factors in hole cleaning. High deviation gives poorer hole cleaning.
- Mud properties like density, rheology and type gives differing positive or negative contributions
- Mud flow rate is important for good hole cleaning. High velocity turbulent flow is very good for preventing cuttings accumulation
- Rotation RPM has a high impact on hole cleaning. In general high RPM is positive and more so for small hole sizes.
- ROP
- Cuttings size

In long horizontal sections hole cleaning is often problematic, with insufficient cleaning as a result of gravity pulling cuttings out of suspension. Rotation is then used to agitate the deposited cuttings. In some cases it is not possible to agitate the deposited cuttings and a bed of cuttings forms.

Cuttings accumulation in the bore hole can result in problems including: excessive over pull on trips, high torque, stuck pipe, hole pack-off, excessive ECD, slow rates off penetration, and difficulty running casings and logs(11).

2.1.10 Buckling

In wells with a long inclined or horizontal segment, drag can become a problem. To keep the weight on bit (WOB) additional axial compression is used. When sufficiently high levels of axial compression are imposed on a drill string it will buckle in a sinusoidal fashion. A further increase in axial tension will lead to helical buckling where the drill string will spiral in the well bore and reach a helical configuration with a massive increase in drag, and possible lock up as result(12).

The pipe starts to buckle in a sinusoidal fashion at the critical buckling force(13,14,15):

$$F_c > 2\sqrt{\frac{EIW_c}{a}}$$

$a = r_w - r_o$

$a = radial\ clearence\ between\ wellbore\ and\ string$

$E = Young's\ modulus\ of\ elasticity\ (N/m^2)$

$I = area\ moment\ of\ inertia\ (m^2)$

W_c = *Wall side force per unit length(N/m)*

$F_c = critical\ buckling\ force$

The “EI” term is a measure of the pipe stiffness, it’s resistance to bending. The Young’s modulus is material specific, while the area moment of inertia depends on material crossection and shape. For a pipe, I is found through the formula:

$$I = \frac{\pi}{64}(D_o^4 - D_i^4)$$

$D_o = pipe\ outer\ diameter$

$D_i = pipe\ inner\ diameter$

The wall side force is calculated from this formula[15]:

$$W_c = 2(\sqrt{(W_{bp}sin(\varphi) + F_b\varphi')^2 + (F_b sin\varphi\vartheta')^2}$$

$W_{bp} = Bouyed\ weight$ *of pipe*

$\varphi = wellbore\ trajectory\ inclination\ angle$

F_b =*buckling force*

$\vartheta = wellbore\ trajectory\ azimuth\ angle$

$'\ is\ the\ derivative\ with\ respect\ to\ measured\ depth$

If sinusoidal buckling has occurred and more axial compression is added the pipe will eventually buckle in a helical fashion. For the Wellplan simulator the onset of helical buckling is set at 2,8 times the force of sinusoidal buckling, and although there are some disagreement over what formulas or values are to be used, because of the limited understanding of the buckling phenomenon this is a common value in the industry[14,15,20].

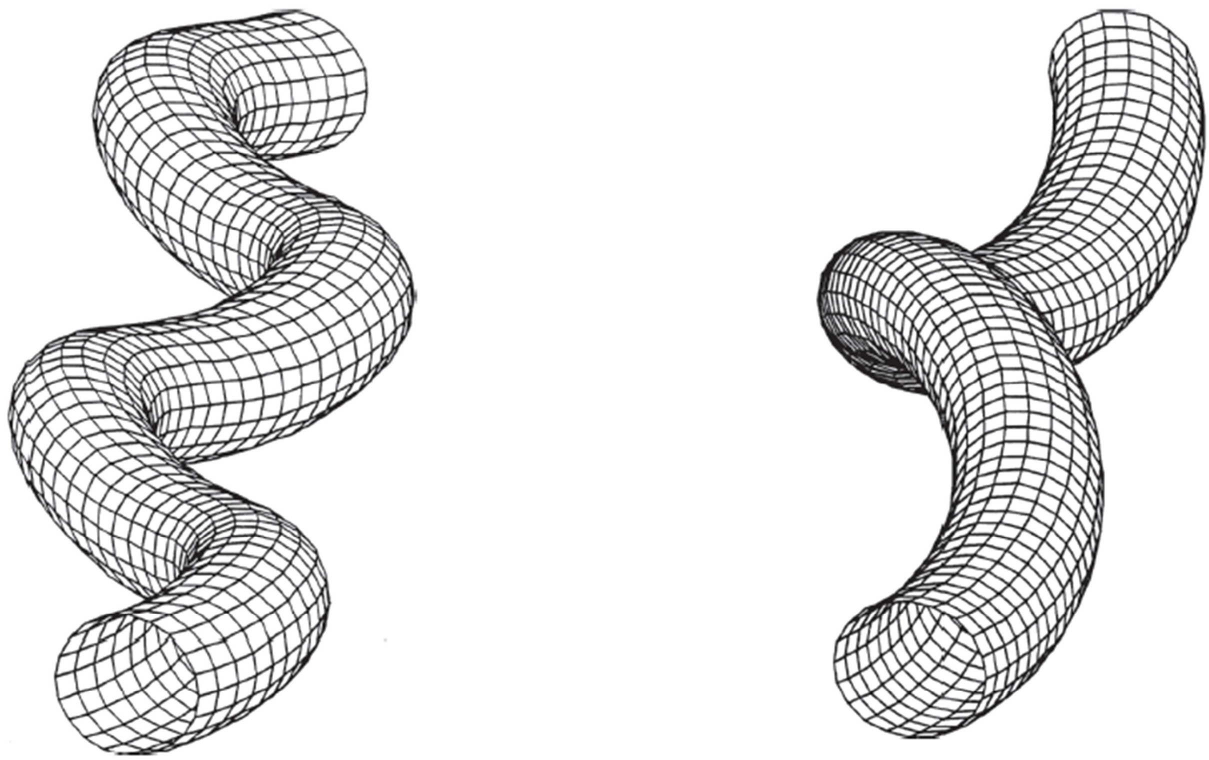

Figure 5: Illustration of sinusoidal buckling and helical buckling[15]

Sinusoidal buckling generates an addition to drag forces but is usually tolerable, while the additional side force generated from helical buckling is much larger and quickly leads to lock-up and a stop in drilling.

The critical buckling force depends on modulus of elasticity, the area moment of inertia, and wall side force. A lighter material than steel will give smaller wall side forces than steel, but if that material is more elastic than steel it could still give a smaller critical buckling load for the same pipe crossectional area.

Manufacturing the pipe with larger OD and the same wall thickness would provide additional buckling resistance, however this will increase annular pressure losses, and much more than the decrease in pressure losses inside the string as a result of the increased ID.

2.2 Fundamentals of hydraulic performance

To obtain good hole cleaning, high mud rates are important in order to agitate cuttings in the well bore and to keep them in suspension. The mud pumps apply an initial pressure to the mud at the top of the string, but this pressure diminishes along the inside of the string until the bit is reached due to frictional pressure loss. More pressure is then lost when crossing the nozzles in the bit and then pressure is lost due to friction in the annulus all the way to the surface.

While frictional pressure loss is not desired inside the string, it is essential for proper bit cooling, lubrication and cleaning. Frictional pressure loss is essential in annulus hole cleaning to suspend and remove cuttings.

The frictional pressure loss in a well increase with length and the additional pressure needed is supplied by the mud pumps. However there are limits to what pressure the pumps can deliver, and also to what differential pressure the drill pipe can withstand. An increase in applied pressure from the pumps will also lead to increased pressure loss in the string and over the bit, so that the annulus will get a smaller increase in pressure than the difference in initial and extra pressure applied from the pumps. To large pressure loss over the bit is also not desirable as it could lead to lower ROP and poorer bit cleaning.

To calculate frictional pressure loss the flow regime has to be determined through use of the Reynolds number(16,17). The formula is valid both for inside the pipe and for the annulus, although the formula for hydraulic diameter differs.

$$Re = \frac{\rho_{fluid} v D_H}{\mu}$$

$Re = Reynolds\ number$

$\rho_{fluid} = fluid\ density$

$\mu = viscosity$

$v = mean\ fluid\ velocity$

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

$Q = volumetric\ rate$

$A = crossectional\ area$

$D_H = hydraulic\ diameter$

Hydraulic diameter inside string

$$D_H = \frac{4A}{P}$$

$$D_H = \frac{4 * 0{,}25\pi D_i^2}{\pi D_i}$$

$$D_H = D_i$$

Annular hydraulic diameter

$$D_H = \frac{4A}{P}$$

$$D_H = \frac{4 * 0{,}25\pi(D_w^2 - D_o^2)}{\pi(D_w + D_o)}$$

$$D_H = D_w - D_o$$

$P = Wetted\ perimeter\ of\ crossection$

$D_w = wellbore\ diameter$

If the Reynolds number is smaller than 2000 the flow is regarded as laminar, between 2000 and 4000 intermediate and if the Reynolds number is larger than 4000 the flow is regarded as turbulent[16,17]. These are however not absolute values, and variation is to be expected.

In laminar flow, fluid flows in parallel layers with no disruption between the layers. Each layer moves parallel to the adjacent one without mixing.

With rising Reynolds numbers eddies and vortexes and other instabilities come into existence. Originally these instabilities originate from the wall of the pipe, but these near wall instabilities will disturb flow in the other layers in turn and cause more turbulence.

The importance of turbulence in pressure loss calculations stems from the greatly increased friction and frictional pressure loss in a pipe with turbulent flow compared to laminar flow.

For calculating pressure losses there are different formula for laminar or turbulent flow, and for string or annulus. Also, these formula depend upon whether the fluid is Newtonian (constant viscosity), or non-Newtonian (flow rate shear dependent viscosity). There are several different mathematical models describing non-Newtonian fluid behavior, but all of these are approximations, even for steady state flow. One of the models commonly used by the oil industry is the Bingham plastic model, which also is the simplest of the non-Newtonian flow models. The formulas used in this model for friction pressure drops in both pipes and annuli are given in the drilling data handbook, and are shown in the table below[18].

	Drill string	Annulus
Laminar	$\Delta p = \frac{LQ\mu_p}{612{,}95 * D_i^4} + \frac{\tau_o L}{13{,}26 D_i}$	$\Delta p = \frac{LQ\mu_p}{408{,}6(D_w + D_i)(D_w - D_o)^3} + \frac{\tau_0 L}{13{,}26(D_w - D_o)}$
Turbulent	$\Delta p = \frac{L\rho^{0{,}8} Q^{1{,}8} \mu_p^{0{,}2}}{901{,}63 D_i^{4{,}8}}$	$\Delta p = \frac{L\rho^{0{,}8} Q^{1{,}8} \mu_p^{0{,}2}}{706{,}96(D_w + D_o)^{1{,}8}(D_w - D_o)^3}$

Table 1: Pressure loss equations from drilling data handbook[18]

$\Delta p = pressure\ loss$

$L = length\ of\ wellbore$

$\mu_p = plastic\ viscosity$

$\tau_o = Yield\ value$

These formulas are valid for Bingham fluids and the calculations in chapter 2.2.1 and 3.3 are based on these formulas. The simulations used for T&D and buckling are also based on the Bingham plastic fluid model.

The string has to be divided into segments for calculations as there are differing well outer diameters along the length of the wellbore such as in the cased and open hole sections.

2.2.1 Diameter

The inner diameter (ID) is critical for hydraulic performance, since it is both important in determining Reynolds number and therefore flow regime, and the frictional pressure loss in the pipe. It is also one of the factors that vary between the different drill pipe alternatives.

For determination of flow regime there exists a linear relation between flow cross sectional diameter D and Reynolds number Re, as seen from the equation of Re.

For the friction pressure loss equations there is a non-linear relationship between hydraulic diameter and pressure losses where there is a large increase in pressure losses when the hydraulic diameter nears zero. For laminar flow pressure loss increases with $1/D^4$, while for turbulent flow it increases almost with $1/D^5$. For complete turbulent flow it increases with $1/D^5$, but it is usually assumed that the turbulent flow is not fully developed. The standard assumption in the Drilling Data Handbook is that pressure loss increases with $1/D^{4.8}$ as diameter decreases.

The values used in figure 7 and 8, are taken from the preliminary mud design to be used at the Skrugard field, and the rate of 2000 l/min is taken from reviewing offshore drilling reports and represents a number somewhere between high and low rates.

