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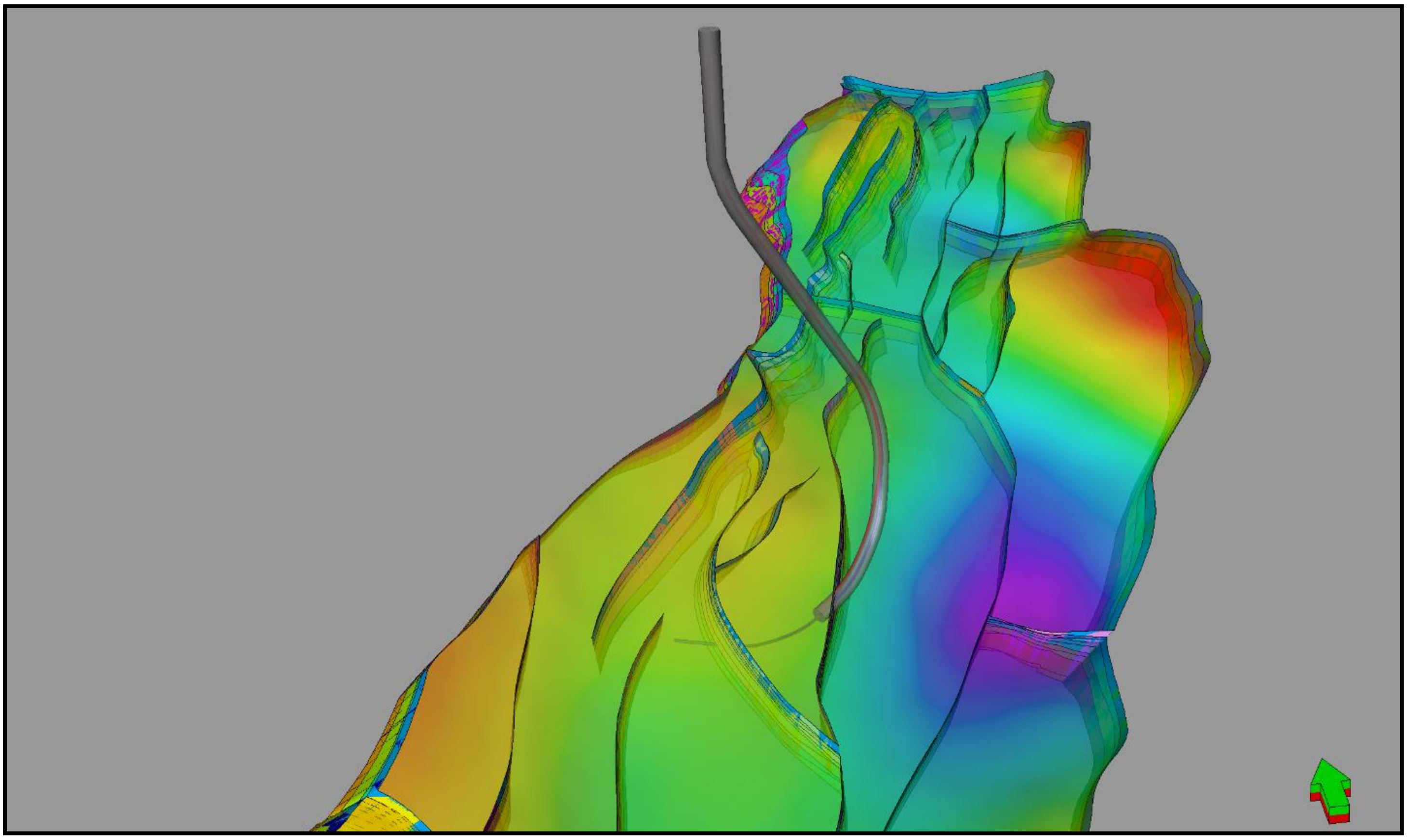
Drilling through the over-pressured formations on Skarv field.



by

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I. Abstract

The main objective of this thesis was an investigation and of drilling operations in over-pressured formations on the J-4H/HT2 well on the Skarv field off the coast of mid-Norway. Abnormally high formation pressures on this well were the direct cause of a stuck pipe incident during drilling followed by consequences for the entire well construction process.

Based on daily drilling reports the paper presents the sequence of events leading to the stuck pipe incident on well J-4H. It establishes a link between conditions in abnormally pressured zones and the causes of slow drilling process, as well as of the wellbore collapsing around the drill string. The ultimate goal was to understand the situation and suggest potential countermeasures. To achieve this, a wellbore stability evaluation was performed to analyze. The relationship between drilling fluids, drilling technology, well integrity and an offset well J-1H were taken into consideration to compare operations in the same environment. Further, looking for the most probable scenario and results, can give the clear picture of missteps which should have been done.

Based on the results alternative approaches are discussed and suggestions are made to improve the quality of operations and avoid similar problems in the future. The wellbore stability analysis showed that more attention should be put on bottom hole assembly design and changes in wellbore conditions. The results of daily drilling reports analyses indicated that the most efficient solution for drilling challenges may be to change the setting deeper an intermediate casing and decrease the drilling mud density after drilling the over-pressured formations, to avoid overbalance.

CONTENTS

II. Acknowledgement

My special thanks for Mr. Claas Van Der Zwaag. I had great opportunity to work with him. Owing to knowledge that I got over Well Completion course, he created interest for well completion topics. He opened my eyes for interesting and challenging stage of well life. I am more than thankful for advices and guidance on this paper.

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Katarzyna Kinga Sienkiewicz

The Master's Thesis is dedicated to my parents for their tremendous support during my studies.

Kasia

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V. List of abbreviations

API	American Petroleum Institute
BHA	Bottom Hole Assembly
BP	British Petroleum
BSR	Blind Shear Ram
CAPEX	Capital Expenditures Creating Future Benefits
CEC	Cation Exchange Capacity (Water Adsorption Capacity)
CST	Cement Support Tool
DDR	Daily Drilling Reports
DOP	Drilling Operation Plan
ECD	Equivalent Circulating Density
EMW	Equivalent Mud Weight
FG	Fracture Gradient
Fm	Formation
FPSO	Floating Production, Storage and Offloading Unit Vessel
GP	Gravel Pack
HC	Hydrocarbons
HSSE	Health Safety Security Environment
ISO	International Organization for Standardization
KOP	Kick Off Point
LMRP	Lower Marine Riser Package
LOT	Leak Of Test
LR	Long Radius
LSOBM	Low-Solids Oil-Based Mud
MD	Measured Depth
MSL	Mean Sea Level
MWD	Measurement While Drilling
NCS	Norwegian Continental Shelf
NGL	Natural Gas Liquids
NOK	Norwegian Krone
NORSOK	The Competitive Standing of the Norwegian Offshore Sector
OBM	Oil-Based Mud
OD	Outside Diameter
OH	Open Hole
OPEX	Operating Expenditures
OWC	Oil-Water Contact
PDC	Polycrystalline Diamond Compact
PDO	Plan for Development and Operation
POOH	Pull Out Of Hole
PP	Pore Pressure
PPR	Predicted Production Rate
PSA	Petroleum Safety Authority
RIH	Run In Hole
RKB	Rotary Kelly Bushing
ROP	Rate Of Penetration
ROV	Remotely Operated Underwater Vehicle

RPM	Rotating Speed
SBT	Segmented Bond Tool
TOC	Top Of Cement
TOF	Top Of Fish
TOFS	Time Out for Safety
TRSCSSV	Tubing Retrievable Surface-Controlled Subsurface Safety Valve
TVD	True Vertical Depth
TVDSS	Total Vertical Depth Subsea
WBM	Water Based Mud
WOB	Weight On Bit
WWS	Wire Wrapped Screens
XMT	Christmas Tree

1. *Introduction*

The aim of this study was to research drilling operation through over-pressured formations in the J-4 well on Skarv field. The major point was stuck pipe incident and actions that were taken. This thesis addresses the problems by investigating field practices that include geology, drilling and completion. The biggest interest was put on operations, which include drilling and completion, well intervention, workover operation, slot recovery, sidetracking, and plugging and abandonment. The main focus was on drilling operations. The whole well planning process was considered with special focus on area geology, formation pore pressure and fracture gradients, logging program, casing program, mud program, cementing program, well control, drilling-time curve, and last but not least hazards in the over-pressured environment.

Description and requests are included in nine chapters. The first chapter describes basically the outline of the work. It consists of the overview of pressures with special focus on abnormal high pressures.

Chapter two presents the Skarv field and it is geology. The Tilje formation is highlighted.

Chapter three describes in general the reservoir.

Chapter four covers regulations and standards. There is a summary of well integrity, based on NORSOK-D10 rev. 4 and BP internal regulations.

Chapter five gives a look at the well from the construction side. It distinguishes drilling operations, casing settings, cementing jobs and well completion application and Mud properties are not revised.

Chapter six presents the operations in the J-4H well from the daily drilling reports. It is the detailed analysis of the incident which took place in the J-4H well. A comparison to well J-1H is made. The last subsection tells about horizontal wells and comparison between main bore and well path.

Chapter seven describes the Fault Three Analyzes. The logic process of the failure is shown.

Results and discussion are presented in chapter eight.

Conclusion summarize the study and give an opportunity for open discussion about the event and proposals for the future.

1.1 Description of the problem and theory

When sufficient and reliable data is available, we can predict different challenges during drilling and avoid unwanted effects. It is very important to monitor drilling operations and react when warning signs are observed.

Stuck pipe is one of common problems encountered in drilling. It results in loss of time due to necessity to free the drilling string. The result is large amount downtime and maintenance costs and schedule delays. If attempts to free the drill sting fail, stuck pipe requires fishing operation which also may take long time and be unsuccessful. Such operations cost even approximately 40% of the total well cost. [23]

Table 1 analyze the relationship between three different reasons for stuck pipe and field observations. However, it is challenging to distinguish hole collapse from hole cleaning problems. Different drilling problems can happen in shale and permeable formations. Hole collapse can be a problem in fine-grained, clastic sedimentary rock. Permeable and impermeable rocks are good environment for improper well cleaning and as a later result- stuck pipe. Differential sticking is a problem in the formation with good petrophysical properties. In shale stuck pipe cannot take place. Observations from drilling operations show that rotation after stuck is impossible. Circulation of mud after stuck gives non ability to rotate and move up and down the drill pipe. [26]

Table 1 Example of stuck pipe diagnostics. [26]

	Hole collapse	Inappropriate hole cleaning	Differential sticking
Drilling environment			
Shale	*	*	Ø
Reservoir rock (permeable)	÷	*	*
Observations during drilling			
Rotating before stuck	*	0	÷
Moving up/down before stuck	*	0	÷
Rotating after stuck	÷	÷	Ø
Circulating after stuck	÷	÷	*
Excessive cutting and cavings	*	÷	÷
Observations after drilling			
Non-gauge hole diameter from calliper	*	÷	Ø
Low density/high porosity/ low acoustic wave velocities	*	÷	÷

Symbols:

Ø - cannot be cause of stuck pipe

÷ - unlikely

0 - indifferent

* - likely cause of stuck pipe

1.2 Pressure concepts (general)

Pressure is the most important parameter in the oil and gas industry. Value of the pressure in the rock pores is called the formation pore pressure (is known as formation pressure). Familiarity with this pressure is meaningful during well planning. Almost every stage of well design is correlated with formation pressure: mud weight selection, drilling parameters, casing design, type of completion. [29]

During the erosion and sedimentation process, grains of sediment overlap on the top of the previous formation. The thickness of layer grows. The distance between adjacent grains decreases and size of pores are smaller. Formation pressure is a system, which includes the following elements : [53]

- the pore pressure,
- the rock grain pressure (matrix stress),
- the total overburden pressure which is supported by the pore and rock grain pressures.

The pore pressure has the main role. It relates to existing gases of liquids in the pore throats. It does not involve the overburden pressure which is supported by the rock matrix. At greater depths, pressure gauge shows higher values of the recorded pressure. [29, 35]

In the drilling environment the most common expression is pore pressure gradient. It is defined as derived from a line passing through a particular formation pore pressure and a datum point at surface. [29]

1.3 Basic principles of abnormally high formation pressures

According to NORSOK Standard D-010, Rev. 4 June 2013 “Well integrity in drilling and well operation”:

“*Abnormal pressure formation or zones where the pore pressure is above the normal, regional hydrostatic pressure”.*

Abnormal pressures are hydrodynamic phenomena in which time plays a major role. A good understanding of the origin, detection, and evaluation of abnormal pressure is crucial to anyone involved in the drilling of oil and gas wells. Abnormal pressure is caused by a combination of: mechanical compaction, thermal expansion and second-stage clay dehydration. [25, 34, 35]

Compare to geology studies, excess pressure, called overpressure or geopressure exists when impermeable rocks (shale) are compacted rapidly, their pore fluids cannot always escape and must then support the total overlying rock column. The mechanisms which generate these situation can be quite complex and vary from region to region. [36]

From the drilling point of view, this is defined as any formation pressure that is greater than the hydrostatic pressure of the water occupying the formation pore spaces. [28]

Fluids accumulated in the pores, no longer communicate 100% efficiently with the water-table (surface communication). A seal or cap is provided to interfere with the fluid column and preventing it from achieving normal hydrostatic equilibrium. [27]

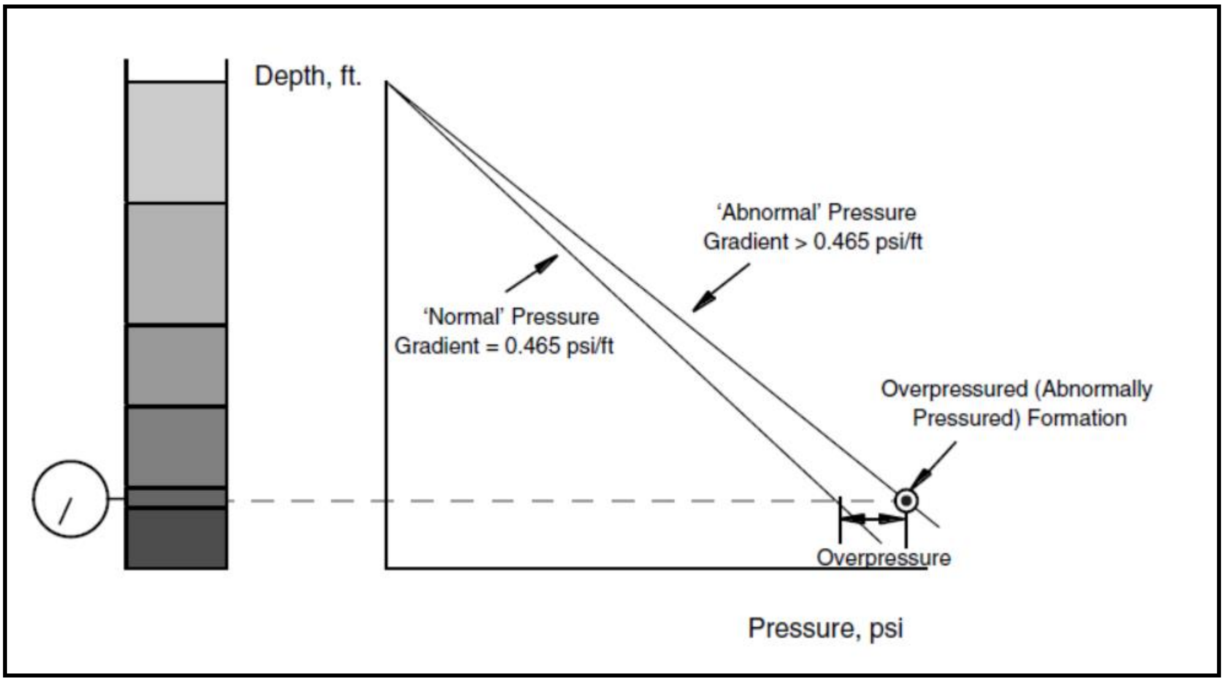


Figure 1. Over-pressured formation. Correlation between pressures at different depths. [36]

As is shown in the Figure 1, abnormal pressure reaches the highest value along with the depth. On the shallowest level it is the same like normal and under-pressured formation. The disparity between normal pressure gradient and abnormal pressure gradient is overpressure. Occurrence of abnormal high pressures is more probable in deeper formations. Overpressure is a difference between normal pressure gradient and abnormal high pressure gradient. [35, 36]

Abnormally high formation pressures are found worldwide in formations ranging in age from the Pleistocene age (approximately 1 million years) to the Cambrian age (500 to 600 million years). They may occur at depths as shallow as only a few hundred meters or exceeding 6 000 m and may be present in shale/sand sequences and/or massive evaporate-carbonate sequences. [52]

It is known from the long time that abnormal pressured formations occur in NCS. There have been reported pore pressures between 0.5 psi/ft and 0.9 psi/ft In the North Sea abnormal pressures take place with widely varying magnitudes in many geological formations. In Mesozoic and Tertiary age formations, abnormal pressures demonstrate a broad variation in magnitude over the entire North Sea area. [25]

1.3.1 Origin of over-pressured formation

To understand the magnitude of over-pressured formations, it is meaningful to have knowledge of the genesis. Undercompaction is the most common circumstance of over-pressured formations creation. [29, 36]

With time sediments settle on already existing formations. They create overburden pressure. The extra load is taken by matrix and pore fluid. Because trapped fluid has not escape, the fluid pressure rises above the hydrostatic value. This formation can be depicted as over-pressured. The pore fluid pressure decisively increases. The overburden is supported just by the pore fluid and the grain to grain contact stress is not rising. This happens due to incompressible attribute of water. As far as undercompaction is concerned, the risk of abnormal pressures depends in essence on the thickness of the clays.