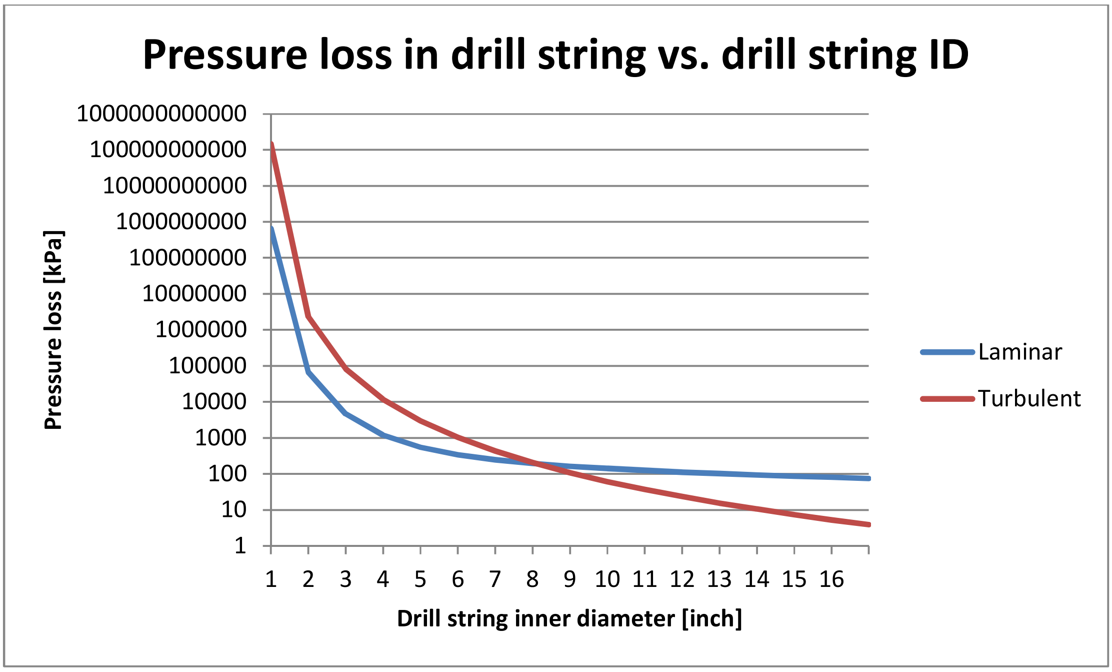

Figure 6: Pressure loss inside drillstring vs. inner diameter of drill string for a 1000 m well with Q=2000l/min, μ_p=20 cP, and 1,22 kg/l

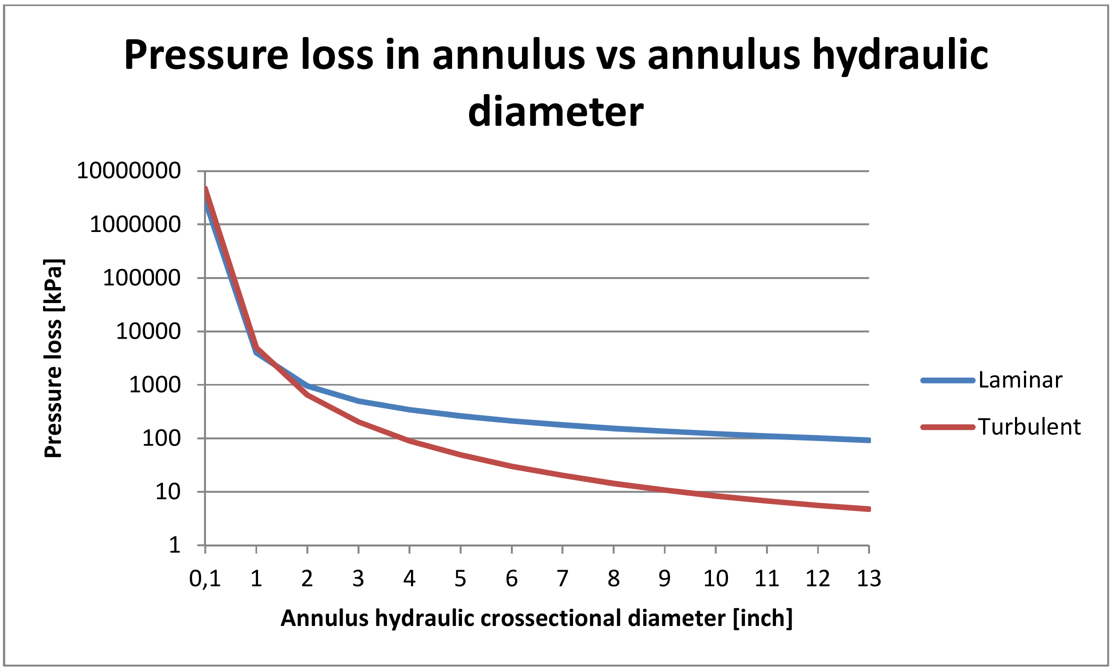

Figure 7: Pressure loss in annulus vs. annulus crossectional diameter for a 1000 m well, m well with Q=2000l/min, μ_p=20 cP, and 1,22 kg/l

2.2.2 Equivalent circulating density (ECD)

ECD is the effective pressure exerted by a fluid on the formation while circulating, but converted to density. ECD is calculated by adding the density of the fluid and the annular frictional pressure loss converted to density. ECD is useful to avoid too large pressure fluctuations in pressure sensitive formations.

While mud density can be within the fracture gradient for the formation, the ECD can be over the gradient and the fluid pressure can then fracture the formation, leading to potential losses and/or kicks.

ECD is usually calculated through the formula:

$$ECD = \frac{\Delta P_{ann}}{g * TVD} + \rho_{mud}$$

$\Delta P_{ann} = Frictional\ pressure\ loss\ in\ annulus\ (pascal)$

$TVD = True\ vertical\ depth$

$\rho_{mud} = Mud\ density\ (kg/m^3)$

ECD can also be expressed as density compared to water (s.g.)

As can be seen from the formula ECD is directly affected by annular pressure loss, which is affected both by annular crossectional diameter and well length. Increasing well length, or decreasing annular crossectional area will directly impact annular pressure loss and therefore ECD.

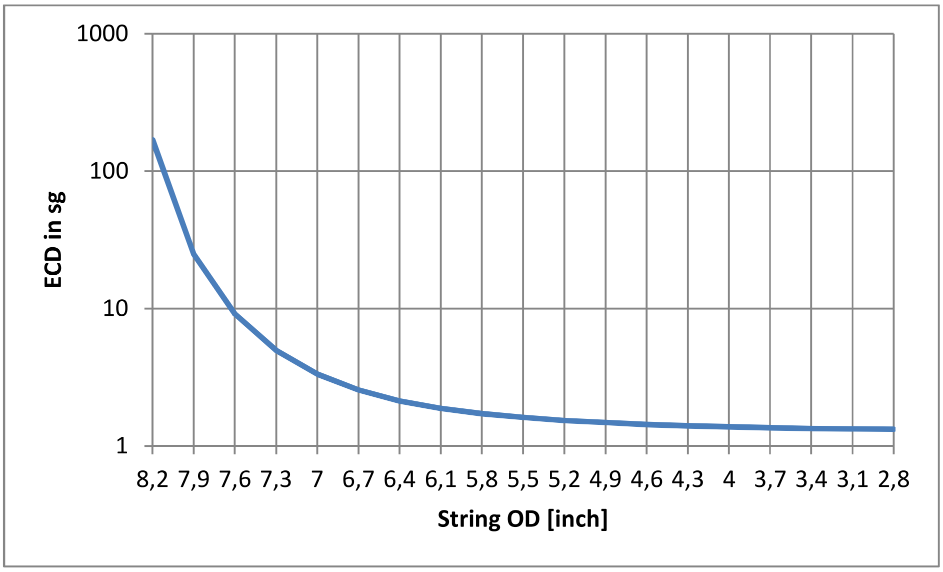

Table 2: ECD as a function of string OD

2.3 Wear

Abrasive wear is a result of drill pipe contact with borehole/casing wall.

Wear rates are dependent on:

- surface hardness of the pipe material
- friction
- sliding distance
- rock abrasive properties
- pressing against formation force
- lubricating properties of drilling fluid[21].
- With differing materials there will be different pressing against formation force, and surface hardness, resulting in less wear for the lighter and harder materials.

Excessive drill pipe wear could lead to loss of pressure integrity, possible leakage, or twist off of the string.

Casing wear may also be a problem in long wells, as it may result I loss of pressure integrity and possible leakage.

Casing wear depends on:

- Wear when installing the casing
- Surface roughness and material of the drill string
- Pipe pressing against casing force
- Hardness of the drill string material
- Lubricating properties of the dilling fluid

2.3.1 Surface hardness

The surface hardness of drill pipe depends on material and treatment of the material. Steel can for example come in many hardness grades dependent on hardening or tempering, and increased hardness often gives reduced ductility and toughness. Hardened steel often have increased hardness, tensile strength and yield strength, and lower ductility and toughness.

There are several hardness scales in use, with the Rockwell C scale often used for steel, and the brinell scale frequently used for less hard materials such as aluminum.

When converted from Rockwell C S-135 steel is about 270 BH on the brinell scale, which is about twice as hard as aluminum for example, which is typically 120-140 HB(9,38).

Surface hardness is essential in wear, as harder surface will result in substantially less wear when drilling, if all other factors are the same.

2.4 Fatigue

Material fatigue is a failure experienced by materials that undergo cyclic loading stresses. The material failure occurs at much lower stresses than the material tensile/yield strength because of the cyclic loading. Fatigue behavior is usually described in a S-N diagram with stress amplitude (S) and number of cycles (N) at the two axis.

Fatigue can be a problem in drilling because of bending and rotating simultaneously in curved regions of the well path. If the stresses experienced are large enough fatigue accumulates with every revolution of the string(2).

3. Alternative materials for drill pipe

It is important to point out that, since the field used in this thesis is about to be developed, the alternative pipe materials presented is based on what is presently available for drilling. Aluminum, titanium, and high strength steel is under production and easily available in the short term. Composite pipe needs to be designed for the specific application, and produced in large quanta. With the timeframe of several years before the drilling campaign in the Skrugard area it should be available for drilling.

A summary table of the material properties compared to S-135 steel will be presented at the end of this chapter. The properties for aluminum used for calculations in the whole chapter 3 are obtained through Alcoa Oil&gas(29,30). Titanium values are obtained from titaniumengineers(31), CDP values are obtained from ACPT Inc(47) and for high strength steel trough Grant Prideco(45).

The CDP pipe can be manufactured to meet many requirements by adjusting the angle of the fibre weaving. With more axially oriented fibers, the tension yield strength will increase, while orienting the fibers less axially will give torsional strength, and higher pressure rating. For the calculations in this chapter, the properties of the CDP from the Statoil report is used(47).

Drill pipe dimensions available for the different alternative materials available differ. This is because some materials rely on thicker walls to achieve the necessary stiffness, yield strength, and/or other qualities. The tool joints are the same for all the alternatives, and this is realistic because all the alternative drill pipe materials are manufactured with steel tool joints.

Material	S-135	TDP	ADP	UD-165	CDP
pipe OD [inch]	5,5	5,5	5,68	5,5	6
pipe ID [inch]	4,778	4,5	4,68	4,94	5
Wall thickness [inch]	0,361	0,5	0,5	0,28	0,5
Tool joint OD [inch]	7,5	7,5	7,5	7,5	7,5
Tool joint ID [inch]	3	3	3	3	3
Tool joint wall thickness	4,5	4,5	4,5	4,5	4,5

Table 3 - Drill pipe and tool joint dimensions for the different drill pipe alternative materials

3.1 Use in the field

3.1.1 Aluminum DP

Aluminum has been used for drilling wells for decades, mostly in Russia and the former Soviet Union, where aluminum alloy drill pipe (ADP) is, and has been since the 50's, commonly used[24,25]. In the 1980's ADP averaged about 80% of all drill pipe in operation in the soviet union[21].

3.1.2 Titanium DP

TDP has been manufactured and used on a limited scale for ultra-short radius drilling (USR), but because of the high cost (7-10 times that of steel) it has seen limited use in drilling. Because of qualities like low density, high strength, flexibility and superior corrosion resistance, titanium is very suitable for drilling[26].

3.1.3 Composite DP

In 1998 the U.S. Department of energy funded a three year program to develop and qualify CDP. Today both $3^5/_8$ and 6 inch OD CDP is available for use in drilling, but is not widely adopted by the industry[27]. This is probably because SDP is usually sufficient for drilling and CDP is more expensive and less known in the industry. Like the other alternatives CDP has strengths and weaknesses that makes it potentially useful in drilling some wells, while it will be a bad alternative for drilling other wells.

3.1.4 High strength steel DP

Over the last years high strenght steels like Z-140, V-150 and UD-165 has been developed, with much higher yield strength than ordinary S-135. The Z-140, V-150 and UD-165 is not yet been adopted by API but as can be seen from figure 9 both Z-140 and V-150 has been sold and used extensively for over ten years now, while UD-165 is a relatively new product and has just been sold for a few years [28].

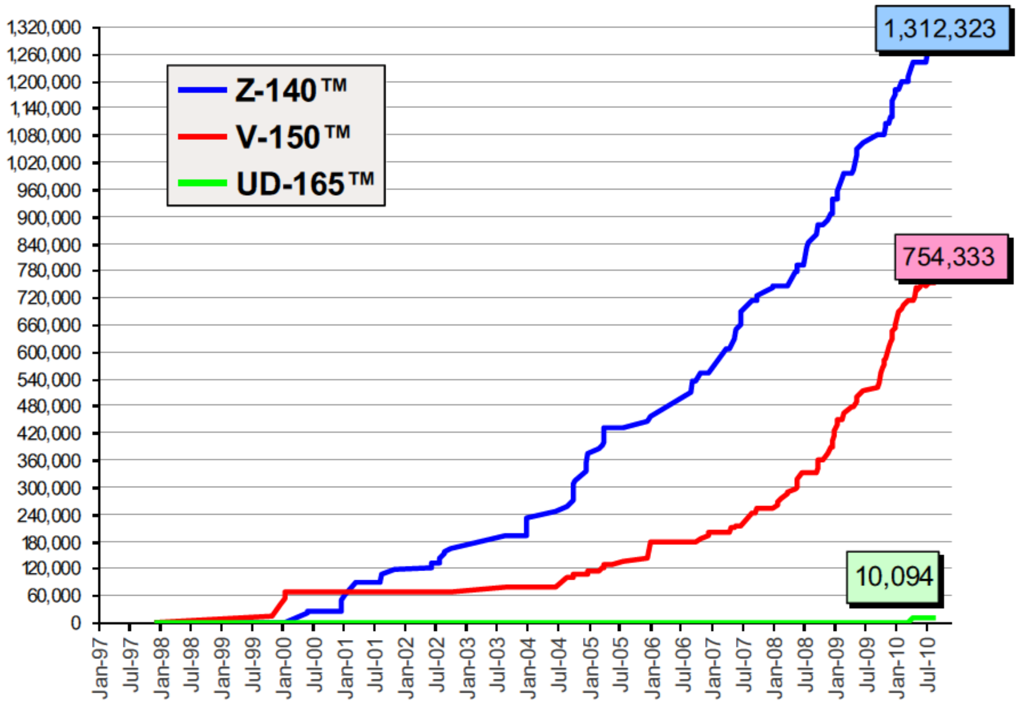

Figure 1 – Cumulative footage of high strength drill pipe sold to date. Grades Z-140, V-150 and UD-165 have not yet been adopted by API but have been in use for many years.

Figure 8: Cumulative sales of high strength steel DP in feet[28]

3.2 Torque and drag

3.2.1 Aluminum drill pipe

ADP offers greatly reduced drag and torque in drilling, as an effect of the light weight. Aluminum alloys are typically about a third of the weight of their steel counterparts, so even with the added weight of steel tools joints 5,68 inch ADP weights 55% of the conventional 5,5" SDP counterpart, when submerged in mud the ADP also benefits from greater buoyancy than SDP, further reducing weight compared to S-135 SDP to 44% in a 1,22 sg. mud.

The yield strength of the strongest aluminum alloy used in DP is 69 ksi, and about half of the 135 ksi of S-135 SDP[5]. Aluminum is also more sensitive to increased temperature than steel and, the yield strength of aluminum can be further reduced by temperatures above 250°F[27].

The STWR for aluminum is 15% higher than for S-135 DP submerged in 1,22 sg. mud.

With under half of the buoyed weight of S-135 DP there will be a large decrease in friction and torque and drag. The low weight and high strength to weight ratio means that ADP will be able to drill longer wells as long as torque and drag is the limiting factor.

The low Young's modulus of aluminum (35% of S-135) makes ADP susceptible to buckling and this can severely limit the length possible to drill, especially in wells with high doglegs. The added wall thickness partially offset the lower Young's modulus, but pipe stiffness is in total half (50%) of S-135 stiffness making buckling a concern. ADP light weight will reduce drag forces somewhat, and this should help in preventing buckling

3.2.2 Titanium drill pipe

TDP (6246 alloy) typically has a density of 4,65 g/cm^3 which is about 59% that of S-135 steel. With tool joints of steel the weight is 70% of S-135 pipe, and adding buoyancy the difference increases to 63% for 5,5" OD TDP submerged in 1,22 sg mud.

TDP has a very high YS of 135 ksi, which equals the 135 ksi YS of S-135. The lower density of titanium gives a remarkable strength to weight ratio of 163% of S-135 STWR.

The reduction in weight translates directly into a large reduction in normal force and friction, and hence torque and drag, for a horizontal section. When accompanied with increased YS compared to S-135 any use of TDP will give the opportunity to drill longer wells.

TDP like ADP has a lower Young's modulus than S-135 SDP. While higher than the Young's modulus of ADP it is still only 55% of the S-135 Young's modulus. This severely impacts pipe stiffness and even with the thicker walls the total stiffness is 71 % of S-135 making buckling a concern. The lower weight will also help to reduce drag and this will help in preventing buckling.

3.2.3 Composite drill pipe

Like TDP and ADP the reduced weight of CDP will give reduced drag. In air CDP weighs only 43% of S-135 DP. This extreme difference is only increased submerged in mud, where the weight of CDP is only 29% of the S-135 weight.

CDP has relatively low YS, but as the weight is so much lower than the weight of S-135, CDP still has a STWR that is 15% higher than for S-135.

CDP has a very low young's modulus of just 16% of the S-135 Young's modulus. Despite the light weight, it is therefore very susceptible to buckling. This is somewhat compensated for by both increasing wall thickness and OD compared to S-135, but the resulting stiffness is still only 28% of S-135 stiffness. The light weight will also to some degree compensate for the low stiffness as the drag forces will be lower.

3.2.4 High strength steel drill pipe

The density of UD-165 is the same as for S-135 making these two steels the same weight for the same volume. Downscaling the pipe wall reduces the volume of the metal, but also decreases the buoyancy of the pipe. In air the weight of a UD-165 pipe is 80% of a S-135 pipe. Because of a very small difference in density the buoyed weight is still 80% of S-135 in a 1,22 sg mud.

UD-165 has a YS of 165 ksi which is 22% higher than the YS of S-135, making it the material with the highest YS of the alternative drill pipe materials. The combination of lower weight and higher YS gives a excellent STWR that is 52% higher than STWR for S-135, and UD-165 pipe is only bested by TDP in STWR.

The lighter weight of the UD-165 alternative should help to reduce torque and drag and help to extend well length if torque and drag are limiting factors.

Young's modulus for S-135 and UD-165 is the same, but since the cross sectional area is different, UD-165 has 19% less stiffness than the S-135 alternative. This of course means that UD-165 is more susceptible to buckling than S-135 DP.

UD-165 DP could be produced with the same dimensions as ordinary S-135, and would then have the same stiffness, and the same buckling resistance. The UD-165 pipe would in this case also have the same weight, and since buckling is the limiting factor in this field, it would not increase maximum drillable length. UD-165 could be manufactured to other dimensions, but since the yield strength is not a limiting factor, S-135 could be manufactured to the same dimensions and be the cheaper alternative.

3.3 Hydraulic performance

The values used for calculation of pressure losses are from the oil based mud (OBM) proposed used for drilling Skrugard and are the same, except for ID and OD, for all the alternatives:

L [m]	Q [l/min]	μ_p [cP]	τ_o[lb/100ft^2]	ρ [kg/l]
3454	2000	20	21	1,22

Table 4: Values used for calculation of pressure losses(32)

The mud that is used for drilling is a OBM with density 1,22 s.g. Rheological data are:

RPM	Θ	Type of mud
600	61	Oil based
300	41	
200	34	Length: 3458m
100	25	
60	21	
30	17	
6	13	
3	11	

Table 5: Rheological data for the mud that is planned used at this point in drilling the Skrugard field(32)

The formulas used are from the drilling data handbook, and although tool joint size is not accounted for in a separate part of the formulas, they are accounted for by the numerical factor and the exponents in the formulas.

The diameter of the wellbore also differs along the well, with a diameter of 8,535 inches for the cased hole, and 8,5 inches for the open hole. The 9,625" OD (8,535" ID) casing is set at 1580 mMD and the open hole extends the remaining 1878 mMD of the well. For the full casing program see table 6.

3.3.1 S-135 Steel DP

The pressure loss in a pure S-135 drill string is 68 bar, for a length of 3458m, while the ECD is 1,44 s.g. As the mudweight is 1,22 sg the frictional pressure loss accounts for 0,21 sg of the ECD value.

3.3.2 Aluminum DP

Aluminum pipe has thicker walls compared to S-135 SDP to achieve the necessary structural properties (torsional strength, tensile capacity, pipe stiffness and pressure integrity) needed to replace SDP. The added wall thickness is either accommodated by enlarging OD reducing ID or both. This increases frictional pressure losses in the string or annulus or both, reducing hydraulic performance and/or increasing ECD.

For aluminum the combined pressure losses for a 3458 m well, using the Drilling data handbook formulas, will be 77 bar. This is an increase of 9 bar, or 13%, compared to using S-135 DP and would have little impact on hole cleaning. With longer drilled distances this will change however.

The ECD when using an all-aluminum string, compared to a S-135 string, will increase from 1,44 s.g. to 1,48 s.g. The increase is quite small for the selected rate, but if the rate is increased the ECD difference will increase as well and may impact drilling the well. The difference in ECD will also increase with increasing well length.

3.3.3 Titanium DP

TDP has thicker walls compared to S-135 SDP to achieve the necessary structural properties, in this case mostly related to buckling. The added wall thickness is either accommodated by enlarging OD reducing ID or both. This increases frictional pressure losses in the string or annulus or both, reducing hydraulic performance and/or increasing ECD.

For TDP the combined pressure losses for a 3458 m well, using the Drilling data handbook formulas, will be 81 bar. This is an increase of 13 bar, or 19%, compared to using S-135 DP and would have little impact on hole cleaning. With longer drilled distances this will change however.

ECD will be the same for TDP as for S-135 as OD is the same, and the ECD will follow the ECD for S-135 steel drill pipe with extended bore length.

3.3.4 High strength steel DP

High strength steel has thinner walls than S-135 so it is no surprise that the total frictional pressure losses are 9% smaller than for S-135 at 62 bar. This will lead to increased hydraulic performance.

ECD will be the same as for S-135 DP since the OD is the same, and the ECD will follow the ECD for S-135 steel drill pipe with extended bore length.

3.3.5 Composite DP

For a composite drill string the OD is enlarged to reduce buckling. This affects annular pressure losses and therefore ECD. CDP has a frictional pressure loss of 78 bar for the selected volumetric rate. This is 15% more than for S-135 and is comparable to the values for TDP and ADP. ECD however is significantly higher for CDP than for the other alternative materials due to the large OD. ECD is 1,57 sg, which is 0,14 sg more than for S-135. The extra ECD is of course only a probem if the window between the pore pressure gradient and the fracture gradient is small, or if the fracture gradient is low.

The increased ECD could mean that shorter sections can be drilled before casing is run, and smaller hole sizes to target depth.

3.4 Wear

3.4.1 Aluminum drill pipe

When it comes to wear ADP has about half the Brinell surface hardness (120-140 HB) than SDP (about 270 HB converted from Rockwell C), and this gives a higher rate of wear[43].

As wear is also influenced by weight in sum wear on ADP is usually lower than on SDP all factors being equal. ADP can also be produced with a thicker layer in the middle of the pipe for increased toughness in high-wear environments[21]. Wear problems can be a factor in dog-leg (DL) areas where the ADP suffers contact with the borehole wall, especially if the drill pipe also is subjected to high tensile stresses[2].

3.4.2 Titanium drill pipe

TDP hardness surpasses that of S-135 SDP. For the titanium alloy used in the TDP for this thesis the brinell hardness is 428 (converted from Rockwell C)[31]. This combined with the lower weight that also reduces wear points to TDP wear being significantly less than S-135 wear.