Abnormal pressure exists when rock is sealed in place. This can subsist when pores are not interconnected. The seal defends against alignment of the pressures which takes place within the depth and geological order. It can be formed by gravity faulting during deposition. This is a physical seal. The barrier is allowed to be created form calcium carbonate deposition and restricts permeability. The other chemical example is digenesis during compaction of organic substances. It is probable that seal is created simultaneously with physical and chemical action. To compare with rock, overburden pressure is increasing with burial progress. Size of pores is changing and porosity is decreased. Fluids trapped in pores do not have opportunity to escape.

Tectonic stresses can create different deformations and change fluid pressure and distributions of masses. This has a direct or indirect influence on fluid pressure distribution. The other relation between fluids in pores and tectonics is fluid pressure, depending of the stresses and extension deformations as a final result. At any time activity of tectonic leaves various effects. Massive moves of formations like: folding, faulting, sliding and slipping, earthquakes and diapiric shale and salt moves, they can be disclosed as local or regional actions. Lateral compression is able to uplift light and submissive sediments or fracture and create the fault of stronger once. In the situation when original pressure is maintained the uplifted formation, then is over-pressured.

It is important to mention about transition zone. This area is located between normally pressured zone and the over-pressured zone. Both in the transition, as well as in over-pressured formation the pressure is higher than hydrostatic pressure. The size of layer of the transition zone is related to permeably of clay, drainage conditions and time. Abnormal pressure is easier to observe when changes between the different pressure zones are unhurried. It is known that crew monitors different drilling parameters. Mud specifications and cuttings should be observed to notice growth in pressure in the transition zone. Early recognition can give opportunity to be accordingly prepared to entrance abnormally high pressured formation. Existing pressure in the transition zone is relatively high, but the fluid in the pores cannot flow into the wellbore because the seal has extremely low permeability. However, entering the high permeable over-pressured formation the situated in pores fluids will flow into the annulus. [29, 35]

1.4 Detection and evaluation of abnormal pressures

Prediction and detection of abnormal pressures can be splitted for three parts. There are techniques used to predict (before drilling), detect (whilst drilling) and confirm (after drilling). The first step to recognize abnormal pressured formations is predictive method. It covers studies of regional geology. [29]

To estimate the incidence of over-pressured formations, the geophysical measurements can be carried out. Seismic information can be used to identify transition zones or presence of hydrocarbons. Interesting parameters are: formation velocity, gravity, magnetics, and electrical prospering methods. The other method is the investigation of data from other drilled wells in the same area. Historical evidences usually include mud weight values, problems during the drilling, lost circulation or kicks. Measurement while drilling data and wireline logs are very valuable. [35]

1.4.1 Parameters for identification

They are several methods while drilling, which can help detect abnormally pressured sequences.

Table 2. Disclosure of over-pressured formation. Methods while drilling. [35]

Real-time methods	Methods depending on the lagtime	Cuttings analysis methods
Penetration rate	Mud gas	Lithology
d exponent	Mud density	Shale density
Sigmalog	Mud temperature	CEC
Normalised drilling rate	Mud resistivity	Shape, size and abundance of cuttings
Torque		Cuttings gas
Overpull and drag		x-ray diffraction
Hole fill		Oil show analyser
Pit level, differential flow, pump pressure		Nuclear magnetic resonance
MWD		

One of the real-time methods is observation of penetration rate. This value decreases with depth because of declining porosity. This is due to the weight of sediments which lie above. The listed factors have important influence:

- lithology,
- compaction,
- differential pressure,
- WOB,
- RPM,
- torque,
- hydraulics,
- bit type,
- personnel and equipment

Mentioned above ratios are dependent of each other. When the crew uses tested equipment for drilling operation and control very attentively WOB, RPM and torque values, even small changes in the lithological compositions will not be a big problem.

From the mechanical point of view, penetration rate increases with the weight on the beat. The use of MWD allows the connection between penetration rate and torque measurements. Amount of energy to break the rock gives torque value. Rate of torque depends on the hardness of the rock. Although, this parameter is never taken into account directly because it is not easy to access. Rock porosity plays first fiddle in production of hydrocarbons. From different laboratory researches it is proved that drilling rate decreases when the pore pressure (difference between mud column pressure and formation pressure) rises. It shows strong relationship between penetration rate and differential pressure. To use properly the reliability of the measurements it is relevant to employ drilling models, such as the “d” exponent, the sigmalog or the normalized drilling rate.

From the field work it was decided to create a solution of penetration rate which eliminates effects of drilling parameter variations. It should represent measurements of formation drillability. This factor is called compaction exponent-“d” exponent. It is the relationship between drilling rate, WOB, rotating speed and diameter of bit. When there are not significant changes in the lithology, the dimensionless exponent shows good signs for the state of compaction (could be porosity) and differential pressure. It can be obtained with solving following equations. The EQ. 5 was created by Bingham.

EQ. 1

$$\frac{R}{N} = a \cdot \left(\frac{W}{D}\right)^d$$

In this equation the US units are valid.

EQ. 2

$$d = \frac{1.26 - log_{10}\frac{R}{N}}{1.58 - log_{10}\frac{W}{D}}$$

In this equation the SI units are valid.

<u>Where:</u>

R-drilling rate

N-rotating speed

W-weight on bit

D-bit diameter
a-lithological constant
d-compaction exponent

Jorden & Shirley (EQ. 2) included in their solution constants which would allow standard units of measurement. In this example lithological variable in not existing when the lithology is constant. It can be deducted that drilling rate is the opposite of “d” exponent. Transition and undercompacted zones can be detected, because within the depth, differences are definitely of those factors are recognizable. The exponent changes when the mud weight is modified. This means that differential pressure has influence on the compaction factor. There are a few recommendations for use of the “d” exponent and it should be kept in mind that it is an efficient technique. To locate the abnormal pressured formation, the formulas are used with intended limits under appropriate drilling conditions. However, calculations have to be linked with the other methods.

Overpull appears when hook weight is higher than free string weight. Although such may cause while pulling out of hole, or additional weight may have to be applied while going in hole, even to extent of re-drilling. Increasing depth, amount of contact between the borehole walls and the drill string, and torque are strongly related with each other. With drilling improvement the mentioned items increase too. Situation can be different in differential pressure when over-pressured formation occurs. As the conclusion, bottomhole drilling parameters and formation should be evaluated, to drill through the over-pressured formation. For the abnormal pressure detection, the influential information is a recording from MWD tool in shale formation. [25, 35]

Hydraulics has tremendous impact for drilling efficiency. Mud properties, like viscosity, filtration rate, incidence of solids can affect penetration rate. Mud-gas logs are used to detect over-pressured zones. Gas detection in the mud is underlying to detect abnormally pressured formations. In the permeable formations with pores which is penetrated while drilling, gas can come out. The volume is controlled by differential pressure. Gas results in density changes. A decrease in mud way out is due to expansion of gas. Lighter mud cannot prevent the high pressure zone. Differential pressure has to be stable through the whole drilling process. To come across the overpressure formation mud weight should increase. Observation of gas abundance helps to detect a state of differential pressure, especially when transition zone does not exist. Detection of the mud temperature is worthy of attention. In the theory, temperature gradients in undercompacted series are abnormally high, compare to normally pressured formations. In this case it is strong relation with temperature measurements using logging tools. Mud resistivity is detected to find contrast between mud and formation water. Continuing with mud feature, I want to discuss the monitoring and interpretation of mud data, which is evaluated in the chapter 6.1.4. [24, 35]

Detailed examinations and observations of drilling cuttings are practiced when the area is not identified. When the cuttings have been dried and sorted, the detailed description can help in observation of abnormal high pressured formations. Likewise, knowledge about the arrangement of the lithology is very crucial. Familiarity with the depth of transition zone can help with preparations for high pressure occurrence. If seals, drains or thick clay exist, this gives real factor to analyze. When over-pressured formations are identified with the undercompacion origin, the only influence has the thickness of the clays. Faulting position says about changes in the stratigraphy. Different changes may establish a detection factor. The oldest method of detecting abnormally pressured formations is measurement of clay and shale density. Undercompacted shales present rapidly less incensement of density. The mud type is meaningful. Fluids based on water do not prove correctly with shales. The over-pressured zone is approached when the penetration rate increases. The result is the incensement of cuttings volume on shaker. Experience shows that the transition zone gives angular and sharp shapes of the cuttings. There are different comparing to rounded, as in normal-pressured environment. From the over-pressured structure cuttings become usually large and splintery in appearance. X-ray diffraction and cuttings gas are the methods not reliable enough. The most essential factor from this group is lithology interpretation. However, it must be liked to each of other parameters. [24, 35]

Table 3. Disclosure of over-pressured formation. Methods after drilling. [35]

Wireline logs
Resistivity/conductivity
Sonic
Density
Neutron porosity
Gamma ray/spectrometry

Methods which are used in the end of a drilling phase cannot provide information about the presence can importance of abnormal pressured layers. The most common practice is MWD and most of them are able to involve before the end of a reaching the depth, during intermediate logging runs or tests. Type of wireline log depends of preferences of data. [35]

2. Additional Background information

2.1 Skarv and Idun field

The Skarv Idun Development Project consists of the development of two hydrocarbon accumulations consisting of multiple reservoirs:

- Skarv-oil and gas field
- Idun-gas field

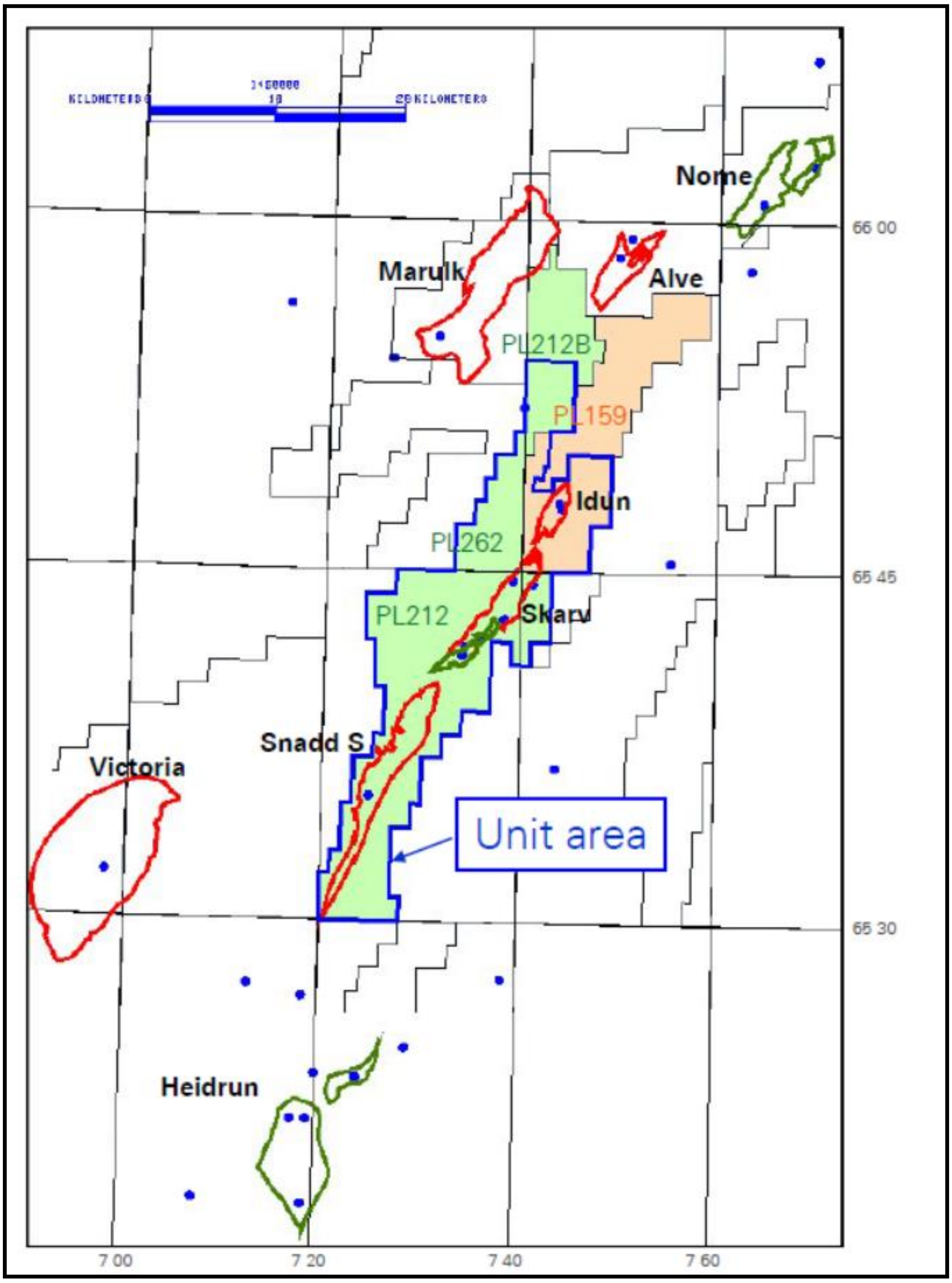


Figure 2. Field location map. [16]

Skarv and Idun fields are settled in a part of the Norwegian Continental Shelf off mid-Norway area in the Norwegian Sea. Destination to Sandnessjøen is around 200 km. This location is called Halten Terrace area. The Skarv field was discovered in 1998. It is located in the sub-blocks 6507/5, 6507/6, 6507/3 and 6507/2. In 1999 Idun was discovered in blocks 6507/3-3. The blocks were awarded in production licenses PL212 (1996), PL212B (2002) and PL262 (2002). (Figure 8) These two gas and oil reserves were found between Norne field (35 km to the North) and Heidrun field (45 km to the South). The water depth reaches 350 m and 450 m. The project is operated by main operator BP (23.84%) with Statoil (36.17%), E.ON Ruhrgas (28.08%) and PGNiG Upstream International owns 11.92%. Skarv is part of BP's concept called Fields of the Future and the cutting-edge technologies were implemented in the order to adapt Integrated Operations Environment. The development plan was created with a big attention on the environment. Seabed in Haltenbanken Area is covered by corals and a lot of fishing actions are taken.

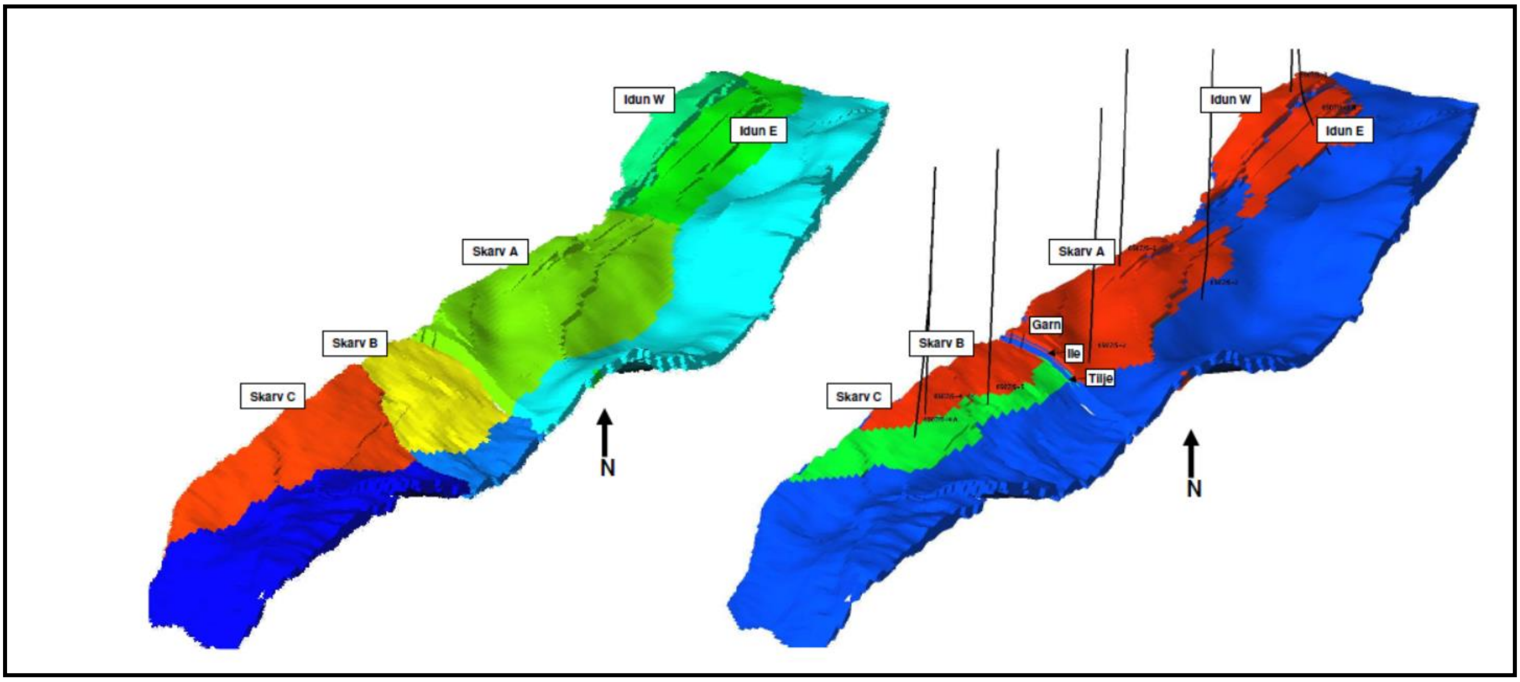


Figure 3. Segments on the Skarv and Idun structure.