Studies have however shown increased wear in titanium when rotating inside steel casing. When the oxide layer protecting the titanium has been mechanically worn away titanium acts as an anode to steel and corrodes. TDP wear is still in the region of SDP wear, and is if anything less susceptible to wear than SDP[33].

3.4.3 High strength steel drill pipe

Wear for UD-165 should be less than for S-135 as the pipe itself is lighter. With less gravity force pushing the pipe into the formation the wear should be substantially less. This steel grade is also significantly harder than S-135 with a brinell hardness of 360 HB compared to 270 HB for S-135, and this should help in reducing wear.

On the other hand the pipe wall is thinner and this would mean that even if total wear is less than for S-135, a larger percentage of the pipe wall would be removed than for S-135.

3.4.4 Composite drill pipe

There is little field data on CDP wear, but this is a known problem and steps to reduce wear have been taken. Pipe body wear is handled by applying coating to the pipe, or winding wire on the outside of the pipe. What effects these coatings have on wear remains to be seen.

3.5 Fatigue

3.5.1 Aluminum drill pipe

A study by Lubinsky et al.[40] concluded that ADP would "suffer much less fatigue damage than SDP in dog-legs". The low pipe stiffness is probably the reason why ADP sustains less fatigue than SDP in dog-legs.

3.5.2 Titanium drill pipe

Like ADP, TDP has been found to be much more resistant to fatigue than SDP[41], which is one of the reasons that it has been used for ultra-short radius drilling where dog legs are up to 230^{o}/30m. Like ADP this probably is an effect of the low pipe stiffness.

3.5.3 Composite drill pipe

Composite fatigue testing is more complex than for other materials. This is because composites can be wound in different directions, and combined with different resins. It is therefore hard to say something about this kind of material fatigue capabilities.

3.5.4 High strength steel drill pipe

UD-165 has been fatigue tested together with the V-150 grade steel. The testing was run at 10 Hz until failure or 1 million cycles, with progressively higher stress up to the steel grades respective yield strength. UD-165 performed better than V-150 and reached 1 million cycles with 166,3 ksi stress(48).

From these results it would seem that UD-165 is resistant to fatigue.

4. The Skrugard field

4.1 Location

The Skrugard field was discovered in 2010/2011 and is situated in the Barents sea about 240 km from Hammerfest LNG, 200 km from Bjørnøya and approximately 100 km north of the Snøhvit field. Seadepth is around 370 m and reservoir depth is approximately 1300 m(35,36).

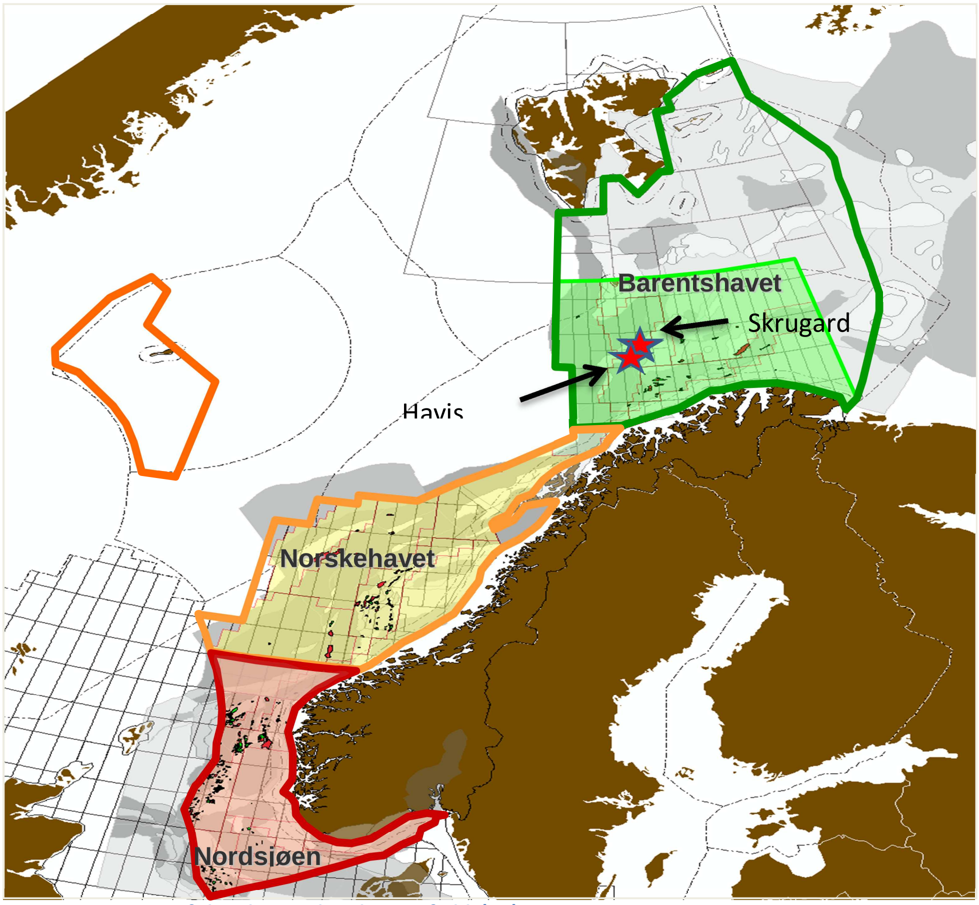

Figure 9: Location of the Skrugard and Havis fields(37)

Skrugard is located next to the Havis prospect which was discovered in January 2012. The two fields are just 7 kilometres apart and there are several other prospects in the vicinity. It is therefore possible that more than one field will be producing to the Skrugard production facility. The plans for developing this field and the Havis field is far from finalized, but there are challenges to be met with regards to the fields arctic placement and the distance to land in an area with little existing infrastructure.

There are also environmental concerns to contend with as the Barents sea is an important fishing zone both for Russia and Norway. The arctic ecosystems is by environmentalists considered too vulnerable to risk oil extraction, but the Norwegian government has refused to establish protected areas, and the entire Barents sea is therefore open for drilling through normal concession rounds.

4.2 Seabed conditions

Extensive sea bed surveying has been carried out on the Skrugard area using ROV.

The seabed slopes very gradually towards the north of the field, from a depth of 349 m in the south to 409 m in the north.

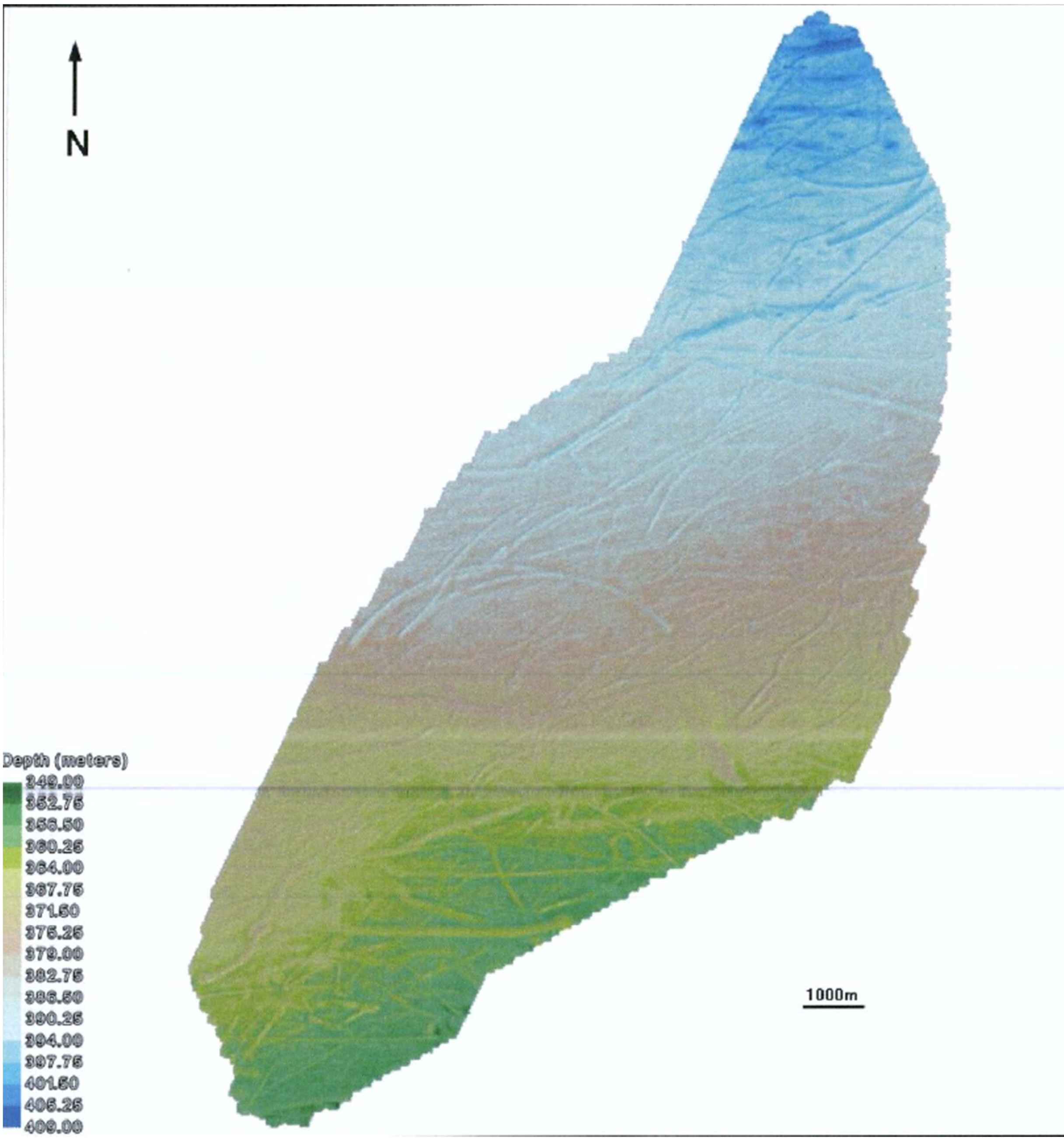

Figure 10: Map of the Skrugard/havis area with depth shading(34)

There are numerous elongate depressions with U-shaped profiles, probably ice-berg plough marks. The slopes down these scour marks are very steep (commonly 20^{o}, several examples up are 35^{o}). The larger plough marks are typically 100 m wide and 10 m deeper than the local seabed.

The seabed predominantly consists of very soft clay, interlaced with small boulders. The whole area shows signs of intensive trawling activity and a few anchor marks.

The ice-berg plough marks have impact on the template locations for the field. The templates cannot be placed in the steep inclines towards the plough marks and several templates has been moved down into the large scour marks, while other has been moved away from them(34).

4.3 Sandbody distribution

The Skrugard field is comprised of three major sandbodies oriented in a north-south direction as illustrated in figure 1. There is likely communication between the three both through the oil zone and the underlying aquifer(36).

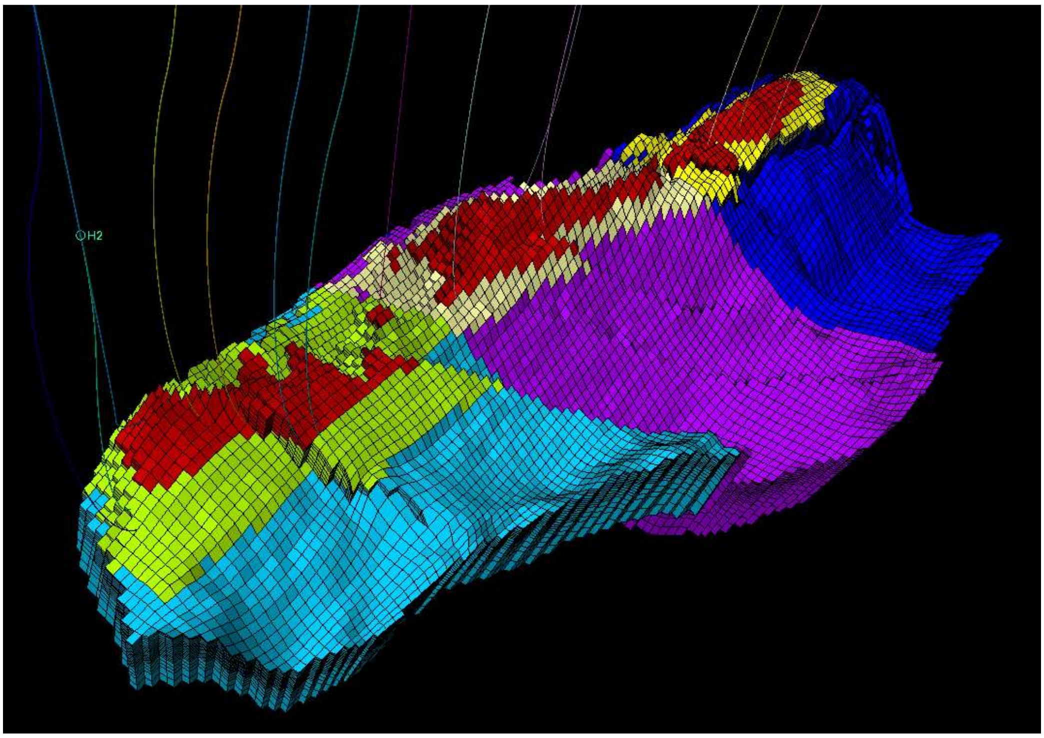

Figure 11: Illustration of the Skrugard reservoir indicating the three major sandbodies (37)

As is seen from figure 3 there are quite a few faults within the reservoir which could contribute to zonal isolation to some extent.

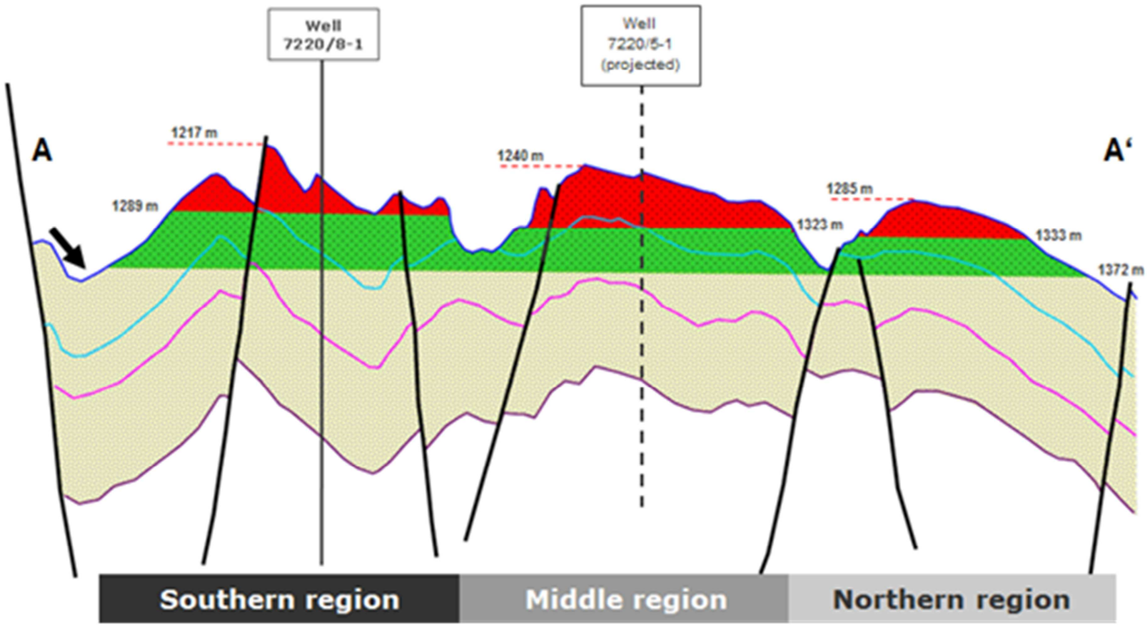

Figure 12: Illustration of fault lines inside the Skrugard reservoir (37)

The reservoir is planned developed with 14 oil producing wells, 7 water injectors and 3 gas injection wells[38].

4.4 The reservoir

The reservoir is situated in the Stø, Nordmela, Tubåen, and possibly Fruholmen formations. These formations date from the early to middle jurrassic age. The cap rock is a late cretaceous shale [38].

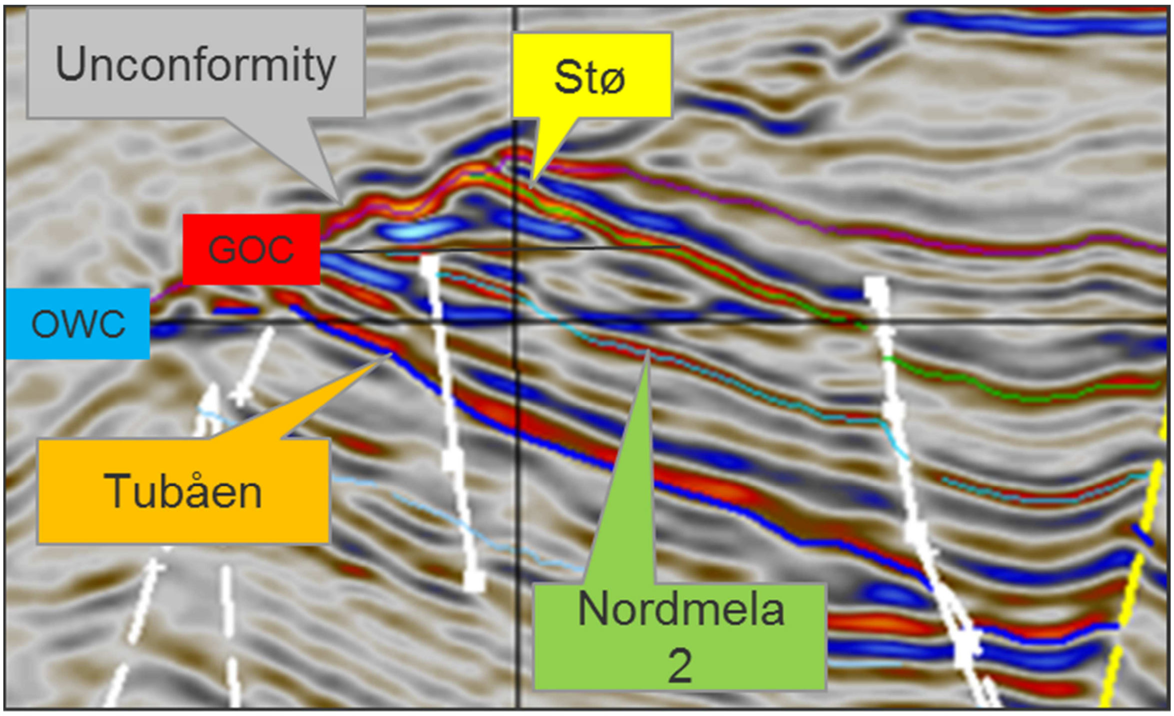

Figure 13: Seismic image with main oil-relevant formations outlined(38)

The reservoir pressure is quite low at 141 Bar making injection important to maintain production and the temperature at 38°C is low, giving viscous oil. The porosity is measured to be 22 % and with a permeability of 1,1 Darcy, the reservoir conditions must be said to be good[38].

The reservoir has high scaling potential due to high levels of Ba^{2+}, Sr^{2+} and Ca^{2+}[39].

4.5 Hydrocarbon data

The reservoir sections have varying hydrocarbon columns, with the southernmost part of the reservoir containing the largest column of 155 m, 83 of them containing oil and 72 m of gas cap. The oil which has an API density of 31 at standard conditions is a Light/medium crude oil with a GOR of 60 Sm^3/Sm^3 [38,39].

Estimated hydrocarbon volumes range from 150 to 250 million barrels of oil equivalents (BOE), but could be as high as 500 million BOE. Statoil is operator of the field with a share of 50%, with Eni (30%) and Petoro (20%) as partners[35].

Together with the Havis field located in the same license the hydrocarbon volumes is 400 to 600 million of recoverable BOE[35].

4.6 Development

The field is planned developed together with the Havis field as a subsea development with hydrocarbons returned to rig. The subsea part of the project consists of a series of templates situated at the sea bed, each with a small number of wells, production, injection or both, associated with them.

The most likely scenario is returning the oil production an floating production, storage, and offloading platform to be processed and temporarily stored for shipping to shore, while the gas and water will be reinjected[38].

4.7 Special considerations

The Skrugard reservoir is very shallow with a TVD down to the reservoir of only 1297 m. This is quite a challenge as the planned horizontal or near horizontal production wells has to be kicked off as early as possible in order to build the required angle without extreme dogleg sections. The weak unconsolidated formation at this shallow depth could resist the attempts at steering, forcing higher doglegs at greater depths. The unconsolidated shallow formations could also collapse or be dug out and this could result in problems such as mechanical sticking.

The reservoir is low temperature at only 38 degrees Celsius, making recovery of oil challenging because of the high viscosity the oil has in the formation. With regards to the low pressure, successful injection is essential to keep oil production at high rates.

5. Results

5.1 Base case data and well information

Below is illustrated the well path of a typical Skrugard oil producer, and this producer reflects well the challenges in drilling shallow reservoir, with 2 sections of high doglegs with around 3,5 degrees continuous build, and with a horizontal tail section. The torque and drag simulations are based on this design.

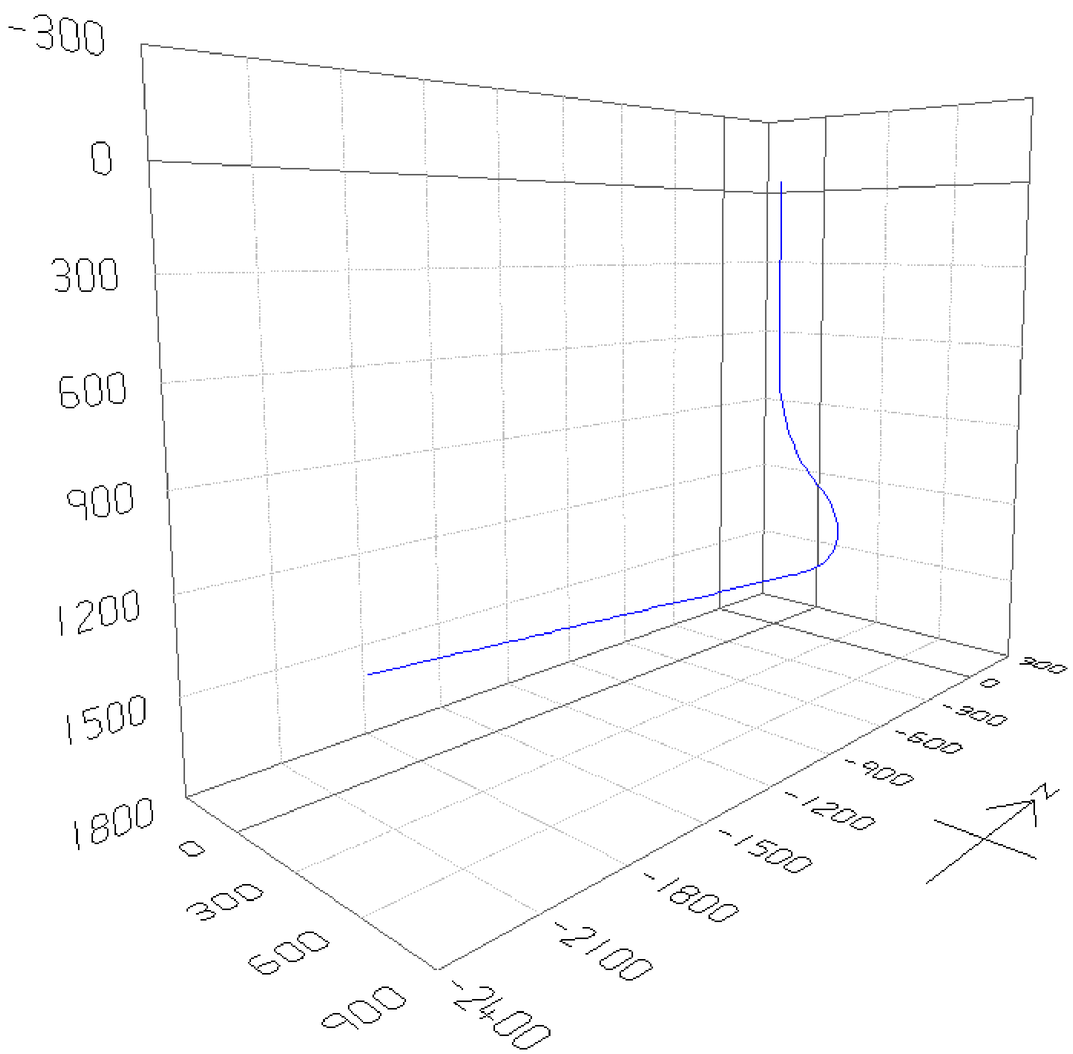

Figure 14: Wellpath of a typical Skrugard oil producer

The full wellpath description is included in appendix 1 for the first 3509mMD, the wellpath used for the max length simulations is the same, only with a lengthened horizontal section. The mud used in the simulations is the same mud as was used in the pressure loss calculations (table 4&5).