The field consists of three segments A, B and C. Segment A contains mainly gas condensate in the Garn and Ile formations. The B and C contain oil with associated gas caps. The Idun field has western and eastern segments. (Figure 9) The left-hand figure illustrates the fluid distribution in whilst the right-hand the Skarv and Idun segmentation. There are 16 development wells in 5 templates for both Skarv and Idun.

Seven wells are oil producers, four are gas producers and four are gas injectors. Production is ensured by FPSO vessel, which was ordered and specially built for this field and is the biggest gas condensate unit in the world. The storage capacity reaches of 875.00 barrels of oil. According to the Fields of the Future concept it can be fully remotely controlled. The remaining resources are estimated 367.4 million boe. Planed production for 2014: oil 54700 b/d, NGL 15600 b/d, gas 371 million scf/d. Gas in conveyed from FPSO and transported from producers by 80 km, on 26'' pipeline to The Åsgard Transportation system and after to processing plant in Kartrø. The first drilling campaign was accomplished in 2012 and in December 2012 the production started. The next stage of drilling is planned in 2016.

The whole installation is expandable and allow for tie-in of new discoveries in the future. Predicted capital expenditures are 31 billion NOK. The period of production is planned for 25 years. [15, 16, 17, 45]

2.2 Geological information

Table 4. Geology in the well J-4/ Skarv. [19]

Even/Unit Top	mTVDSS	mMD BRT	Lithology	Comments
Quaternary	346	346	Clay, boulder clay	Depth of the J template
Naust	580	580	Claystone, silestone, sandstone,	Gas/shallow water flow
Kai	1383	1441	Claysone,minor salt, sandstone	Potential for elevated gas readings
Brygge	1814	1969	Claystone	
Tare	1979	2169	Tuffoceous claystone	
Tang	2028	2228	Siltstone, claystone	
Nise	2083	2299	Claysone, siltstone, sandstone	
Lysing/Lange	2685	3010	Claystone, sandy limestone	
Gråsel sand	2967	3307	Sandstone	Expect oil reservoir
Spekk	3172	3531	Organic rich claystone	High pressure
Melke	3310	3664	Claystone with limestone stringers	
Garn	3543	4058	Sandstone	Gas reservoir
Ile	3590	4200	Sandstone	Gas reservoir
Tilje	3661	4544	Sandstone, silstone	
TD	3678	5491	Sandstone	Expected all oil

From the geological side the field lies on a narrow fault-bounded terrace that forms part of the Dønna Terrace in the Norwegian Sea. Situated between the Trøndelag Platform to the east and the Rås Basin to the west, this portion of the margin represents the hanging-wall blocks of the major structural high forming the Nordland. [17]

The shallowest sediments subsist of soft mud with sandy intervals. Naust represents upper glacial deposits. Silty and sandy clays and claystones build the formation. There are inserts of sands and rare limestone stringers. Shales forms Kai formation. The Brygge, tare and Tang show similar types of rocks. Shales and porous tuffs are in majority. Tuffs have tendency to be water-reactive. This is the reason to use oil-based mud. Claysones are the layers in Nise Fm. From the production point of view, sandstones represent good space for hydrocarbons. They are in the Lysing and Lange. Organic matter appears in Speek Fm. Garn, Not and Ile formations are not good known because trajectory was not passed through the main Skarv fault block. Presence of fault A600 is the reason that well was not drilled sequentially through the reservoir unit. However, these formations consist mostly of sandstones separated by claystones. [15, 16, 17]

The pressure regime in the reservoir is complex. The prognosis was used for the casing design for J-4H well. Over-pressured formations start close to the top of the Kai and increases until Nise Fm. The association can be found in smectitic and illitic clays appear in the lower Tertiary. High pressured layers are scaled down through the Nise formation and greatly to the top of Lysing. Over-pressure starts rising again in Lange to the maximum value in top of Melke Fm. The mature Spekk formation contains with porous and permeable sandsones. This interval caused problems during drilling. [15]

2.3 Tilje formation

In this chapter Tilje is described as a potential of hydrocarbons. The whole project of the well J-4H was based on estimation of rocks petrophysical properties.

The upper section of the formation has hyper heterolithic character. It consists of alternating and interbedded sandstones, siltstones and shales and was deposited in a tidal influenced, marginal marine coastal structure. The lithology varies considerably over small distances. The poor reservoir quality is a result of both depositional facies and subsequent digenesis. This formation demonstrates heterogenous restricted/marginal marine reservoir interval. [14]

It does not mean when pores have big diameter, the permeability is high. On the other side, when permeability achieves big value, this suggests that is high procentage of porosity. Pore system consists of both microporosity and macroporosity. Grains tend to dissolve and it has influence on proportion of the macropores. The result is trend in poor connection between macropores. Average porosity is 14.9% and arithmetic mean permeability around 42 mD. Mudstone intervals form laterally extensive permeability barriers or baffles and therefore vertical permeability presents high restrictions. Deeper layers exhibit increased marine influence and this results in a slightly more homogeneous character to the Tilje that contains a number of relatively thick sand bodies representing stacked, marginal marine to slightly restricted marine shoreface.

There have been done several numbers of correlations in production zone between different wells. The reason of disparities in reservoir quality is change in sediment fabric. Reservoir interval was divided into 14 discrete layers. The criteria were attemption of capture the gross changes in sediment fabric and floods between them. [17]

Table 5. Description of layers. [17]

Layer	Description
Tilje 1 (T1 d-a)	Heterolithic
	Two mudstones interbedded with diversity of sand-rich non-marine to marine sediments
Tilje 2 (T2 e-a)	Sandstones (stacked, marine to marginal marine)
	Contains of mud stone
	Very characteristic is a strong influence of marine
	At lower parts is a mixture of shallow to marginal marine shorece sandstone
	At upper parts are marine shelf sediments
Tilje 3	An inherence of extensive lagoon bay mudstone
	Mudstone is at the base
	Middle and upper parts are dominated by stacked, restricted shoreface and shallow shelfal mudstones
Tilje 4 (T4 c-a)	Heterolithic, thinly interbedded sandstones and mudstones
	More proximal and restricted depositional setting than Tilje 3
Tilje 5	Unit of transagressive sandstone

The objective was to drill 12 ¼’’ until the top of the formation 3661 mTVD. Inclination of well trajectory was quite high, around 71º. Run and cemented 10¾’’x 9⅞’’ production casing. The reservoir contains gas and condensate is located in Middle and Lower Jurassic sandstones. At well J-4h Tilje was separated for five segments consist with sands: L, K, J, H, F. There is an underlying oil zone in the Garn and Tilje formations. After different tests, it was found out that the Tilje formation has relatively poor reservoir quality. This fact obliged to drill gas injection wells and maintain the initial reservoir pressure. Cross flow incident between Tilje and Garn was taken into account during preparation the project. The general risk was oil loss into Garn fm because if eventually 4000 psi differential pressure with respect to Tilje. To achieve success, zonal isolation was significant. The 9 ⅞'' casing shoe was set on top of Tilje and cemented in place across Ror and Not shales. However, this operation was hazardous because of unknown strength in Tilje. After pumping the cement, the only event was difficulty with covering all required intervals. The intention was to isolate Tilje reservoir from the Ile and Garn reservoir. What is more, it was relevant to avoid contact with any HC or permeable zones in overburden layers. Based on the previous experience, this formation had a identified risk in losing cement for 9 ⅞'' when setting shoe. This operation was successful without losses and good cement job. Production from this formation was planned with value with capacity at least 7 mstb/day. Data from other wells showed expected fluid gradients:

- Gas 0.148 psi/ft
- Oil 0.273 psi/ft
- Water 0.44 psi/ft

The phenomena were reservoir pressure measurements. Deeper formations showed lower pressure value that potential sources lie above. In pursuance of principle, they should have higher pore pressure because of overburden. [13, 19]

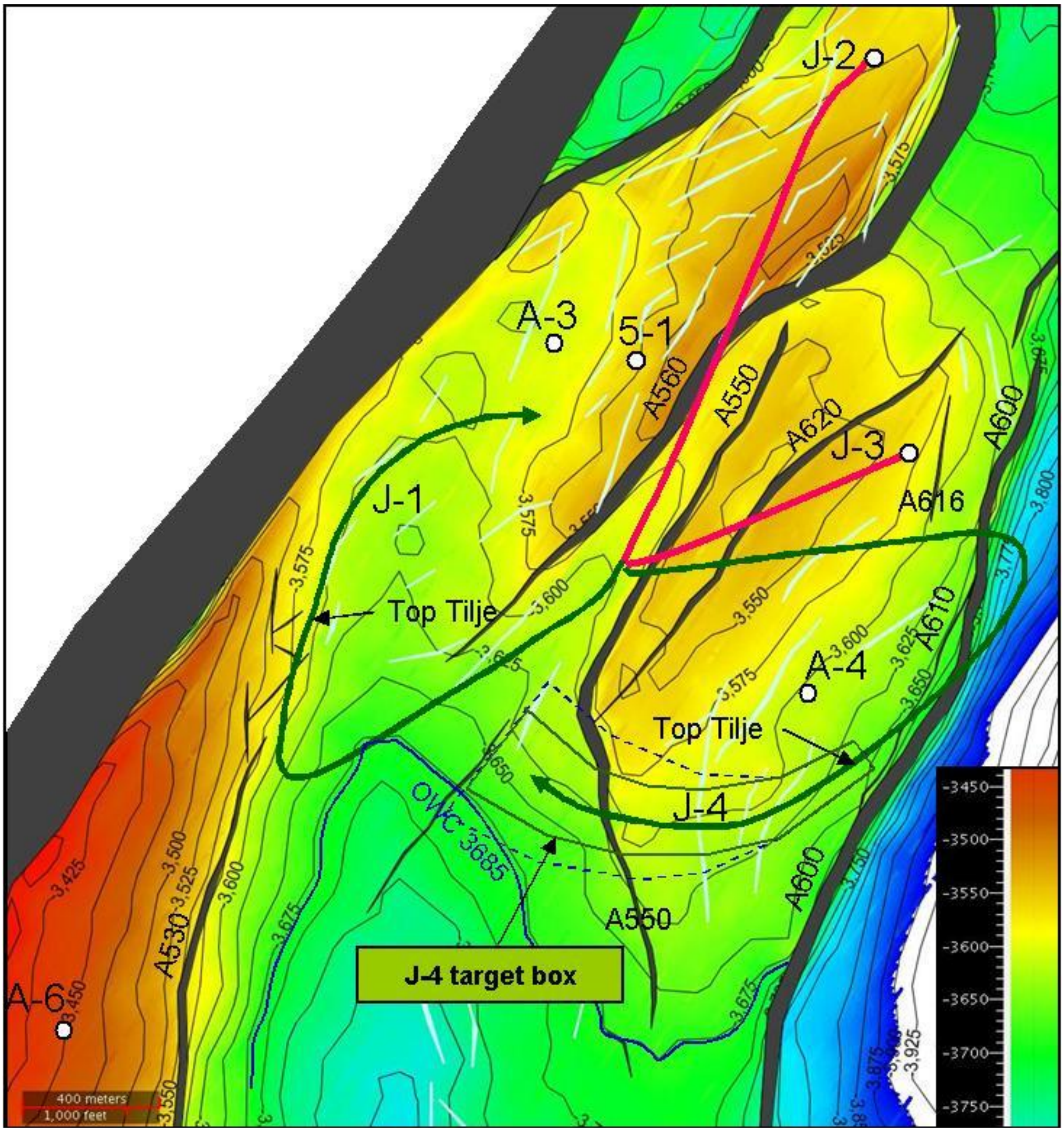


Figure 4. Top Tilje depth map. [10]

Figure 4 shows J-4H on the left side (eastern part) on green color. Production is supported from injection well J-3H. Fault polygons are presented. They occur on Top Tilje and J-4H target box. It is worth to mention that OWC in this formation is on the depth 3685 mTVD.

Geology in the Skarv field is very challenging. Presence of the over-pressured formations and faults enforces engineers to pay attention on the lithology.

3. Reservoir section analyses

Gas and condensate is produced from the Middle and Lower Jurassic sandstones. The reservoir is subdivided into four different formations from top to base: Garn, Ile, Tofte and Tilje. Garn and Tilje have underlying oil deposits. Nowadays HC are exploited form Tilje fm. Accumulation of organic matter is located at a depth 3300-3700 mTVD in sand units. The temperature is between 140-150 °C. Reservoir pressure reaches value 370 bar. The oil gravity attains 23.8 API. The gas gravity was measured 0.78. The gas-oil ratio for oil reservoir is 224 Sm^3/Sm^3. To increase flow rate value, was necessary to use neighboring well for gas injection. The reservoir is divided into several fault segments. [30]

Initial reservoir conditions and fluid properties are different for hydrocarbons from Garn and Tilje formations. Garn is filled with oil and gas deposits. Depth achieves 3300-3700 mTVD, with pressure 360-386 bar and temperature 135-145 °C. Oil gravity for Garn is very close to Tilje ans is 33.6 API. Gas gravity is 0.69 (gas) and 0.76 (oil). The gas-oil ratio is 5089 Sm^3/Sm^3 (gas) and 213 Sm^3/Sm^3 (oil). Condensate-oil ratio for Garn's gas gets to 196.5 Sm^3/MSm^3. [15]

Table 6. Reservoir characterization. [19]

Unit	Min	ML	Max	Comments
Lysing	4575 psi 1.20 sg	4957 psi 1.3 sg	5109 psi 1.34 sg	Unlikely to be any porosity
Gråsel	5519 psi 1.31 sg	6067 psi 1.44 sg	6235 psi 1.48 sg	Offset pressure measured with RCI tool. Good pressure control.
Garn		5484 psi 1.09 sg		If present: virgin reservoir pressure, well constrained with RCI measurements.
Ile		5505 psi 1.07 sg		If present: virgin reservoir pressure, well constrained with RCI measurements.
Tilje		5453 psi 1.05 sg		Virgin reservoir pressure, well constrained with RCI measurements.

Arrival pressure at the FPSO for the gas reserves is 30 bar (435 psi). In the future when the gas rates will fall to low rates, it can be possible to decrease this arrival pressure leading to increased gas reserves.

It was decided to use gas injection for pressure support for the oil production. For this choice the evaluations were done, including disciplines: reservoir, economics, facilities, drilling and HSSE.

There are evidences of gas in the 12 ¼" section in the main bore. The same casing diameter on the side track demonstrates flow opportunity. Junction is more deviated and has bigger angle of curvature. It gives better benefits for quantity and quality of production. Correspondingly it is an extension of wellbore section in the reservoir. From the economical and logistic side, it is more practical to penetrate reservoir with lateral branch from single location, than to drill new well. [15]

In the future there are plans to produce hydrocarbons from other promising layers. Shallower formations, like Kai and Lysing/Lange show HC potential. Sands in Lange are recognized as thin stringers in several wells. In the other well three failed attempts with TesTrack^{TM} tool were made. There were selected two potentially hydrocarbon layers. Shallow part shows high porosity, some permeability and therefore flow potential. Deeper sand accumulation presents low porosity, so it is likely to be 'tight' with no mobility. The main sand fairway with promising properties is interpreted to be on the footwall side of the major bounding fault. Wells which will be drilled in the nearest future should focus on promising Lysing/Lange sands. To increase field life, Garn and Ile reservoirs should be developed. Production from mentioned layers in new wells has to be planned with more attention on this cause. [12]

Reservoir description helps to understand the topic. Evaluation of the Tilje formation and hydrocarbons potential shows if risky drilling operations through the over-pressured formations are worthwhile.