The simulator used is Wellplan™, which is developed by the Halliburton owned company Landmark. This program is widely used and is used for well-simulations in Statoil.

The casings are set on the depths given below.

Section Type	Measured Depth (m)	Length (m)	ID (inch)	Friction Factor	Item Description
Riser	375	375	20	0,15	Riser: Vertical, OD = 21,000 in, ID = 20,000 in
Casing	475	100	9,66	0,15	10 3/4 in, 60.7 ppf, C-90,
Casing	1543	1068	8,535	0,15	9 5/8 in, 53.500 ppf, C-95
Open Hole	3509	1966	8,5	0,28	

Table 6: Casing program description

The bottom hole assembly used is of a "standard" variety including a motor. The actual assembly to be used is not planned yet, and as it is of the same design and materials for all alternatives the composition is not of great importance for these calculations.

Section Type	Length (m)	Measured Depth (m)	OD (in)	ID (in)	Weight (ppf)	Item Description
Drill pipe						Different types of drill pipe weight and material
Heavy Weight	9	3344	5,875	4	54,6	Heavy Weight Drill Pipe, 5,875 in, 54,64 ppf, SAE 4145 [SH], XT57
Accelerator	3,05	3347	6,5	2,5	105,1	Accelerator, 6,500 in, 105,08 ppf, 4145H MOD,
Heavy Weight	45	3392	5,875	4	54,6	Heavy Weight Drill Pipe, 5,875 in, 54,64 ppf, SAE 4145 [SH], XT57
Jar	9,5	3401	6,5	2,5	150,0	JRH Dailey Hyd., 6 1/2 in
Heavy Weight	9	3410	5,875	4	54,6	Heavy Weight Drill Pipe, 5,875 in, 54,64 ppf, SAE 4145 [SH], XT57
Drill Collar	9	3419	6,75	3	96,7	Non-Mag Drill Collar 6 3/4 in, 3 in, 4 1/2 H-90
MWD	9,45	3429	6,75	2,81	90,3	Logging While Drilling Stethoscope 675, 6,75 in
MWD	7,53	3436	6,75	5,109	84,4	MWD Tool Telescope 675 HF, 6,75 in
MWD	7,68	3444	6,75	2	107,1	Logging While Drilling Ecoscope w 7 7/8 stab, 6,75 in
MWD	5,6	3450	6,75	2,81	98,4	Logging While Drilling Periscope 675, 6,75 in
Mud Motor	7,7	3457	6,75	3,935	104,8	Bent Housing Xceed 675, 6.75 in
Bit	0,73	3458	8,5			Polycrystalline Diamond Bit, 2x15, 2x16, 0,738 in²

Table 7: bottom hole assembly

The depths included in the table are only valid for the fixed length simulation.

Other important parameters:

		unit
WOB	5	tonne
Torque at bit	5000	Nm
Running in/out	18,29	m/min
Running in/out rotation speed	50	RPM

Table 8: Important parameters for simulations

The properties sheets used for the simulations of each material can be found in the appendix.

5.2 Performance of the different materials

5.2.1 S-135 steel

When using S-135 steel for drill pipe the maximum torque obtained at 3458m MD is 28096 Nm.

The maximum possible length to drill with steel pipe only, is limited by helical buckling while tripping in at 3945 mMD with a torque of 32845 Nm.

5.2.2 Aluminum

For ADP with steel tool joints the maximum torque obtained at 3458m MD is 18519Nm. This is 34% less than drilling with S-135 SDP, this is attributed to the lighter weight of ADP compared to SDP. This value is obtained without considering friction from the helical buckling that happens at 2567 mMD and torque 14945 Nm, that would effectively stop further drilling.

The maximum possible length to drill with ADP only, is 2567 mMD where the pipe will buckle when tripping in even with 50 RPM rotation, due to the torque-value of 14945 Nm. This is 35% shorter than SDP used in the same well.

5.2.3 Titanium

For TDP with steel tool joints the maximum torque obtained at 3458m MD is 21414Nm. This is 24% less than drilling with S-135 SDP, this is attributed to the lighter weight of TDP compared to SDP. This value is obtained without considering friction from the helical buckling that happens at 3269 mMD and torque 20268 Nm, that would effectively stop further drilling.

With titanium drill pipe the maximum possible length to drill is 3269m MD and limited by buckling while tripping in. This is 17% shorter than with standard S-135.

5.2.4 Composite

For CDP with steel tool joints the maximum torque obtained at 3458m MD is 17475Nm. This is 38% less than drilling with S-135 SDP, this is attributed to the lighter weight of CDP compared to SDP. This value is obtained without considering friction from the helical buckling that happens at 1915 mMD and torque 4113 Nm, that would effectively stop further drilling.

With CDP the maximum possible length to drill is 1915 mMD and limited by buckling while rotating on bottom, This is 52% shorter than with standard S-135.

5.2.5 High strength steel

For a UD-165 high strength steel string with the same tool joints as used for the other material strings, the maximum torque obtained in drilling to 3458m is 23749 Nm. This means a reduction compared to S-135 DP of 15%.

The UD-165 string also avoids the buckling issues of both the ADP and the TDP string and allows for drilling to target depth without buckling.

The maximum drillable length is 3558 mMD using the all UD-165 strength steel string, this is 10% shorter than what is possible with an S-135 string.

5.2.6 SDP/ADP tapered string design

To see if a tapered design can have advantages that the other pure material strings do not, a design with 1500 m of ADP in the lower part of the string was simulated. The wellbore trajectory, mud properties, and other factors are the same as for the uniform material strings.

ADP is chosen because it is, by the author, regarded as the material most likely to be used as a replacement for the steel string. Aluminum has seen extensive use in drilling and is therefore better known than TDP or high strength steel. TDP is a better material for drilling, but is just too expensive (7-10 times as expensive) to be a likely solution to the Skrugard drilling scenario. High strength steel could be a good alternative but the downscaled thinner walls is more susceptible to wear than ordinary S-135 DP, and in a field with high dog-legs that will most likely be a problem. In addition since yield strength is not a limiting factor a S-135 string can be produced with downscaled walls, and be cheaper than an UD-165 string.

The tapered string has a maximum torque obtained at 3458m of 20755 Nm. Compared to using only S-135 this gives a reduction of 26%. This is a significant improvement on an all steel string, and this tapered design even performs better than an all TDP drill string.

There is also no buckling problem with this design for the 3458m wellpath, which is as expected with less friction down-hole from the lighter ADP and the stiffer S-135 SDP taking the largest buckling loads in the upper parts of the string.

The maximum drillable length with this design is 4485 m before onset of helical buckling, which is 14% longer than for an all steel drill string. This result can be further improved to some degree by increasing ADP string length but the amount of ADP is limited by the onset of buckling in the aluminum part of the string if the length of this section is too long , and 1500 m is near the limit for maximum ADP content of the string.

	S-135	TDP	ADP	CDP	UD 165	SDP/ADP tapered string	Units
Weight w/tooljoints	26,33	19,33	14,6	11,4	21,1	26,33/14,6	ppf
Compared to S-135 drill string	100 %	70 %	55 %	43 %	80 %	100% / 55%	
Wall thickness	0,361	0,5	0,5	0,5	0,28	0,361/0,5	inches
Wall thickness compared to S-135	100 %	139 %	139 %	139 %	78 %	100 % / 139 %	
Max torque in drilling example well of 3458 mMD	28096	21414	18519	17475	23749	20755	Nm
Compared to S-135 Drill string	100 %	76 %	66 %	62 %	85 %	74 %	
Max drillable length	3945	3269	2567	1915	3558	4485	m
Compared to S-135 Drill string	100 %	83 %	65 %	49 %	90 %	114 %	

Table 9: Summary of alternative material strings compared to S-135 drill string

6. Conclusion

Because of the limited length requirement, torque and drag, hydraulic performance and high yield strength is not always critical to succeed in drilling the shallow reservoir wells. For highly deviated wells with high dog leg sections, as is often the case in shallow reservoirs, the limiting factor is often buckling. The small radii of curvature from vertical to horizontal gives added friction and bending loads on the drill string which increases the possibility of buckling.

The example well used for the simulations was from the Skrugard field, and the calculations and simulations were done for presently available drill strings of different materials, both standard S-135, titanium drill pipe, aluminum drill pipe, composite drill pipe, and high strength (165.000 psi yield strength) UD-165 steel.

In shallow reservoirs the overburden is often unconsolidated and directional drilling is often not possible in the first section of the well, as is the case in the Skrugard field. This increases dog legs further and in the example well leads to two high dog leg sections with 3,3^{o}/30m and 3,8^{o}/30m over 530mMD and 635mMD respectively.

Simulations of the drill string loading during rotary drilling clearly showed that the limitation for drillable length was the onset of helical buckling, long before axial load, pressure load, bending load, or torque load became critical. Buckling while running casing is not considered a problem as the casings can be floated in, by filling them (partly) with air.

Buckling resistance depends on pipe stiffness which increases with pipe diameter, wall thickness and Young's modulus. The pipe outer diameter is limited by the wellbore diameter, and in the example well could not be increased too much without seriously increasing flow resistance in the annulus, with high ECD s an effect. The wall thickness varies between the alternatives, but for the non-steel alternatives it can not be increased sufficiently, due to mud flow resistance, to approach steel pipe stiffness. Young's modulus is material specific, but the non-steel alternatives all have a much lower Young's modulus than steel.

For presently available drill strings with approximately 5,5 inch outer diameter the most buckling resistant pipe is the standard S-135 drill pipe, and none of the alternative materials performs better than S-135 in this respect, due to the low Young's modulus of the alternative materials.. The UD-165 pipe can be manufactured with the same dimensions as S-135 and would then be just as resistant to buckling. However the pipe would weigh the same as S-135 as well eliminating the advantages of light weight.

The only design that would allow for longer wells than the pure S-135 drill pipe string is the tapered design including 1500 m aluminum drill pipe. This alternative allows for drilling longer distances (14% extra in the example well), or reducing torque (26% reduction in example well).

This result is of course only valid for the specific scenario in the example well. Since buckling is the limiting factor, the tapered string will perform even better compared to S-135 drill pipe if the dog-legs, are reduced as will be the case in at least some of the wells. For a scenario with lower dog-legs the other designs will also perform better.

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Nomenclature

$F_F = friction\ force$

$\mu = Friction\ coefficient$

$N = normal\ force\ (a\ force\ perpendicular\ to\ the\ contact\ area)$

$M = Mass\ of\ pipe$

$\rho_{pipe} = density\ of\ pipe$

$V = volume\ of\ pipe\ material$

$r_o = pipe\ outer\ radius$

$r_i = pipe\ inner\ radius$

$L_{tj} = Length\ of\ tool\ joint$

$L_{pipe} = Length\ of\ pipe$

$M_M = mass\ of\ male\ tool\ joint$

$M_F = mass\ of\ female\ tool\ joint$

$g = gravity\ constant$

$\alpha = borehole\ inclination$

$R = friction\ force$

$\mu = friction\ factor$

$\beta = buoyancy\ factor$

$\rho_{fluid} = density\ of\ the\ fluid\ the\ pipe\ is\ submerged\ in$

$\rho_{mo} = density\ of\ mud\ outside\ pipe$

$\rho_{mi} = density\ of\ mud\ inside\ pipe$

$STWR = strength\ to\ weight\ ratio$

$YS = yield\ strength$

$m_{submerged} = submerged\ weight\ of\ one\ joint$

$a = radial\ clearence\ between\ wellbore\ and\ string$

$E = Young's\ modulus\ of\ elasticity\ (N/m^2)$

$I = area\ moment\ of\ inertia\ (m^2)$

W_c = *Wall side force per unit length(N/m)*

$F_c = critical\ buckling\ force$

$D_o = pipe\ outer\ diameter$

$D_i = pipe\ inner\ diameter$

$W_{bp} = Bouyed\ weight$ *of pipe*

$\varphi = wellbore\ trajectory\ inclination\ angle$

F_b =*buckling force*

$\vartheta = wellbore\ trajectory\ azimuth\ angle$

$'$ *is the derivative with respect to measured depth*

$Re = Reynolds\ number$

$\rho_{fluid} = fluid\ density$

$\mu = viscosity$

$v = mean\ fluid\ velocity$

$Q = volumetric\ rate$

$A = crossectional\ area$

$D_H = hydraulic\ diameter$

$P = Wetted\ perimeter\ of\ crosssection$

$D_w = wellbore\ diameter$

$\Delta p = pressure\ loss$

$L = length$

$\mu_p = plastic\ viscosity$

$\tau_o = Yield\ value$

$\Delta P_{ann} = Frictional\ pressure\ loss\ in\ annulus\ (pascal)$

$TVD = True\ vertical\ depth$

$\rho_{mud} = Mud\ density\ (kg/m^3)$

Abbreviations

T&D – Torque and drag

DP – Drill pipe

ADP – aluminum drill pipe

TDP – titanium drill pipe

SDP – steel drill pipe

DL – dog leg

DLS – dog leg severity

YS – yield strength

STWR – strength to weight ratio

MWD – measurement while drilling

TVD – Total vertical depth

ROP – rate of penetration

ECD – equivalent circulating density

WOB – weight on bit

ID – inner diameter

OD – outer diameter

MD – measured depth

OBM – oil based mud

LNG – Liquefied natural gas

ROV – remotely operated underwater vehicle

Appendix

The properties of S-135 is obtained through the wellplan standard catalogue.