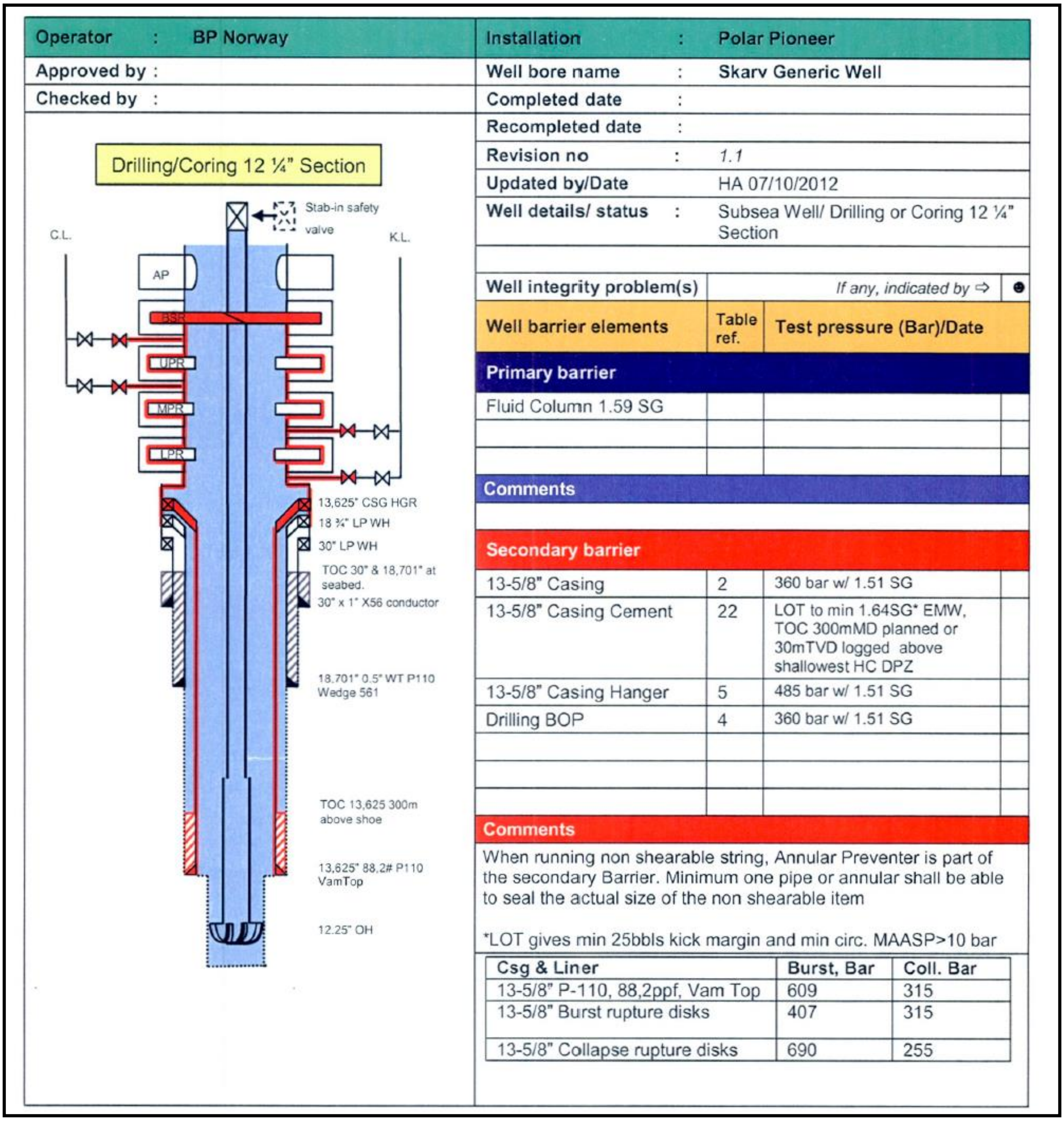
4. Well Integrity

Every operation, which includes hydrocarbons occurrence has to follow Norwegian standards and regulations, governed by Petroleum Safety Authority of Norway. During the drilling operation, it is significant that each stage of this process has to be well-done. In accordance with Norwegian standards well integrity concept is a basic and underlying conception for drilling activities. NORSOK D-10 rev. 4 2013 determines types of barriers, well schematics in different lifetime phases. Familiarity with this document helps to reduce costs, lead time and eliminate unnecessary activities, developments and operations on the NCS. Standards refer to international regulations: ISO and API. Over a dozen of offshore experience was a base for creation the 'Well integrity in drilling and well operations'.

In the 13⅝" casing the FasDrill plug was installed. The mechanical plug had the responsibility to temporary abandoned the well. On the top was squeezed 50 m height cement column. It was done for a future production tree installation and drilling and completion of the reservoir section. [10]

4.1Drilling activities

The most important findings to appear from the NORSOK D-10 is in the Figure 11. There is location of WBE in the wellbore during drilling the 12¼" section. Well schematic with primary and secondary well barriers describes drilling activity in a safe manner. Over-pressured formation was drilled with 1.59 sg fluid as a first well barrier that prevented flow from a potential source of inflow. The purpose is to exert a hydrostatic pressure in the wellbore and prevention from influx/inflow of hydrocarbons. Intermediate casing (13⅝"), cement behind it and casing hanger are the secondary well barrier. Casing contributes isolation and stops uncontrolled flow of formation fluid. It has to be designed with minimum acceptance factors, including loads, effects of temperature, corrosion, erosion and pressure. Planned casing cement length shall be minimum 100 m MD above the casing shoe. The sealing needs to be verified. Blind shear ram (BSR) is the secondary well barrier element located in the BOP. Minimum two well barriers shall be in place when is the abnormally pressured formation with potential to flow to surface. In situation where is no potential to flow, minimum one well barrier is recommended. All well barriers have to be properly selected and designed. The weight of drilling mud was prepared to prevent the formation pressure. This means that it withstood the maximum differential pressure. Casing, cement and BOP were pressure tested, to make sure that no single failure could lead to uncontrolled flow of hydrocarbons to the external environment. The WBE are independent of each other, as suggested in the Norsok D-10. After setting the casing in this section, well was temporary abandoned, to prepare installation of HXT with vessel. [37]



Operator : BP Norway
Approved by :
Checked by :

Installation : Polar Pioneer
Well bore name : Skarv Generic Well
Completed date :
Recompleted date :
Revision no : *1.1*
Updated by/Date HA 07/10/2012
Well details/ status : Subsea Well/ Drilling or Coring 12 ¼" Section

Well integrity problem(s) *If any, indicated by ⇨* ●

Well barrier elements	Table ref.	Test pressure (Bar)/Date	
Primary barrier			
Fluid Column 1.59 SG			
Comments			
Secondary barrier			
13-5/8" Casing	2	360 bar w/ 1.51 SG	
13-5/8" Casing Cement	22	LOT to min 1.64SG* EMW, TOC 300mMD planned or 30mTVD logged above shallowest HC DPZ	
13-5/8" Casing Hanger	5	485 bar w/ 1.51 SG	
Drilling BOP	4	360 bar w/ 1.51 SG	

Comments

When running non shearable string, Annular Preventer is part of the secondary Barrier. Minimum one pipe or annular shall be able to seal the actual size of the non shearable item

*LOT gives min 25bbls kick margin and min circ. MAASP>10 bar

Csg & Liner	Burst, Bar	Coll. Bar
13-5/8" P-110, 88,2ppf, Vam Top	609	315
13-5/8" Burst rupture disks	407	315
13-5/8" Collapse rupture disks	690	255

Figure 5. Skarv drilling 12¼" section of the well J-4H. [10]

4.2Well barrier elements acceptance

Environment conditions during and after interference, need to possess the same conditions. It is important to design abandonment operation. Allow for up two deep set permanent plugs across the 9⅞'' section. Either two plugs are required to set and isolate reservoir below, or if hydrocarbons present behind the casing one plug for the lower reservoir and one plug above the upper HC zone. It was gone over Norwegian standard document with a fine-tooth comb.

Based on the knowledge of lithology, my suggestion is to classify cap rock as a well barrier element. It can act as a '*physical element which in itself does not prevent flow but in combination with other WBE's forms a well barrier'.*

The clue is '*to provide a continuous, permanent and impermeable hydraulic seal along the casing annulus to prevent flow of formation fluids and to resist pressures from above and below'* . [37]

This definition is taken from NORSOK D-10 rev. 4 table 52. Creeping formation can eventually close the annulus between casing and open hole provides an eternal seal. This element is primarily used in a permanently abandoned well. The fact that formation with higher pore pressure is defined as a WBE can surround the casing and then replaces cement in B annulus (annuli between the production casing and the previous casing string). The acceptation criteria are presented in appendix A.

There are several requirements, which formation should fulfil. The most important point is formation shall be able to carry through an eternal hydraulic pressure seal. Based on standards minimum cumulative formation interval shall be 50 m MD. The minimum formation stress has to withstand the maximum applied pressure and maximum differential pressure. Position and length of the creeping formation has to be verified. To get reliable data two independent logging measurements shall be applied.

Well designed and executed slot recovering can get many profits. It is easier and cheaper to make a junction in borehole, than drill, run casing and cement new well. The mainbore should be permanently abandoned. Pressure integrity has to be achieved by casing and completion.

The J-4H was sidetracked without re-entry to the main bore again. In pursuance of NORSOK D-10 rev. 4 cement plugs were set. In order to avoid migration of HC to the surface, a good abandonment job has to be done.

The issue covering this phenomenon is wider discussed in chapter 6.

5. Drilling challenges on Skarv A & Idun

5.1Well J-4H/HT2

5.1.1 Strategic objectives

The planned well life is for 15 years. The producing section was drilled with satisfactory hole quality, without skin damage and solids production. For the Skarv field well objectives and functional requirements were defined to abide aspects: HSSE rules, reservoir management, well integrity (NORSOK), operability, and capacity. HSSE plays the main role. It was essential to drill the well without dangerous incidents and injuries. Haltenbanken area is environmentally sensitive point on the Norwegian Sea. The goal was to minimize discharges to the water and reduce impact of chemicals. Good management consists of monitoring pressure and temperature in the well. Stability of the hole with weighted mud and good drilling and tripping practices were key factors to successfully achieve the reservoir. Any challenges and predictable situations were contained in the specific documentation. The last but not least look-out was delivery the well on deadline and take into consideration CAPEX and OPEX. The production rate was planned from Tilje to achieve 7 mstb/d. The PPR diagram (Figure 12.) in upside case shows how oil, gas and water rate will change within time. In the beginning of well life the oil and production rate has the highest value. At the same period of time water production is near zero. The red curve presents increasing volume of gas, which is produced. The trend is rising in the first five years and between 2017 and 2026 it is almost stable, and after in 2027 will get the highest point and all at once runs down to point zero. Following the normal reservoir life time level of OWC is changing. The well starts to produce water from aquifer. The biggest amount of water should be recorded on 2025. [11, 15, 16]

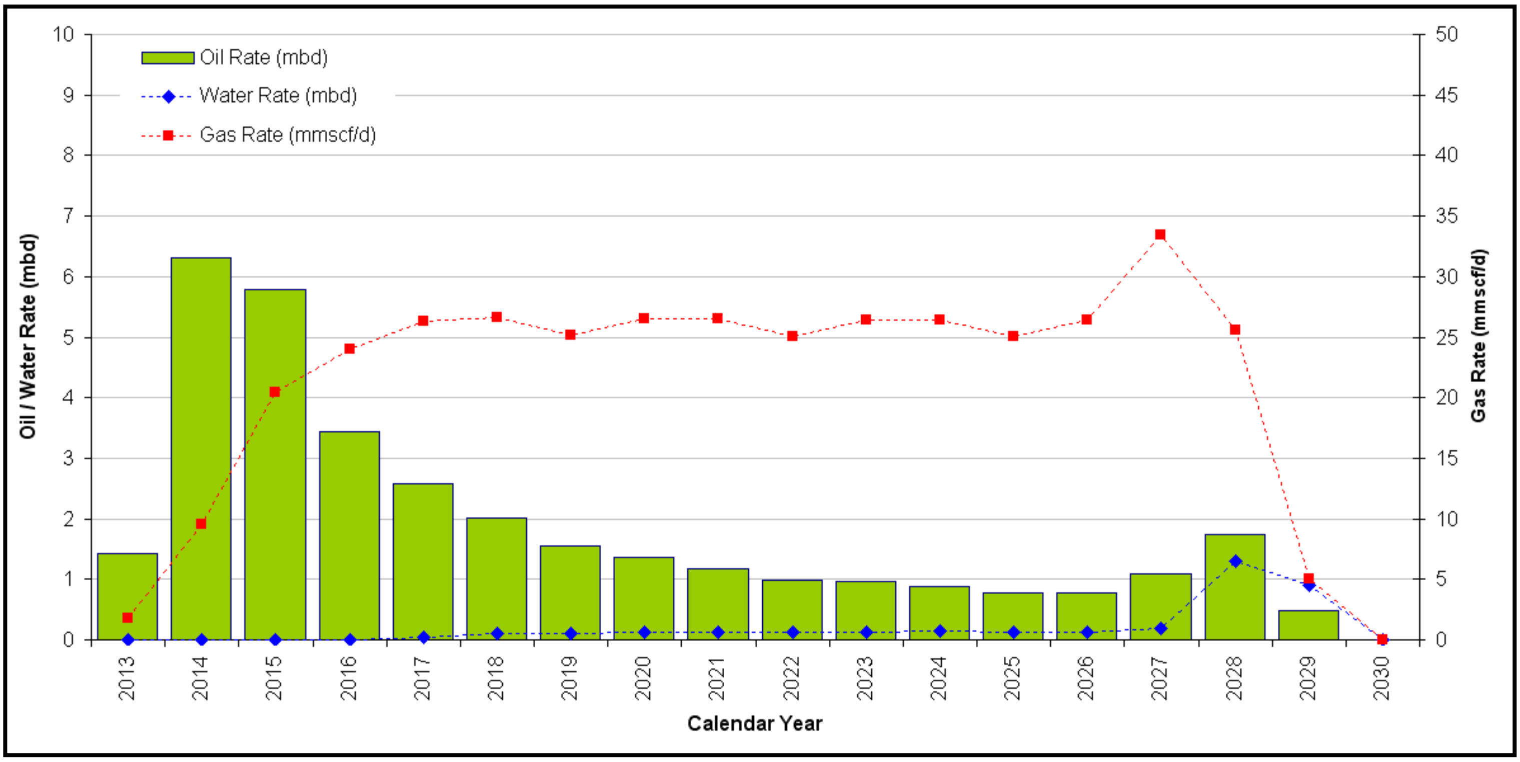
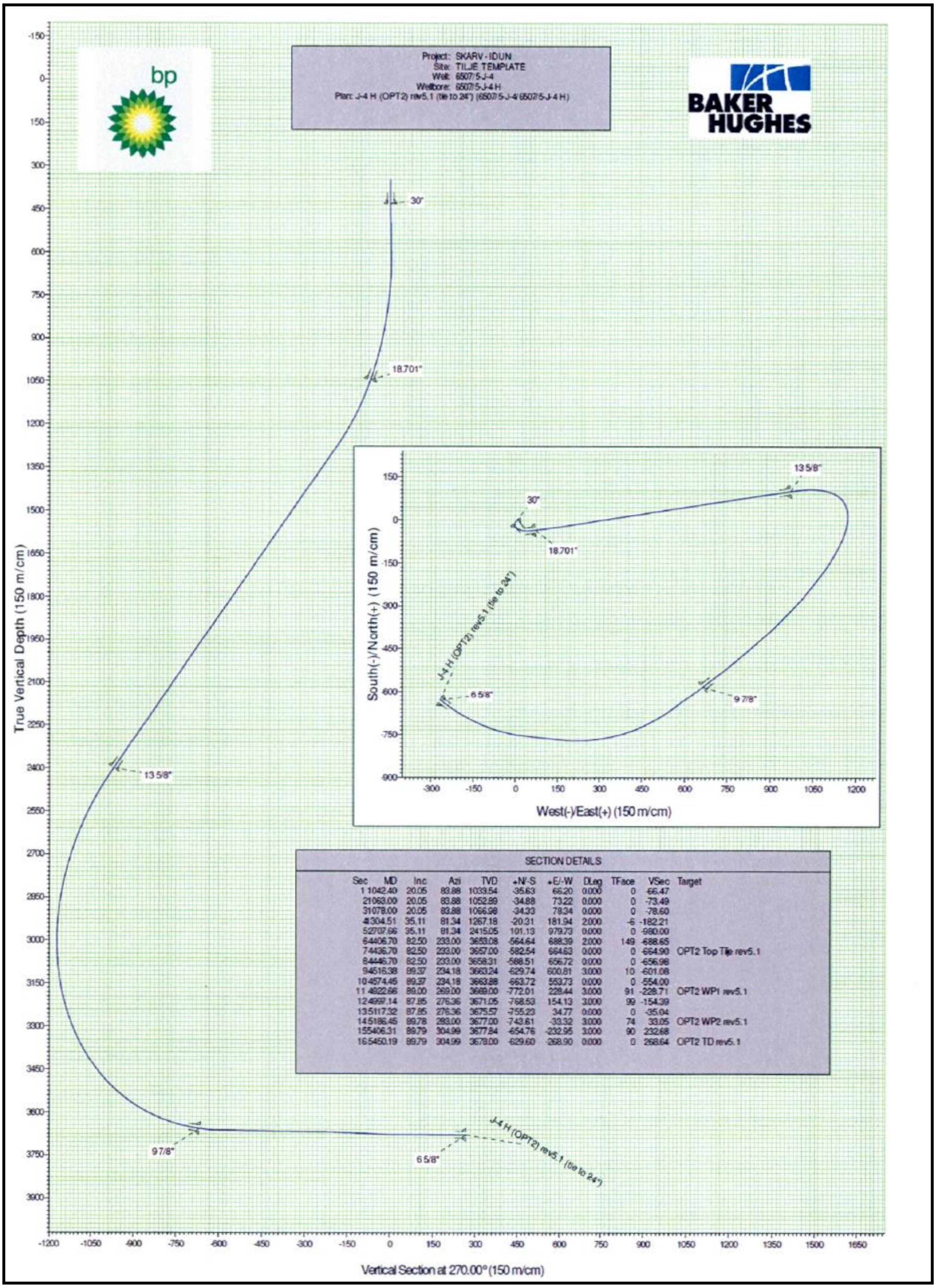


Figure 6. J-4 Upside Case Predicted Production Rate. [19]

5.1.2 Profile of the well and trajectory

The J-4 H/HT2 horizontal producer was drilled in the south eastern section of the Skarv A segment high structure, with gas support from J-3H to the northeast, the well encountered the Gråsel (Cretaceous), Garn and Ile reservoirs in a structurally complex fault terrace, and prior to drilling horizontally through the faulted Tilje reservoir. As mentioned on the previous chapter, the well is located in block 6507/5 and penetrates Tilje L, K, J, H and F sands. It is principal to have all needful data for well design and later production process. Pressure data was planned to collect, to determine fluid gradient in formations Gråsel, Garn and Ile. Well was connected to the Skarv A/Tilje template. From this point hydrocarbons are transported to FPSO.