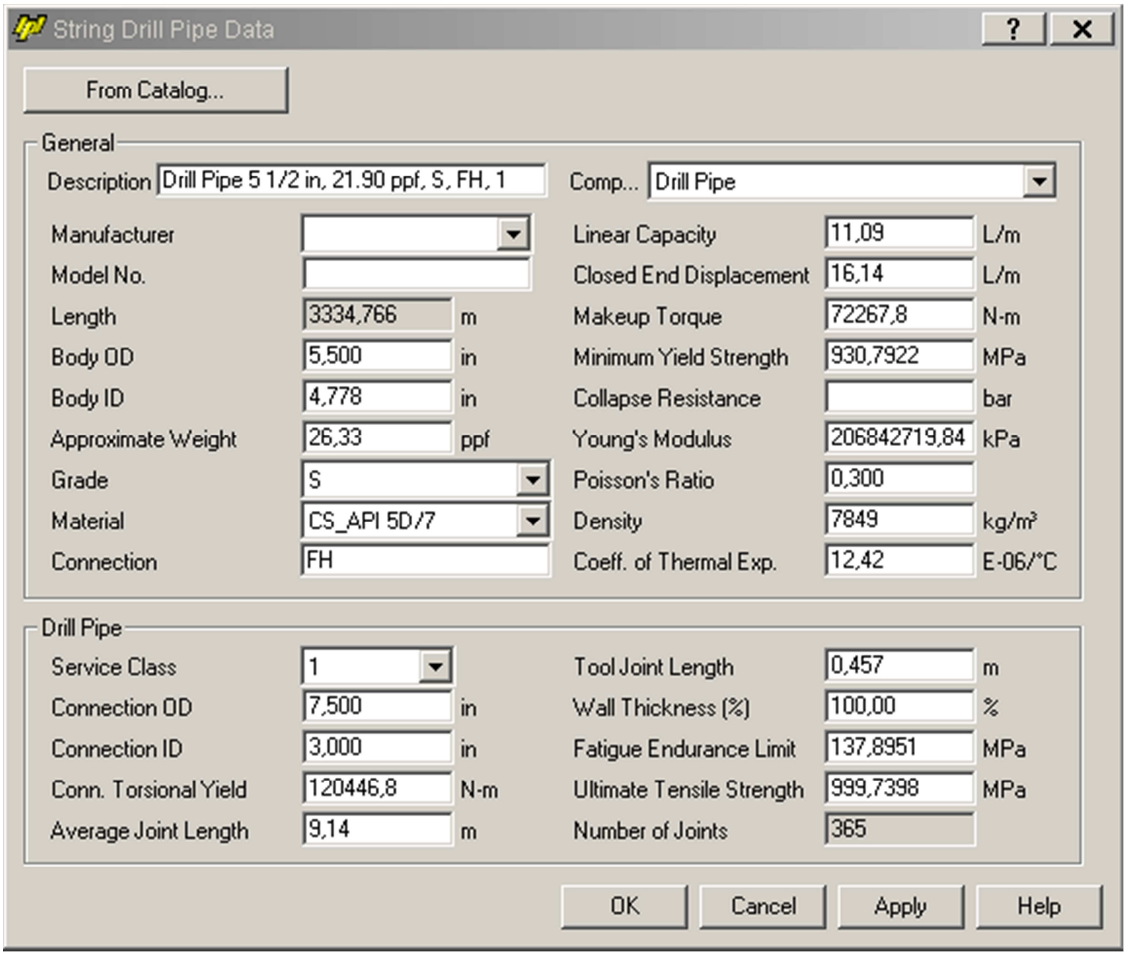

Figure 15: S-135 simulations properties sheet

The properties of aluminum pipe is obtained through Alcoa Inc, who is a producer of commercially available drill pipe[42,43].

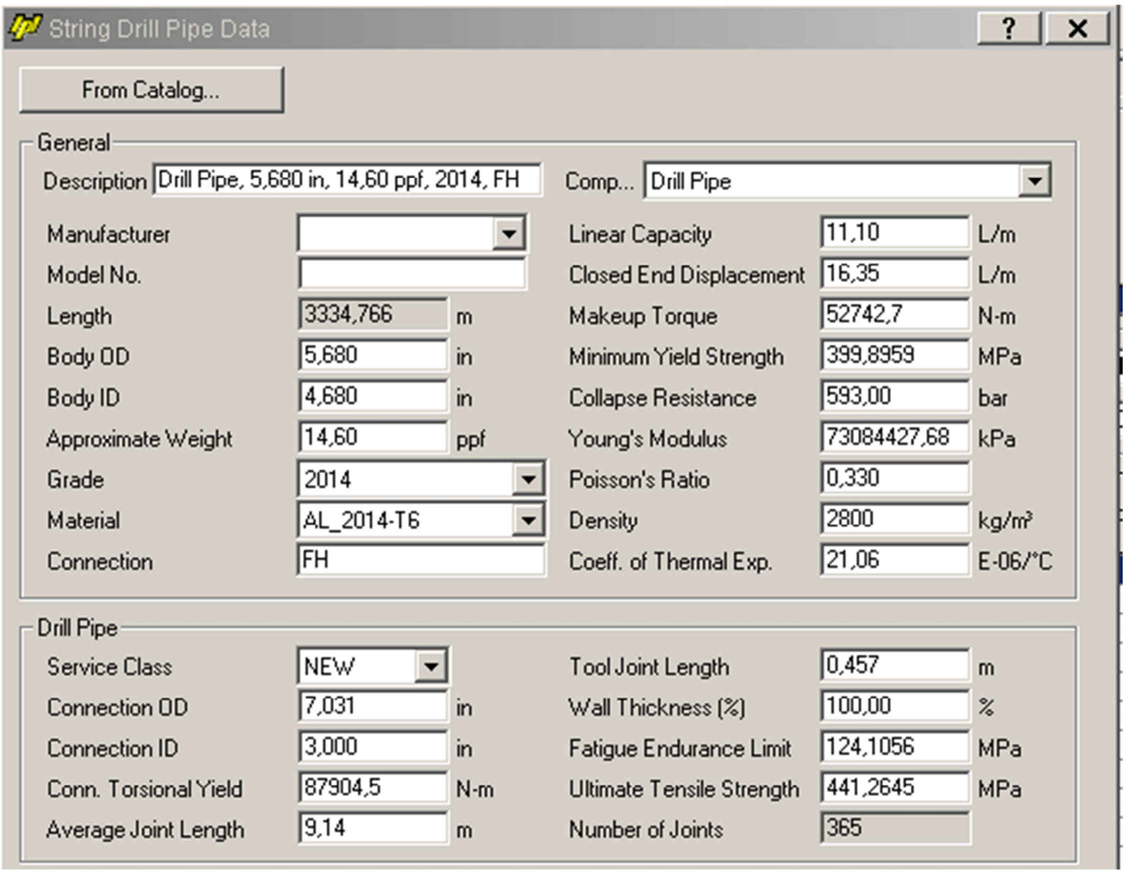

Figure 16: ADP properties simulations sheet.

The properties of TDP is obtained through titanium engineers inc who produces TDP[31].

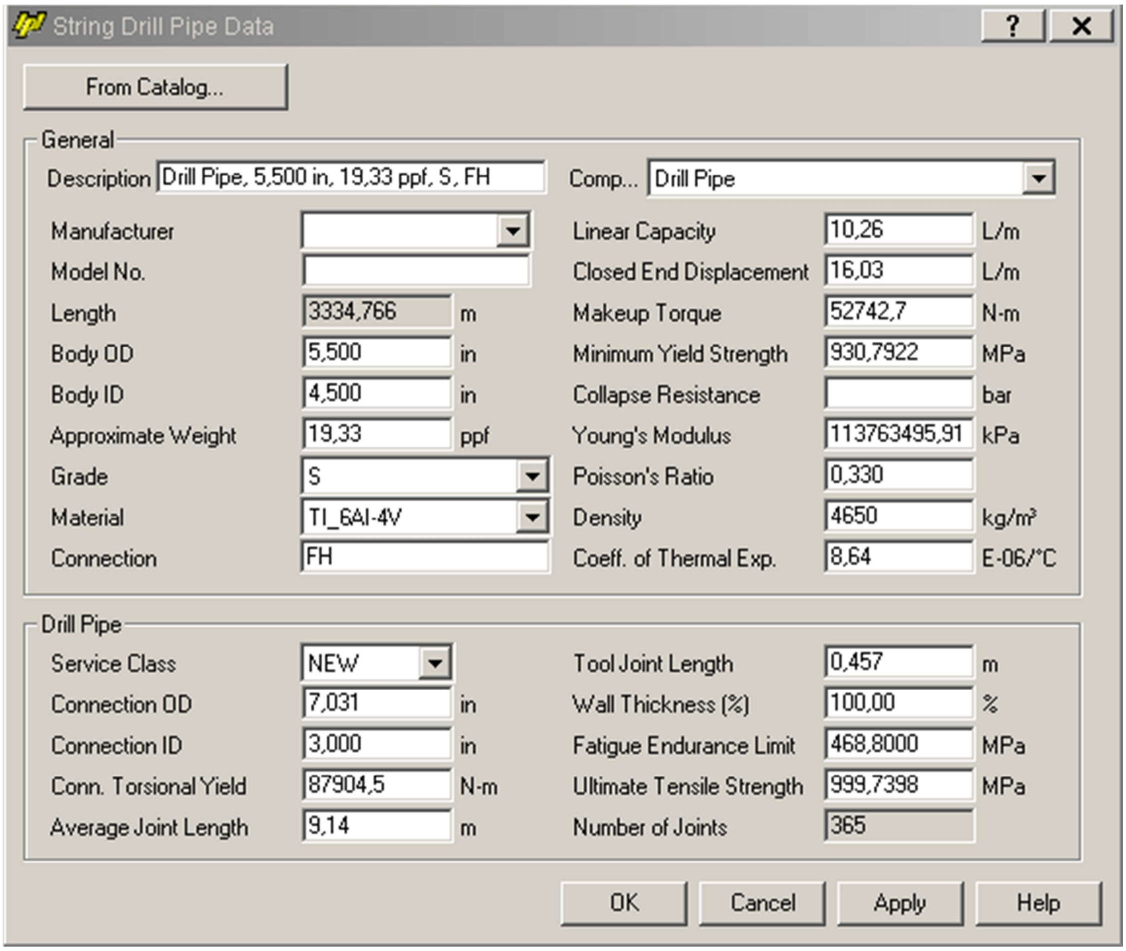

Figure 17: TDP properties simulations sheet. The material is set to TI 6Al-4V in the simulations sheet but the values that needs to be changed has been changed manually. The "grade" setting is set to S because it has to be set to something, but the relevant values have been changed by hand

The properties of UD-165 is obtained though Grant Prideco[44,45]