Project: SKARV - IDUN
Site: TILJE TEMPLATE
Well: 6507/5-J-4
Wellbore: 6507/5-J-4 H
Plan: J-4 H (OPT2) rev5.1 (tie to 24") (6507/5-J-4/6507/5-J-4 H)

SECTION DETAILS

Sec	MD	Inc	Azi	TVD	+N/-S	+E/-W	DLeg	TFace	VSec	Target
1	1042.40	20.05	83.88	1033.54	-35.63	66.20	0.000	0	-66.47	
2	1063.00	20.05	83.88	1052.89	-34.88	73.22	0.000	0	-73.49	
3	1078.00	20.05	83.88	1066.98	-34.33	78.34	0.000	0	-78.60	
4	1304.51	35.11	81.34	1267.18	-20.31	181.94	2.000	-6	-182.21	
5	2707.66	35.11	81.34	2415.05	101.13	979.73	0.000	0	-980.00	
6	4406.70	82.50	233.00	3653.08	-564.64	688.39	2.000	149	-688.65	
7	4436.70	82.50	233.00	3657.00	-582.54	664.63	0.000	0	-664.90	OPT2 Top Tie rev5.1
8	4446.70	82.50	233.00	3658.31	-588.51	656.72	0.000	0	-656.98	
9	4516.38	89.37	234.18	3663.24	-629.74	600.81	3.000	10	-601.08	
10	4574.45	89.37	234.18	3663.88	-663.72	553.73	0.000	0	-554.00	
11	4822.66	89.00	269.00	3669.00	-772.01	228.44	3.000	91	-228.71	OPT2 WP1 rev5.1
12	4997.14	87.85	276.36	3671.05	-768.53	154.13	3.000	99	-154.39	
13	5117.32	87.85	276.36	3675.57	-755.23	34.77	0.000	0	-35.04	
14	5186.45	89.78	283.00	3677.00	-743.61	-33.32	3.000	74	33.05	OPT2 WP2 rev5.1
15	5406.31	89.79	304.99	3677.84	-654.76	-232.95	3.000	90	232.68	
16	5450.19	89.79	304.99	3678.00	-629.60	-268.90	0.000	0	268.64	OPT2 TD rev5.1

Figure 7. Trajectory of the J4-H well. [10]

Figure **7** presents vertical section of the well. It is presented how complex and curved well is. The azimuth is increasing diametrically at the depth between 2415 m TVD and 3653 m TVD. Changes in the inclination and azimuth could be the reason of improper logging operation with stuck as a final. This type of trajectory is also challenging with the casing design.

5.1.3 Drilling, casing and cementing work

Each well on Skarv's field was designed with high integrity, safety and economical patterns. During preparation drilling plan, engineers have to take into account dozen factors, which are fully evaluated. Casing is a major contributor to stable the wellbore. Even small fail can cause irreversible losses. Hole stability, formation pressure and integrity, parameters of drilling fluids, hole cleaning process, cementing precautions, hole curvature, mechanical equipment and economy are main elements of casing design and setting depth. The POLAR PIONEER semi-submersible drilling unit drilled the well. It was designed to be capable of operating in harsh environments.

Table 7. Mud weighs in 6507/5-J-4 H. [14]

Section	Depth (m TVD)	Mud type	Mud weight range (sg)	Comment
36''	366-435	sea water/hi vis sweeps	1.03-1.30	Displacement to 1.30 sg KCL/Polymer WBM
24''	435-1052	sea water/hi vis sweeps	1.03-1.30	Displacement to 1.30 sg KCL/Polymer WBM
17 ½''	1052-2401	carbo sea OBM	1.50-1.53	
12 ¼''	2400-3660	carbo sea OBM	1.53-1.59	BHA stuck, plugged hole and sidetrcked

Table 8. Mud weigh on 6507/5-J-4 H2. [14]

Section	Depth (m TVD)	Mud type	Mud weight range (sg)	Comment
12 ¼’’	2661	carbo sea OBM	1.59	Kicked off at 3003 m MD
8 ½’’	3661-3678	Omniflow OBM	1.30	Displaced fr M omniflow OBM to LSOBM,the same sg

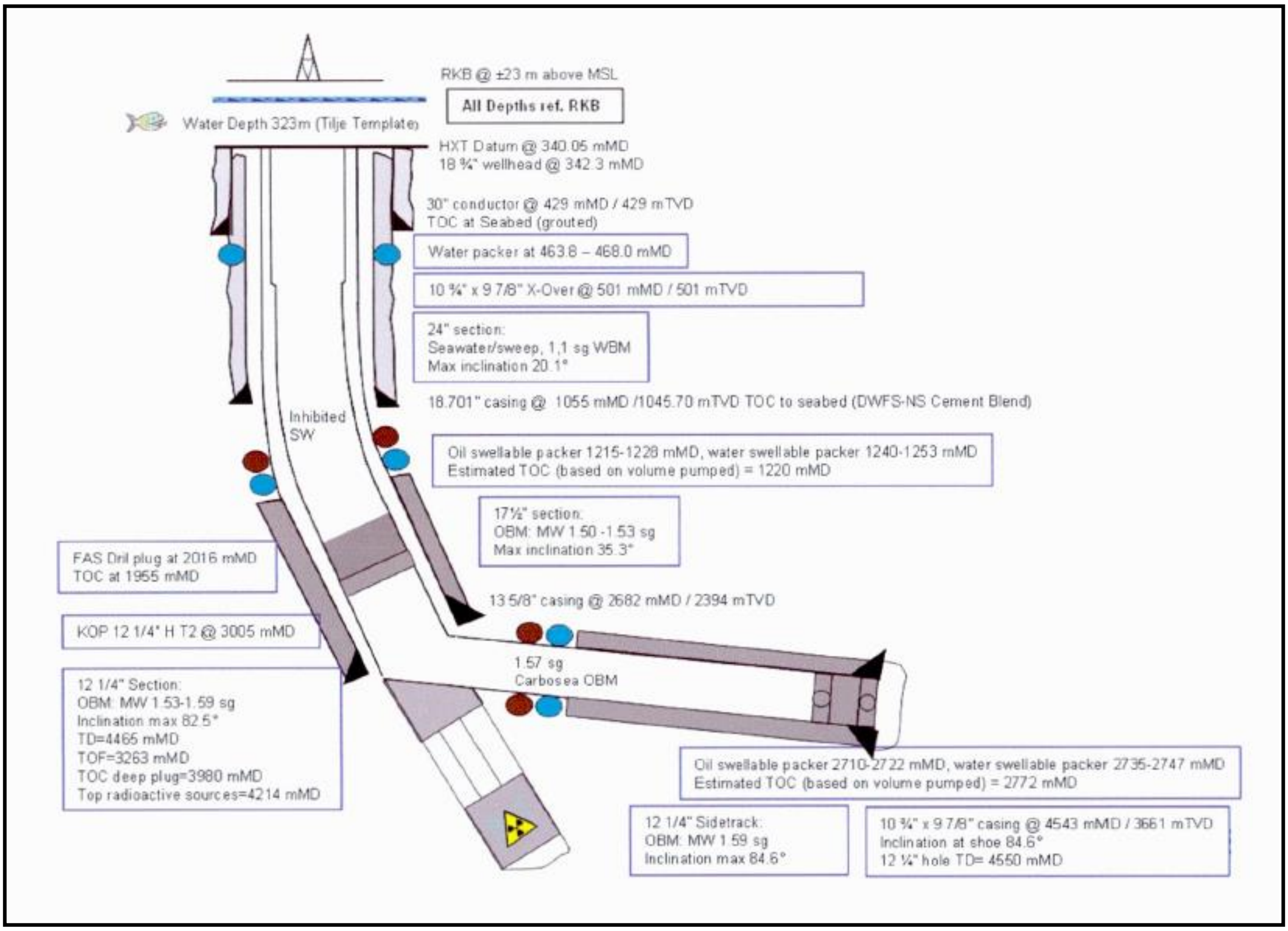


Figure 8. Well schematic down to top reservoir of J-4H well. [11]

36” Section (30’’ conductor)

The well was drilled with 17 ½’’ bit but with 26’’x 36’’ assembly, which made bigger diameter. During the progress with drilling competent formation was penetrated from 356 m MD to 429m MD whist steadily increasing bit weight and RPM. To create the hole, sea water was used to transport cutting up to the surface. Conduct shoe was set at 429.3 m MD. [7]

24” Section (18.7’’ surface casing)

The interval between 429.3 m and 435 m was drilled out. From the depth 435 m sea water and regular high viscosity sweeps were used. At this point Gyro directional surveys was working and it was provided on wireline. From the depth 930 m MD to TD drilling slurry was changed to KCL mud. The majority of this section was to drill it in sliding mode, started as a vertical hole and in the end gain inclination of 20º and azimuth 84º. Measured average rate of penetration was registered 27 m/hr. It was not notified and technical problem with drilling string.

The final depth was 1055.5 m MD and TVD 1045.8 m TVD RKB in Naust formation. Surface casing was cemented in place to seabed. To avoid contamination between cement and cement plug, tail slurry cement was pumped. As the last stage of this job, pressure test was performed. SBT was used for cement evaluation. It measures the quality of cement effectiveness, vertically and laterally around the circumference of the casing. After cementing surface casing, the well was suspended. [7]

17½’’ Section (13⅝’’ intermediate casing)

It was planned to drill intermediate casing to provide protection against caving of weak or abnormally pressured formations and enables the use of drilling fluids of different density necessary for the control of lower formations.

This section was drilled with two bits. The first bit had been damaged. Polycrystalline diamond compact bit (PDC) type is used to cut shear rock with continuous scraping motion. [50]

It is designed to damage shale formations in combination with OBM, which was pumped in this section. Dropping ROP and unusually large cuttings on the shakers gave warning signs. It was realized that bit was not suited to the harder rocks in the Naust fm. From the previous experience the A template was had beed used to set 13⅝" casing. The reason was the strength of Brygge formation. Tare and Tang Fm were recognized as potentially unstable. After entrancing the Tare fm, is was decided to pull out the BHA and changed the bit. The minor damages were on the face of the bit. Several noses were lost.

Casing shoe was set at 2682 mMD in Nise formation and TVD reached 2394.2 m. During cementing work, there were several stops due to problems with bulk supply. The oil and water swellable packers were located on homogenous shave interval (1215 m MD to 1252 m MD). This was done to separate hydrocarbon zone in Naust fm. According to the Norwegian standards, the casing is not cemented to the seabed. TOC is just above Kai Fm. The oil and water swellable packers were mounted. The temporary plug was set inside the well at the depth 1900 mMD. [10]

12¼'' Section

MWD tool was run to collect required data. On the first run the connection with tool was lost, so was decided to remove and run in the hole new assembly. Directionally the well path followed the planned well trajectory very closely. For taking pressure points, it was decided to use TesTrak tool. The reason of the assortment was drilling cuttings logistic problem.

The stuck event was in Ile and Ror formations. That happened when preparation for pressure measurement was taken. The end of casing was on the top of Tilje formation at 4545.2 m MD.

There were investigated four probable scenarios: [7]

1. Mechanical stuck in the claystone at the top of Ror
2. Faulted zone
3. Differential stuck in the Ile formation due to high overbalance (pp=1.07 sg, MW=1.59 sg)
4. Reduction of the effectiveness of the filter mud cake caused by the pipe movement.

Side track

12¼'' Section (10¾'' x 9⅞'' production casing)

In the main bore a new 150 m cement plug was set. The same assembly was used to drill the side-track. The bit inclination was kept 21.4° to get a kick off at the depth 3003 m MD. In Garn reservoir faulted zone was drilled through, but without any problems and losses. Casing was set at the depth 4542.9 mMD (3661.1 mTVD) with inclination 84.55°. Side track penetrated eight sections in Tilje formation and 4 faults. There were appointed well barriers. As a primary barrier was oil-based mud and the secondary was cement behind 13⅝" casing, casing itself, seal assembly and BOP. As a final for drilling this section, the 9⅞" was set in top of Tilje to isolate the Ror shale. [7,11]

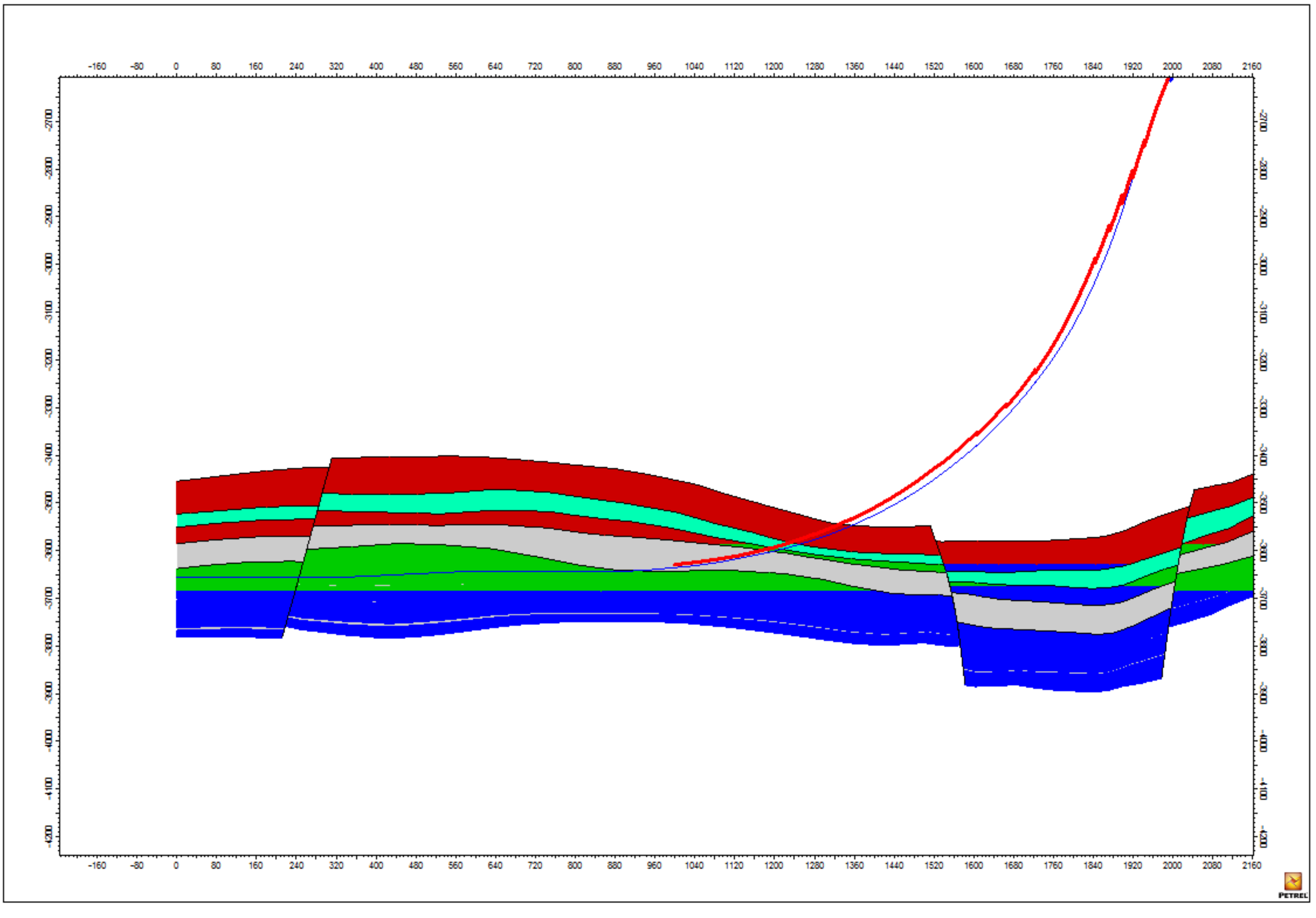


Figure 9. Skarv reservoir intersection with main bore and side track.

Intersection of the reservoir is exposed in Figure 9. Red layers represents gas, green is an oil and water is marked as a blue color. Shales and clays are the impermeable insertions in the reservoir. Shales are located in gas section (bright green), clays are the border between gas and oil occurrence (grey). Depths are related to TVD. The red colon of trajectory is the main bore, which was killed. The blue trajectory is a side track. The well path entrances oil layer and passes fault. The whole trajectory is presented in the appendix B.

8½'' Section production tubing

The last drilled section was a preparation for completion work. The 9⅞'' shoe was set on the depth 400 mMD shallower in top Garn. After cementing, the 8½'' section was drilled and under reamed to top Tilje. Expandable liner was installed 400 m from the casing shoe, to top Tile. This solution includes 7⅝'' OD pre-installed liner, located in previous casing string and expanded around 14.4% to 8½'' OD. The liner is cladded to the 9⅞'' shoe by expanding elastomer sections, which function like liners hanger. The plan was to build section with angle 85° to 90°. Important remark is to displace drilling fluid to completion fluid. Well cleaning process is normally necessary. To manage cleanliness, special mechanical tools and well cleaning fluids were used. Contamination of two liquids is potentially unwanted. Before running lower completion the hole and mud conditions were checked. [7, 11]

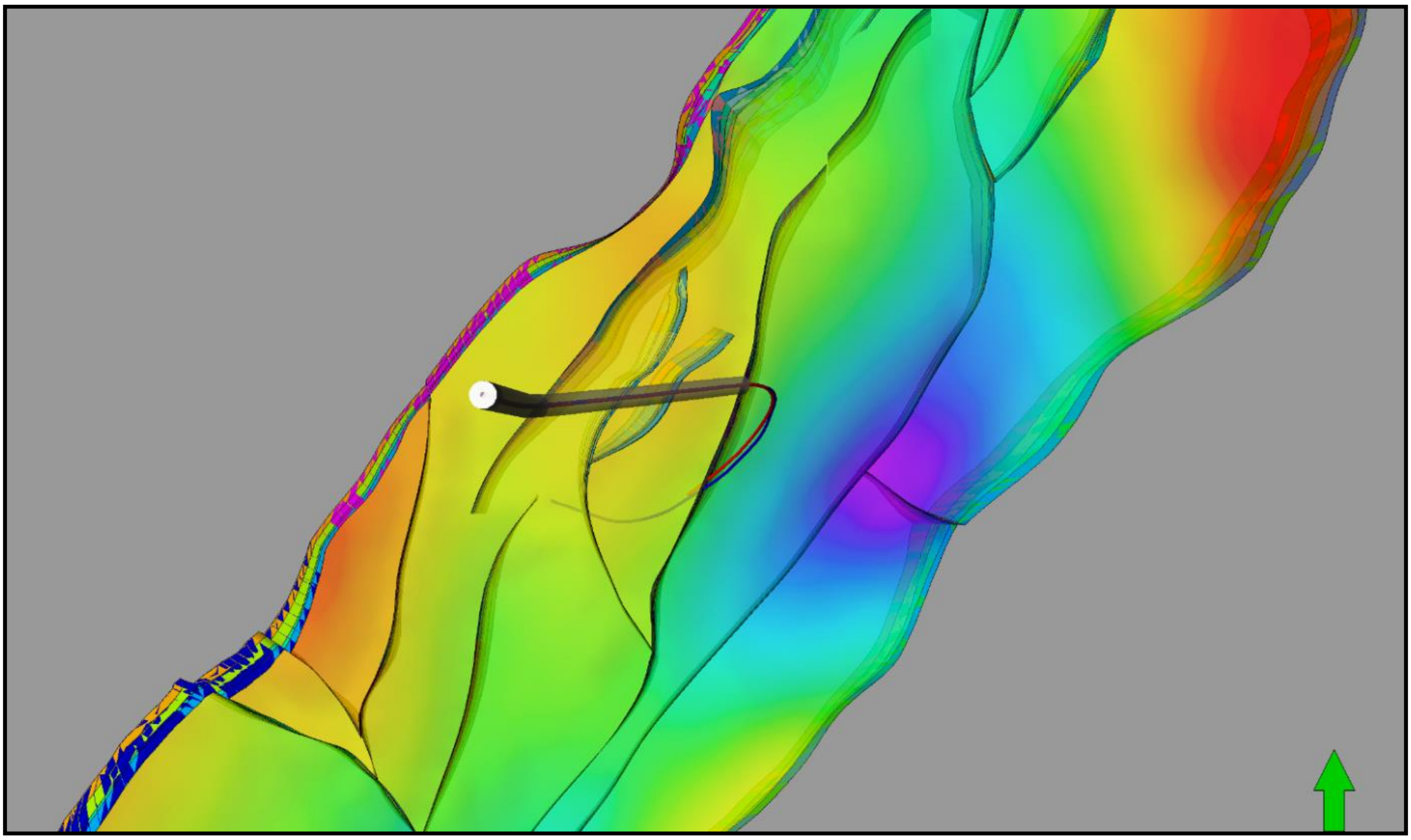


Figure 10. Projection of J-4H with intermediate casing and trajectory.

In the Figure 10 is the perspective from above is presented. Intermediate casing is visible. Drawing represents Tilje oil producer with drilled faults.

5.1.4 Completion

Lower Completion

Investigated well was completed as a horizontal oil producer. The open hole well completion was done in the 8 ½'' section, which is the most robust open hole sand control method. To achieve extension of well life and increase overall productivity gravel pack method was done. This type of completion is very challenging in design and execution stages. Through cross over tool slurry was pumped and created Alpha and Beta waves. It consisted of 20/40 CarboLite gravel. From the calculations, it was investigated around 70% fulfilment of gravel in OH section. The servicing tools for GP are wash pipe and cross over tool. Pumping performance was done in terms of "operations window". Fracture pressure is constant but pressure in opened section was increasing. The “operations window” covered the pressure when gravel started to be located, but did not frac formation. The pressure gauges were monitored. In J-4 well SC-2R gravel pack packer was set. The other elements of equipment were CS-300 gravel pack extension, Knock Out Device and Quick Connect. For prevention of sand production, 5 ½’’ 300 micron wire wrap screen was installed and length 980 m. These kind of screes have triangular wire for keystone shape, which helps i.e., self-cleaning. The flow area is usually from 6% to 35%. Availability in wide variety of materials makes them very popular and often used. Usually they are chosen to retain the coarsest approximately 10% of sand. The aim of WWS is to create a Sand Bridge, which makes impossible for smaller particles to pass through the screen. Bridges are formed only on the one direction and create Natural Sand Pack. The operation took longer time than it had been expected. [7, 13]

Middle Completion

For zonal isolation between reservoirs swellable packers and blank pipe were run, to separate specialized components in a completion assembly. In addition to selective production, glass plug was installed. Before setting the production pacer it was mandatory to change the lower completion fluid to the base oil. [13]

Upper Completion

Finally, the upper completion consists of crossover tubing (5 ½’’ to 7’’), production packer, two pressure and temperature gauges, a TRSCSSV and tubing hanger with crown plugs. It was planned to install horizontal XMT. [13,45]

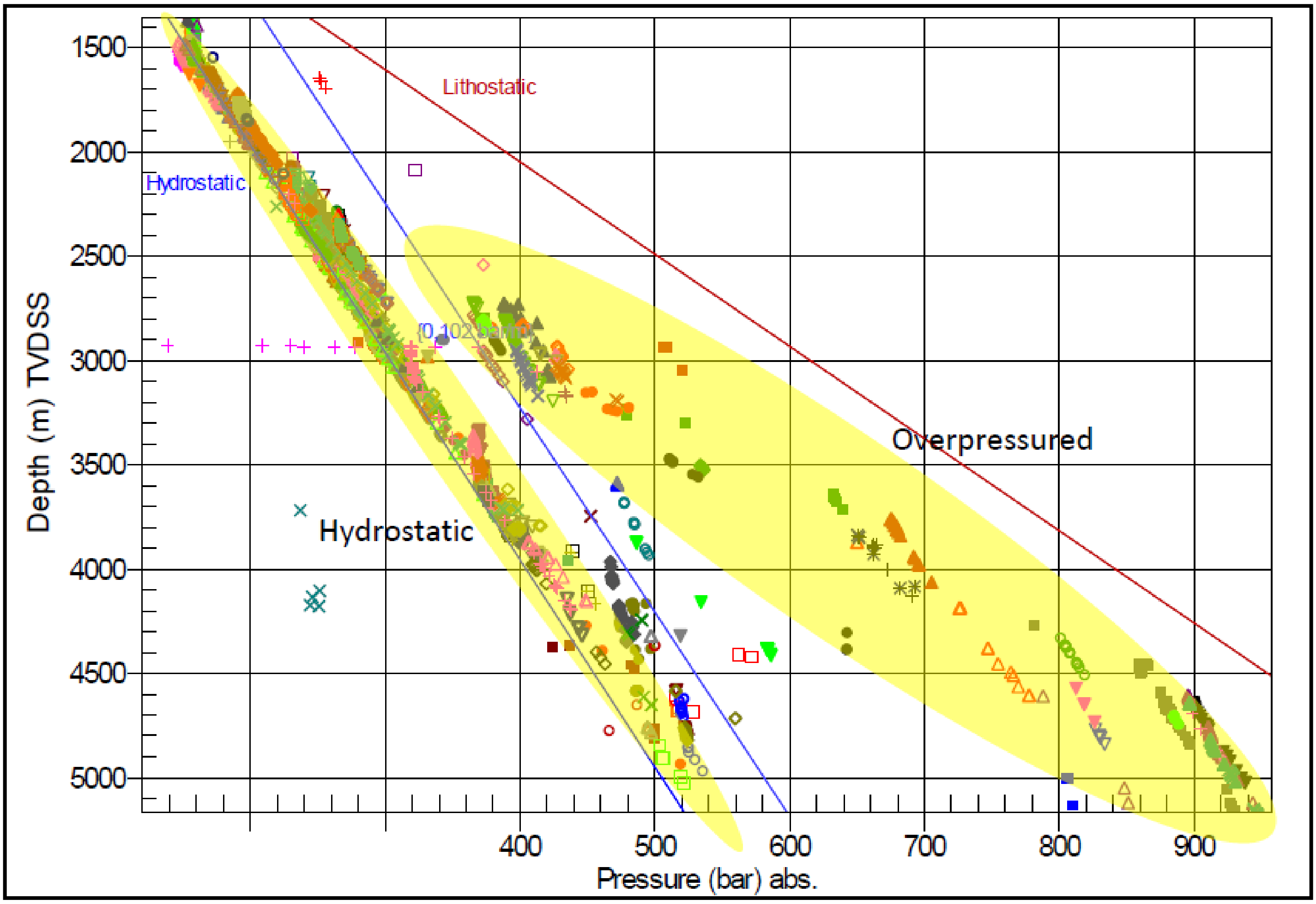


Figure 11. Correlation between pore pressures with increasing depth, Norwegian Sea. [42]

Figure 11 displays measured pore pressures in many wells drilled on the Norwegian Sea, an area of rapid subsidence. Most of the results were recorded in hydrostatic pressures. Over-pressured zone is marked on the right side on the chart. The area of this type of formations is bigger than hydrostatic. High overpressures typically develop from depth 2700 m and below and reach pressure value from 360 bar. The highest measurement was 900 bar at the depth 5600 m. It can be actually figured out that NCS is varied pore pressures. Drilling activities on the Norwegian Sea area have to be done with bigger attention. The drilling technology is going longer and deeper, therefore there are new challenges with offshore drilling.

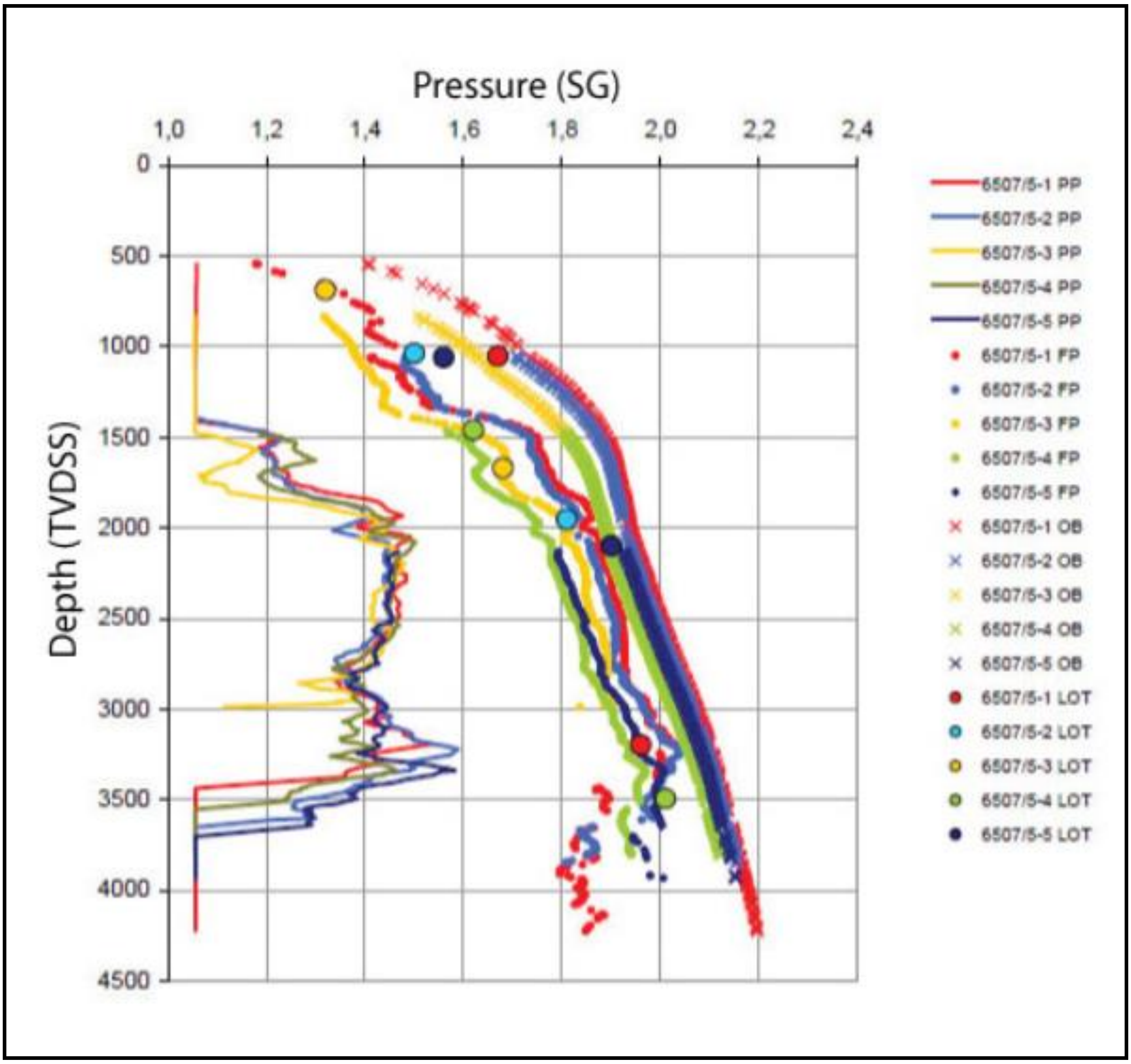


Figure 12. Summary of the overburden pressure model for the Skarv area. [18]

Plot represents the pressure tendencies in different wells in Skarv. Pore pressures are close to normally pressured with 69 bar (1.1 sg) over-pressure. Pore pressure measurements in the overburden above the Skarv Field are limited to the Cretaceous Lysing & Lange Fm sands which have 69÷137 bar (1.3÷1.6 sg) over-pressure. Over-pressure build-up is initiated within the shales Kai Fm. Build-up of over-pressure continues down through the Brygge shales to a maximum of around 83bar (1.45 sg) over-pressure at the base between 2000- 2100 mTVDSS. Estimates of over-pressure gradually reduce within the shales of the Nise Fm to a local minimum over-pressure of 76 bar (1.35÷1.4 sg) towards the top of the Lysing Fm sands 2700÷2750 mTVDSS. Over-pressure estimates begin to climb once more through the underlying Lange Fm sands and shales approaching 137 bar (1.5 sg) towards the top of the Spekk Fm. Estimates of over-pressure within the Spekk Fm shales rise to more than 180 bar (1.6 sg) but caution was advised since porosity estimates in these shales are believed to be questionable due to micro-fracturing and organic content. This Upper Jurassic formation causes the main problems in the well J-4H. Throughout the depth the estimated over-pressure is seen to rapidly reduce towards normal hydrostatic levels through the Melk’s shales towards the top of the Garn reservoir sands. For the observed well the LOT was taken on the depth 1480 mTVDSS and 3500 mTVDSS.