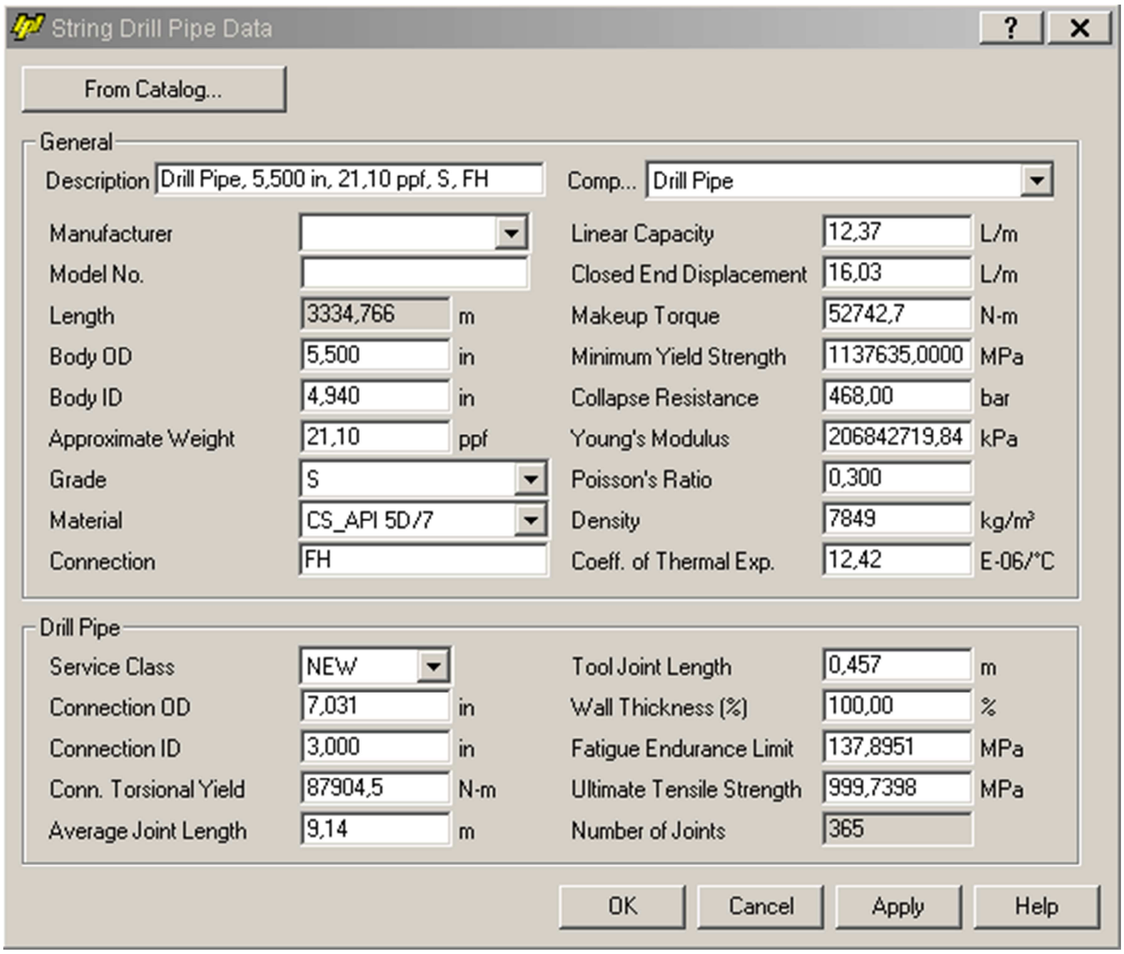

Figure 18UD-165 properties simulations sheet. The material is set to CS_API 5D/7 in the simulations sheet but the values that needs to be changed has been changed manually. The "grade" setting is set to S because it has to be set to something, but the relevant value is entered manually

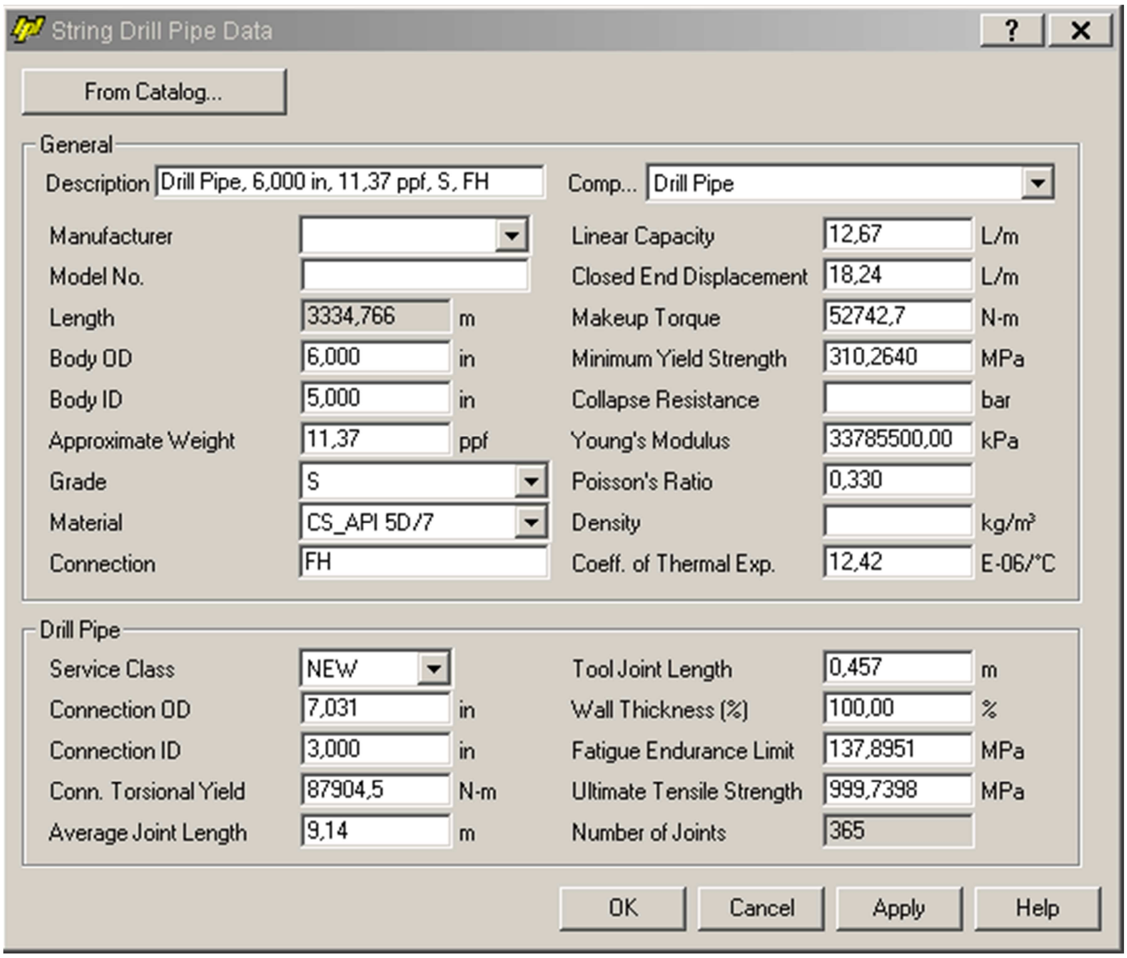

Figure 19 –Properties sheet for CDP, The material is set to CS_API 5D/7 in the simulations sheet but the values that needs to be changed has been changed manually. The “grade” setting is set to S because it has to be set to something, but the relevant value is entered manually.

Full wellpath description:

Wellpath in 30m sections

Measured depth (m)	Inclination (degrees)	Azimuth (degrees)	TVD (m)	Dogleg °/30m
0	0	0	0	0
30	0	0	30	0
60	0	0	60	0
90	0	0	90	0
120	0	0	120	0
150	0	0	150	0
180	0	0	180	0
210	0	0	210	0
240	0	0	240	0
270	0	0	270	0
300	0	0	300	0
330	0	0	330	0
360	0	0	360	0
390	0	0	390	0
420	0	0	420	0
450	0	0	450	0
480	0	0	480	0
510	0	0	510	0
540	0	0	540	0
570	0	0	570	0
600	0	0	600	0
630	0	0	630	0
660	0	0	660	0
690	0	0	690	0
700	0	0	700	0
720	2,2	107,02	720	3,301
750	5,5	107,02	749,92	3,301
780	8,8	107,02	779,69	3,301
810	12,1	107,02	809,18	3,301
840	15,4	107,02	838,32	3,301
870	18,71	107,02	867	3,301
900	22,01	107,02	895,12	3,301
930	25,31	107,02	922,59	3,301
960	28,61	107,02	949,33	3,301
990	31,91	107,02	975,24	3,301
1020	35,21	107,02	1000,23	3,301
1050	38,51	107,02	1024,23	3,301
1080	41,81	107,02	1047,16	3,301
1110	45,11	107,02	1068,93	3,301
1140	48,42	107,02	1089,48	3,301
1170	51,72	107,02	1108,73	3,301
1200	55,02	107,02	1126,63	3,301
1230	58,32	107,02	1143,11	3,301

1251,15	60,65	107,02	1153,85	3,301
1261,83	60,65	107,02	1159,09	0
1290	60,93	111,07	1172,84	3,782
1320	61,37	115,36	1187,32	3,782
1350	61,95	119,61	1201,56	3,782
1380	62,65	123,8	1215,51	3,782
1410	63,48	127,94	1229,11	3,782
1440	64,42	132,02	1242,29	3,782
1470	65,48	136,03	1254,99	3,782
1500	66,64	139,96	1267,17	3,782
1530	67,89	143,83	1278,77	3,782
1560	69,24	147,63	1289,73	3,782
1590	70,67	151,36	1300,02	3,782
1620	72,17	155,02	1309,58	3,782
1650	73,74	158,62	1318,38	3,782
1680	75,37	162,16	1326,37	3,782
1710	77,05	165,65	1333,53	3,782
1740	78,78	169,09	1339,81	3,782
1770	80,54	172,49	1345,2	3,782
1800	82,34	175,85	1349,66	3,782
1830	84,16	179,18	1353,19	3,782
1860	86,01	182,5	1355,76	3,782
1890	87,87	185,8	1357,36	3,782
1920	89,73	189,09	1357,99	3,782
1924,92	90,04	189,63	1358	3,782
1950	90,04	189,63	1357,98	0
1980	90,04	189,63	1357,97	0
2010	90,04	189,63	1357,95	0
2040	90,04	189,63	1357,93	0
2070	90,04	189,63	1357,91	0
2100	90,04	189,63	1357,89	0
2130	90,04	189,63	1357,87	0
2160	90,04	189,63	1357,85	0
2190	90,04	189,63	1357,83	0
2220	90,04	189,63	1357,81	0
2250	90,04	189,63	1357,79	0
2280	90,04	189,63	1357,78	0
2310	90,04	189,63	1357,76	0
2340	90,04	189,63	1357,74	0
2370	90,04	189,63	1357,72	0
2400	90,04	189,63	1357,7	0
2430	90,04	189,63	1357,68	0
2460	90,04	189,63	1357,66	0
2490	90,04	189,63	1357,64	0
2520	90,04	189,63	1357,62	0
2550	90,04	189,63	1357,61	0
2580	90,04	189,63	1357,59	0
2610	90,04	189,63	1357,57	0

2640	90,04	189,63	1357,55	0
2670	90,04	189,63	1357,53	0
2700	90,04	189,63	1357,51	0
2730	90,04	189,63	1357,49	0
2760	90,04	189,63	1357,47	0
2790	90,04	189,63	1357,45	0
2820	90,04	189,63	1357,44	0
2850	90,04	189,63	1357,42	0
2880	90,04	189,63	1357,4	0
2910	90,04	189,63	1357,38	0
2940	90,04	189,63	1357,36	0
2970	90,04	189,63	1357,34	0
3000	90,04	189,63	1357,32	0
3030	90,04	189,63	1357,3	0
3060	90,04	189,63	1357,28	0
3090	90,04	189,63	1357,26	0
3120	90,04	189,63	1357,25	0
3150	90,04	189,63	1357,23	0
3180	90,04	189,63	1357,21	0
3210	90,04	189,63	1357,19	0
3240	90,04	189,63	1357,17	0
3270	90,04	189,63	1357,15	0
3300	90,04	189,63	1357,13	0
3330	90,04	189,63	1357,11	0
3360	90,04	189,63	1357,09	0
3390	90,04	189,63	1357,08	0
3420	90,04	189,63	1357,06	0
3450	90,04	189,63	1357,04	0
3480	90,04	189,63	1357,02	0
3509,24	90,04	189,63	1357	0

Table 10: Full wellpath description in 30 m segments