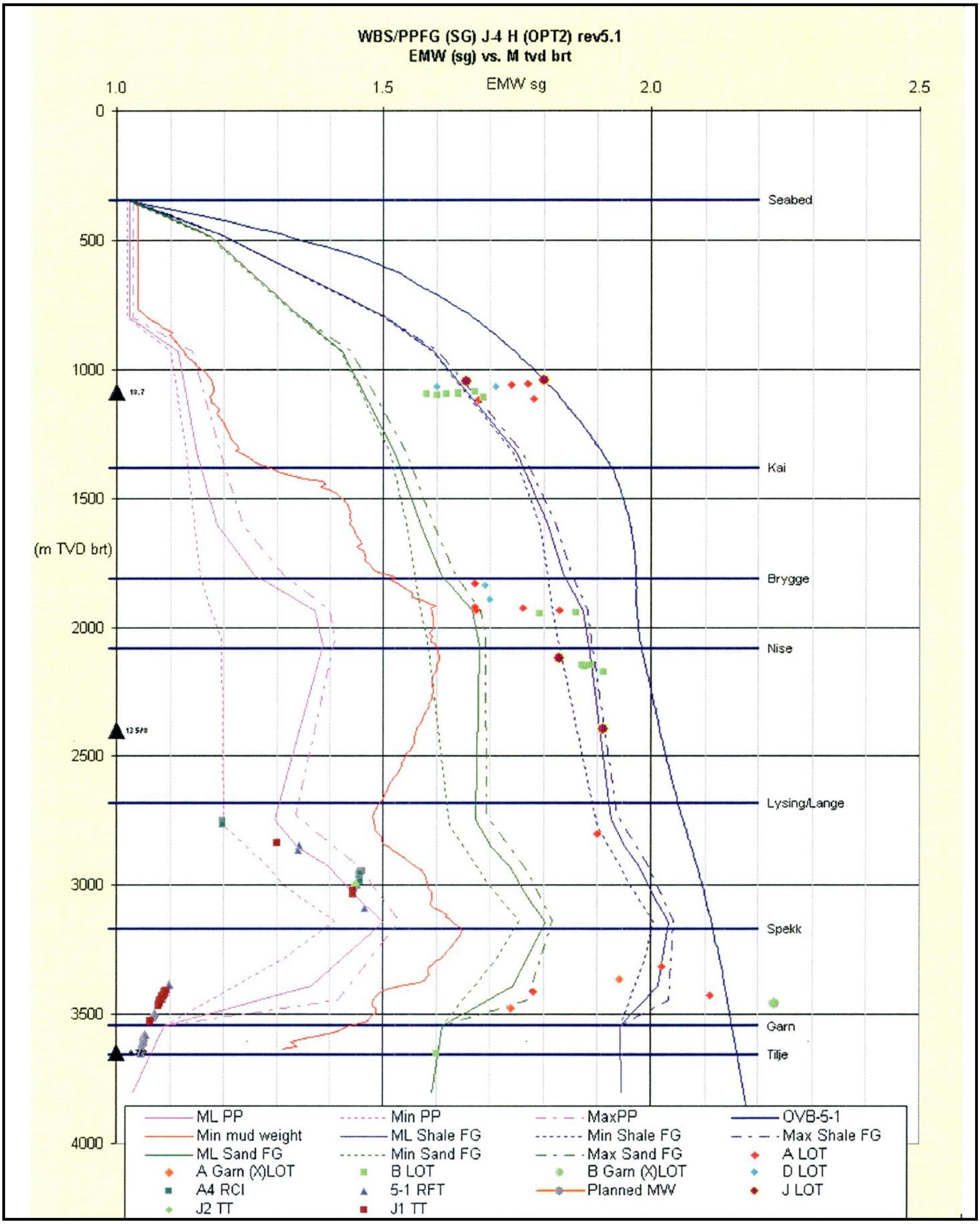


Figure 13. Relationship of depth to pore pressure and drilling mud pressure in the well J-4H. [10]

The diagram (Figure 13) represents diverse pressure gradient curves along the depth in the J-4H well. There are marked casing shoes on the appropriate depths. The top horizontal line represents seabed level. The other lines, which are below it, are the tops of the formations: Kai, Brygge, Nise, Lysing/ Lange, Spekk, Garn and Tilje. During analysis of the plots, the main attention was put on the mud weight.

With deepening of the hole, values of pore pressure, mud weight and fracture gradient are changing. From the surface level until 800 mTVD pore pressure and mud weight are constant. During drilling of the first section, there is not big impact of the layers, which lay above. From this point, linear growth is observed. This means, that to prevent unwanted situation, it is mandatory to pump heavier mud. Drilling fluid has to transport cuttings and counter the pore pressure at each point in the well. As is show in the plot during the drilling the trend of pore pressure changes untypically. Of the top of Nisse fm the pore pressure progressively drops within Lysing/Lang fm. The pressure is decreasing from 1.39 sg at 2083 mTVD to 1.30 sg at depth 2800 mTVD. At this point pressure reaches the lowest value in the well. Declining tendency changes along the depth and from 2800 m TVD raises just above the top of Spekk formation, achieves the highest pore pressure 1.5 sg., before decreasing to 1.11sg at top Garn Formation and decreasing further to 1.05sg in Tilje Formation. The depth is 3172 mTVD. The pore pressure was estimated from the prognosis and drilling data, and there were no indications of pore pressure close to the mud weight or higher. After accomplishment the top point, pressure is going down again and gains number close to 1.0 sg at the reservoir section. This exposes the Spekk Fm has unique high pore pressure. The situation obligates to change properties of drilling fluid. The clue here is mud weight. The solution was to increase mud weight at the depth 2000 mTVD (after drilling Brygge and Tare Fm). This move was an insurance to enter safely over-pressured formations. Overbalance reached 24 bar. Following this train of thought, high overbalance was recorded in the deepest part of the well. Reservoir section had superiority of pressure around 190-200 bar.

In the over-pressured section, the equivalent mud weight exceeds the pore pressure. At this condition is easy way the drill pipe will get stuck. While the drill bit approaches stuck-point, the borehole starts caving in and the torque increases simultaneously. Side track is a consequent of pipe stuck and hole filling up. [24]

Situation when hydrostatic pressure is higher than pore pressure may create major problems. It can dramatically slow the drilling process. This is easy way to frac the rock or limit removal of cuttings from the well. What is more, using mud with poor properties can affect the differential sticking problems. Rock mechanic properties are the most important information for drilling operations and all other open hole section activities. From the LOT data it was possible to create a plot for shale fracture gradient. The chart presents no formation fracture. Mud weight curve does not exceed the minimum shale FG. In the interval 1900 m TVD ÷ 2200 m TVD minimum mud weight value slightly superposes the dimension of minimum sand FG. This means that Brygge, Tore and Tang Fm are mechanically weak. The most probable scenario was the incidence of faults. However, pressure from the operation fluids cannot be higher than existing pressures in formation. The final of this action can cause fluid losses. [10,24]

5.3 Stuck drill string

The drill pipe gets stuck due to different situations. From the industry experience the most frequent are: key eating, pressure differential between formation and borehole, balling of bit and drill collar, sloughing formations, foreign objects, junks in the borehole, poor wellbore cleaning. When the diameter is decreasing the drill string cannot make any progress, then it is stuck in the well. [39]

5.3.1 Causes of stuck pipe incident

During the operation we can observe warning signs to avoid this phenomenon. The principal remark is steadily increasing torque, erratic torque which jumps up and down and torque from a standstill. Cautionary note can be incidence of steadily increasing overpull, erratic overpull and increasing overpull from a standstill. Other issues can have influence for this event, such as: thick filter cake and narrowing the bore hole, balling the assembly (bit, tool joints, drill collars), shale sloughing, accumulation of carvings and cuttings in the annular space, key seats, mud thickening and last but not least carelessness of personnel. It can be therefore assumed that the drill sting movement in the upward or downward direction is impossible but free circulation is easily established, since obstruction exists on only one side of the pipe. Situation looks much different in deviated and horizontal well bores, where the angle can create more difficulties with intervention actions. [32, 48]

Pipe is affected by pipe-sticking forces. The dimension of force is related to differential pressure, permeability of formation, thickness of zone, thickness and slickness of filter cake, length of time the pipe remains motionless against the formation, hole and pipe size, and pipe shape. As it can be inferred, the scale of issue can be variable. [20]

EQ. 3

$$differential\ force = (H_s - P_f) \cdot area\ of\ contact \cdot f$$

Where:

H_s – hydrostatic pressure of mud

P_f – formation pressure

f- friction factor, allows for variation in the magnitude of contact between steel and filter cakes of different composition

EQ. 4

$$area\ contact = h \cdot t$$

Where:

h- thickness of permeable zone

t- thickness of filter cake

EQ. 5

$$differential\ force = (H_s - P_f) \cdot (h \cdot t) \cdot f$$

The most important findings that are shown in the equation 1 tell that the magnitude of the differential force is very sensitive to changes in the values of the contact area and the friction factor, because of fact both are time-dependent. Contact area is between drill collar and borehole. [32]

In other words, when the pipe stays stationary in the well, filter cakes is getting thicker. What is more, during time the friction factor increases with a consequence of more water being filtered out of the filter cake. Furthermore, the differential force is dependent of differential pressure. When the drilling action is taken in overbalanced environment, the attention should be put on warning signs. High probability for differentially stuck are highly depleted formations and no torque recordings. [51]

That happened on the well J-4-H, where the problem was pressure differential. It means that hydrostatic pressure of mud is lower than formation pore pressure. The differential pressure became excessively large across a porous and permeable formation such sandstone or limestone. The most significant reason is that a mud filter cake is built up in those formations during drilling. We do not observe creation of mud filter cakes in rocks like shale, where permeability is very low. It was ensures if circulation was maintained.

There are 3 steps to solve the problem: [48]

1. Determinate depth of the free-point.
2. Separate the pipe.
3. The remaining stuck pipe has to be fished.

Pipe sticking has been a hindrance since early 50's. When the technology was not outstanding and each drilling operation was manual, problems with drill pipe were very common. Nowadays, even when modern tools and advanced monitoring are used, string still has a lot of situations of blockage. Helmick and Longley and Outmans first proposed the mechanism of differential sticking in the late 1950's. The statistics can zoom in this issue (BP investigation in 1989): [41]

- In the North Sea, 29% of the cost associated with stuck pipe due to differential sticking and 70% from mechanical sticking
- In the Gulf of Mexico differential sticking was dominated and ranged 61% of the total cost of nonproductive incidents

This scale shows how big this problem is. In previous years a calculated costs was $250 million each year.

There are two types of pipe sticking:

- Mechanical
- Differential

As a dictionary definition, mechanical sticking is:

"The *limiting or prevention of motion of the drill string [...]. Mechanical sticking can be caused by junk in the hole, wellbore geometry anomalies, cement, key seats or a build-up of cuttings in the annulus".* [50]

This means that mechanical sticking is an impossibility of moving the drill string. It is prevented by mechanical means. The main reason is accumulation of drilling cuttings. They are transported to the surface, but because of mechanical reason they stop in the middle of a way, and fill the area between pipe and casing/wellbore. This matter will be not described in detail in this thesis. [31]

Differential sticking

Helmick and Longley and Outmans first proposed the mechanism of differential sticking in the late 1950's. All improvements are developed based on their studies. The most illustrating explanation of differential sticking is when a portion of the drill string, casing or logging tool lies against the low side of a deviated hole. In the well the pipe is being rotated. Circulated mud lubricates the steal, and pressure is equivalent on every side. On a number of situations rotations is paused and pipe touches filter cake. This isolates from the mud column. State of affairs creates differential pressure between two sides of the pipe and it makes drag when drillers pull out the sting. When drag is higher than pulling power, the stuck pipe is created and willing differential sticking. [21] This occurrence only takes place across permeable rock formations. It is observed in sandstones, where a mud filter cake is built up during drilling. Typically it appears when pipe is not moving. This event can be diagnosed when the drill pipe can be rotated or maneuvered up or down, but unrestricted mud circulation is still possible. [41]

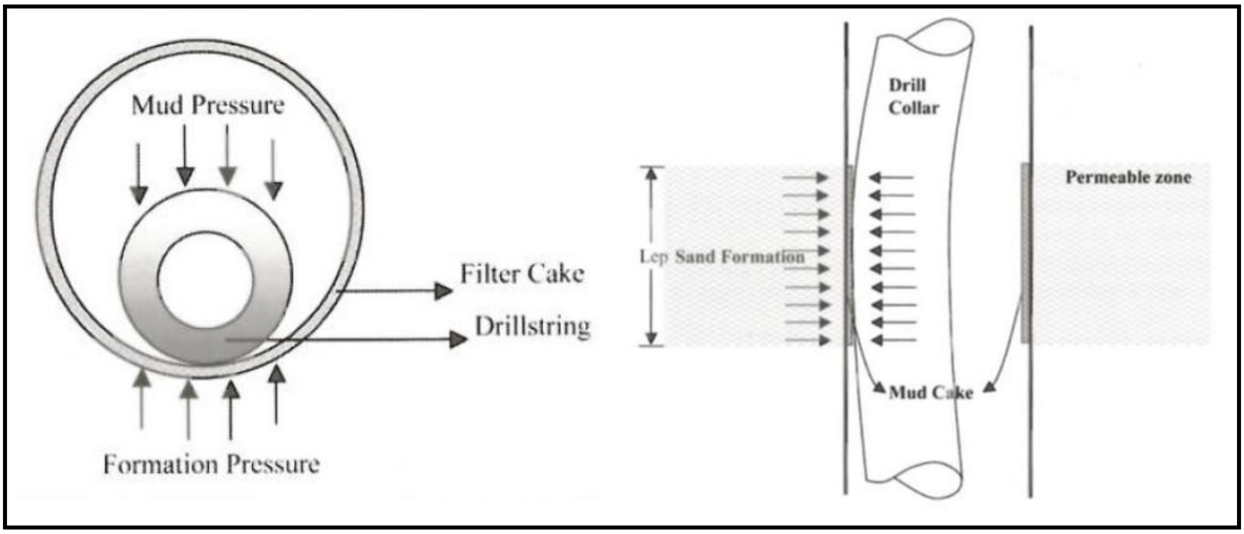


Figure 14. Differential pipe sticking (left). Differential pressure pipe sticking with embedded pipe length (right). [4]

Schemes above (Figure 14.) presents filter cake formation from the top transverse cross-section (figure on the left). There are exposed directions of pressure effects on mud cake. Higher mud pressure from the wellbore affects the formation pressure from permeable sand formation (figure on the right).The drill collar is notably turned to the formation. Drilling fluid pressure creates the force, which deflects the assembly. On the both schematics drill collar (string) is not centralized in the hole. That is in the reality, some part of the sting is closer to the formation wall. This contact makes appropriate conditions for pipe stuck incident. From the experience in the industry, it was observed that differential sticking is limited and arises around the drill collar string. The tool joints behave like stabilizers for the pipe. Amount and distance between collars are important factors in the wall sticking mechanism. The diameter of collar is bigger than drill pipe, which gives opportunity to create wall-collar contact. When the drill string with collars stops moving/rotating, then face between mud cake and wall of collar is not lubricated anymore. [38]

Figure and curve below (Figure 15.) explain how not movement of pipe has influence on pressure changings in the pipe-wall contact. Pressure start declining immediately and pipe becomes immovable. Appropriate pullout force need to be applied. Time is playing the main role, if pipe is longer without moves; it is less probability after some time to free the pipe. The time limit is when cake pressure creates adequate effective stress and cake shear strength is more than the axial and torsional pull out force that can be delivered to the stuck point. The dominant force is related withe the pressure between borehole and formation. Technology in the industry made a step to drill in omnifarious forms and conditions, even in abnormal pressured and with high overbalance. [22]

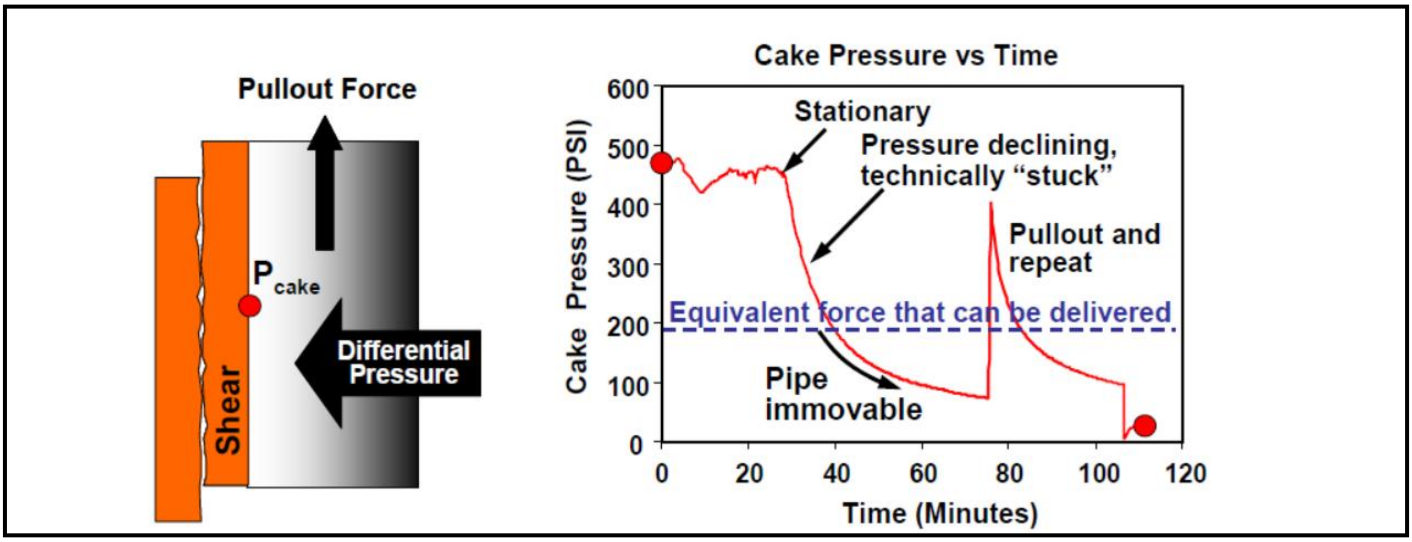


Figure 15. Impact of stationary situation on internal pressure of cake. [22]

5.3.2 Stuck-pipe prevention

In response to equation 5 they are several ways to reduce differential sticking force. One solution is to reduce differential pressure (can be called pore pressure). Drilling with a minimum overbalance gives possibility to avoid influence high formation pressure. As long as mud density increases, it has to be monitored to control the ROP. This note is important in big diameter wells, where large quantities of cuttings are transported to the surface. Following this, thickness of the porous formation cannot be changed; the contact area can only be reduced by making the thickness of the filter cake smaller. This can be arranged with using oil-based mud with minimum of solids. In perfect scenario, drill collars with minimum surface area should be used. In this case contact area of pipe steel in contact with the permeable formation is smaller. The other solution is reduction in the time, because contact area and friction factor value raise with time. These findings are consistent with those of Farahat [32] who says that despite above mentioned methods, the pipe does become stuck; nonetheless there are different methods to free the string. The solution can be the U-tube method, as exhibited in the Figure 16. [32]

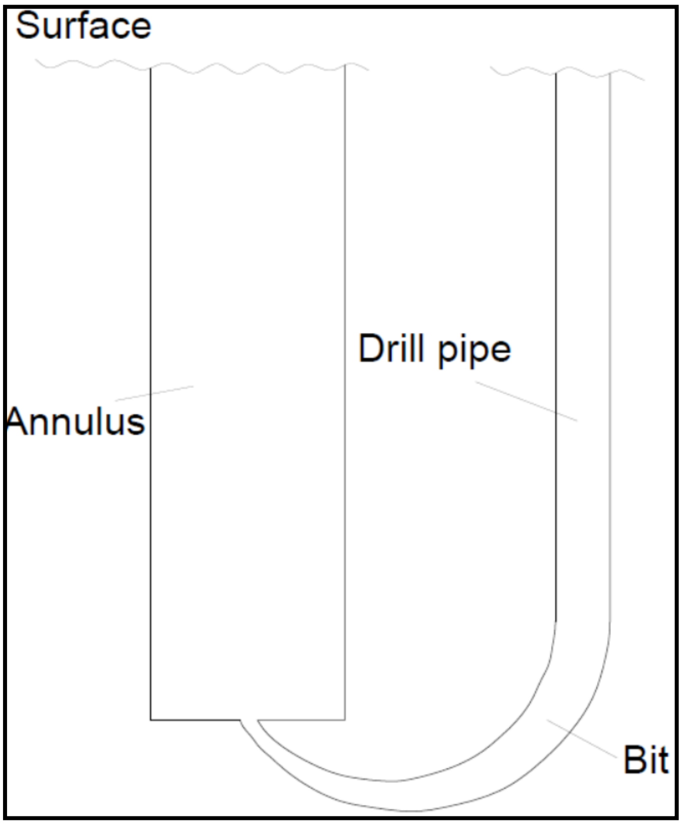


Figure 16. U-tube configuration of a well. [10]

Annulus and drill string with bit can be compared as a U-tube. I will consider on two scenarios:

1) Formation pressure is known
2) Formation pressure is unknown.

At the first point, the overbalance can be reduced to cautious level, using the method of hydrostatic reduction. Hydrostatic pressure should be higher than the formation pressure. To achieve the reduction of pressure, new mud of lower density is pumped. For the same result it is possible to pump small volumes of a fluid of low specific gravity, such as diesel oil. To ensure how much fluid is needed, it is required to calculate value of expected hydrostatic pressure and then convert it to height and volume of the liquid. The amount of low density fluid to be pumped into the drill string and resulting maximum drill pipe gauge pressures are:

EQ. 6

$$V_0 = \frac{L_{st} \cdot V_{dp}}{\rho_m - \rho_o} \cdot \left(\rho_m - \frac{P_p}{0.052 \cdot L_{st}}\right) \cdot \left[1 + \frac{V_{an}}{V_{dp}} \cdot \left(1 - \frac{\rho_o}{\rho_m}\right)\right]$$

It should be noted that precautions have to be taken that formations above the free point do not kick due to the pressure reduction of the annulus. The low density fluid can be pumped into annulus too. This is the alternative procedure. The volumes of low density fluid and volume of mud are determined by: [39]

EQ. 7

$$V_0 = V_{an} \cdot \frac{\frac{P_p - L_{st} \cdot \rho_m}{0.052}}{\rho_o - \rho_m}$$

EQ. 8

$$V_m = V_{dp} \cdot L_{st} + V_{an} \cdot (D - L_{st})$$

Where:

V_{dp}- capacity of drill pipe [bbl/ft]

V_{an}- capacity of annulus [bbl]

V_m- capacity of mud required to pump behind the low density fluid [bbl]

P_p- pore pressure [psi]

P_{dp}- pressure within the drill pipe (measured at the surface) [psi]

ρ_m- mud density [ppg]
ρ_o- density of fluid pumped down [ppg]
V_o- volume of the fluid pumped down [bbl]
L_{st}- length of the drill string [ft]
D- total depth of the well (MD) [ft]

According to the second instance, it is universal to decrease the hydrostatic pressure of mud in not big increments by the U-tube technique until the pipe is free. The other method is to pump water into the annulus and the drill pipe. Those operations bring the values of hydrostatic pressure equal or greater than the formation pressure. Caution should be used in U-tube method. Cuttings and debris can plug the small diameter nuzzles in the drill bit. In this way flow is from the hole back to the nozzles into the drill string. Preventing differential sticking depends on careful mud design and conditions.

The preventive actions are different on each well. It is important to keep in mind, to not stop moving string. Since the BHA is rotating across sensitive formation, thereby progress in drilling is continuously. Not only formation is an issue but also mud properties. High mud weight causes problems. It has to be kept in good shape, to create and as thin mud cake as it is possible. The last, but not least is reduction of contact area. Moreover, the spiral drill collar and HWDP have important impact. Special drilling tools like square, spiral or slick collars are often run with the drill pipes. [51]

When the problem is foreseen in advance it is possible to react at the appropriate time. Chemical changes in the mud can be solution, but the consequences are provided. Putting in different additives to reduce the mud weight can help for freeing the pipe. One of the ideas is gasifying with nitrogen. Dilution is also the way to reduce density. The problem with those types of applications is change with rheological properties. Price of drilling fluids is relatively high, so any reworks in quality and/or quantity have extremely impact on budget. Even with very good string design and lithology discernment, engineers cannot totally prevent differential pressure pipe sticking problems. [4]

5.3.3 Fishing operation

Stuck drill pipe, broken drill pipe, drill collars, bit, bit cones, hand tools, stuck packers are problematic during drilling operations. Those dropped object have to be fished. This type well intervention can be done in the open hole and cased hole section. Every fishing operation is different and specific fishing tool should be used. Fishing tools are designed to be larger than drill sting and to go over and around the fish. Intervention has to be done with big attention. To avoid swelling accident close attention should be paid during pulling out of the hole. Running fishing tool with fast speed, it will act like a piston. This causes excess pressure below the tool and creates problems with drilling mud circulation. It is possible to hit a tight place which might wedge the intervention tool where it is not possible to pull out. Cuttings transportation to the surface is extremely supreme. For the fishing operation different equipment has to be mobilized. Overshot tool is the most used tool. It goes over a fish and enrolls it with slips. The top one is used to get the hook as low as possible on the fish and catch it. The bottom extension operates in conjunction with a milling instrument. Different types of spears are used. Generally there are applied to go inside the stuck pipe, which has a round bore through it. The spear goes through the packer and enlarges below it. After milling away slips, the packer is taken out. Junk basket collects and picks up the small, broken junks from the bottom of the well, which are too heavy to circulate them. Magnets are an indispensable accessory to picks up all small metal object like milling shavings, bit cones, cutters, slips, hand tools and others, from the bottom of a hole, and are used only when objects can be retrieved by magnetic action. Cutting process is done after applying the pump pressure. The mechanical cutter is moving down with rotation and set on the needed depth. After letting go the slips are set and collapse which makes a cut. Hydraulic jar is applied free the fish and move it up. The washover pipe is used when is a stuck event, to washover or around a fish to free it. Different service companies offer a list of milling tools. Metal parts like packers, bit cases, pipe, casing, etc., have to be milled in some stuck accidents. The function of lead impression block is to get a notion of a fish when the size and shape is unknown. The box taps are external catching tools. [47]

6. Evaluation of drilling problems

6.1Analysis of daily drilling reports

Each operation which is done on the rig is reported. This documentation is the most important for the people involved in the project. Situations and actions are connected with date and time when the event took place. This document was the most valuable source of vital data.

6.1.1 DWEB plot of stuck pipe event

During the operation on 12¼’’ at the depth 4230 m MD was a problem with MWD tools. It was unworkable to decode MWD signals. To solve the problem, drilling rig crew tried to contact technical support. To find the reason of bad decoding of signals, the values of pump rates were changed. The stand pipe transducers and valves were checked and they did not show any failures. Decoding was getting back and continued drilling on this section. At the depth 4266 m measurements of pressure were done. Section was drilled to TD into Tilje at 4465 mMD. After the TD was achieved, the logging operation was done. The measurements were done during POOH the wireline. Without rotation, slide drilling string deeper and tried to pick it up. At this moment, on the depth 4242 m, 25 ton overpull was registered. That happened in Garn fm. The pump rate was 3300 lpm and pressure 280 bar. It was decided to apply 50 KNm torque to sting and lowered pipe to 50 ton on weight indicator. This operation did not help to get rotation. It was also impossible to jar down after setting down weight. It was decided to reduce pump rate almost half time to 1500 lpm and pressure to 73 bar. The drill string was jarred down two times with maximum force, but it was still impossible to move pipe down. Torque was bleed off in string and it was pulled up to 280 ton on weight indicator to jar it up. From the logging chart it can be observed that there is decline of RPM and torque logs. The assembly became key-seated. Interesting thing is that flow of mud was still possible. This means that it was enough volume in the annulus between bit and formation to circulate mud. The hole angle at stuck point was approximately 72°. [7]

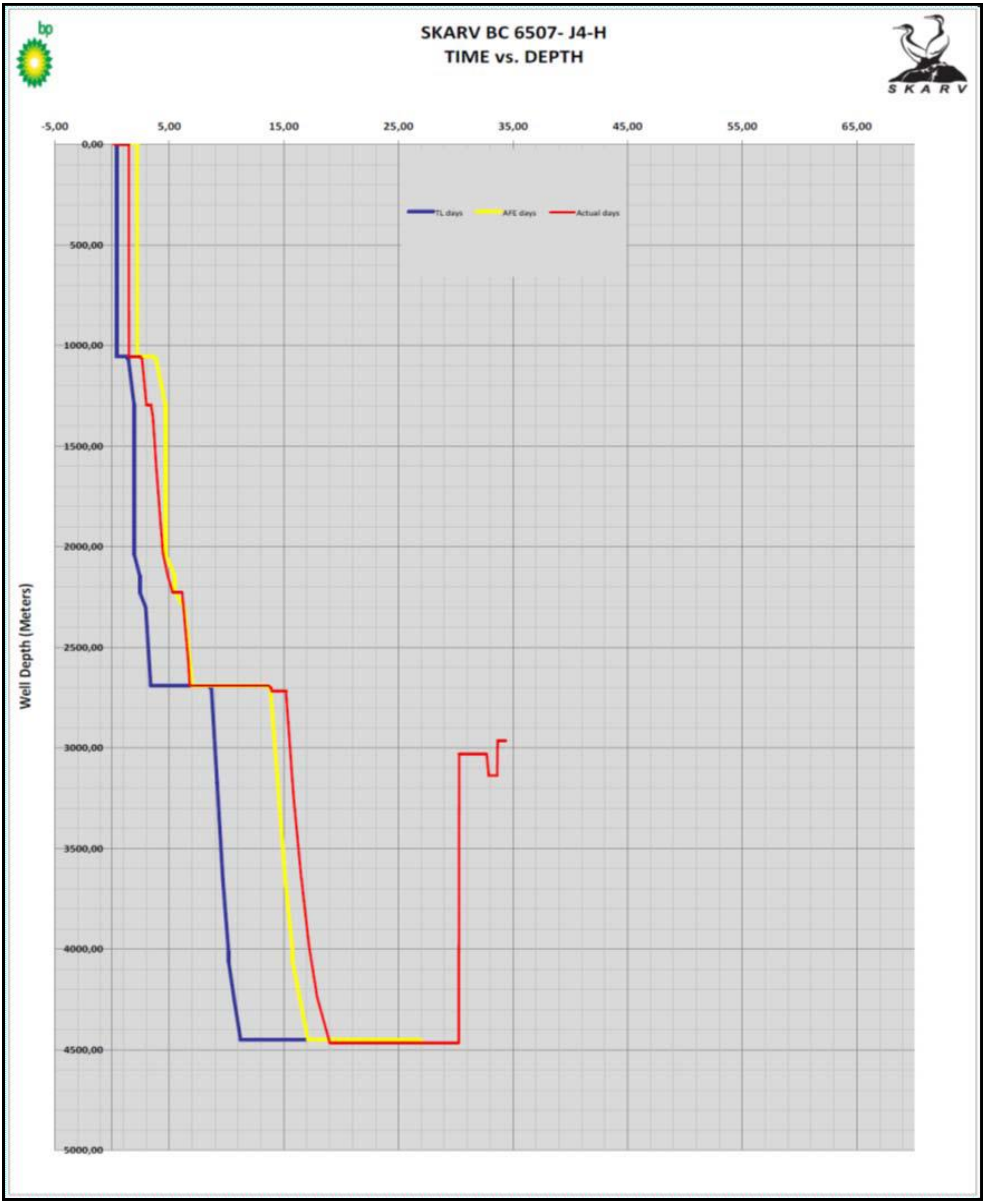


Figure 17. Drilling process within time. [9]

Figure 17. demonstrates dependency between well depth and time. The red curve represents actual days of operation. Horizontal lines with constant depth are casing and cementing activities. If the casing string is set deeper, it needs longer time to cement. This can be observed on the graph. After setting the intermediate casing, the working time changed. Actual days of drilling operations radically exceeded the planned operational time. Time consuming operation started with getting in to the high pore pressure layers. Drilling the 17½” hole took longer time, than was planned. This was caused by low ROP and passing over-pressured formations. The deepest point shows the moment where drill pipe was stuck for around 7 days. This time was spent for pulling out the string. The reason of long stand time was bad weather situation. The pulling out operation is clearly visible. Effort to free pipe was without success. The BHA was cemented in place with TOC in annulus at 3948m and inside DP at 4095m.

6.1.2 Examination of the properties of drilling fluids

Chemical properties of drilling fluids have significant influence for drilling time, costs of project, formation protection, hole cleaning efficiency and environment protection. As it is well known, drilling fluids fulfil several roles in drilling process:

1. Cool and clean the drilling bit.
2. Keep the stability of open-hole sections.
3. Transfer cuttings from the bottom to the top through the annulus.
4. Give a power for motors.
5. Assist and transfer different data.
6. Form a thin, low-permeability filter cake which seals pores and other openings in formations penetrated by the bit.
7. Prevent caving in to the borehole unstable rocks.
8. Withstand pore pressure.
9. Reduce friction between string and hole.
10. Avert influx from formation.
11. Reduce friction between drilling string and hole.

It is worth to mention that is it no injure to drilling personnel or damage to the environment. Mud has compatibility with completion fluid.

First two sections of the J-4H well were drilled with water-base mud. The liquid was based on seawater. Seawater is used for fluid make-up and maintenance on inland barge and offshore drilling operations, where is easy available. A characteristic property is shale inhibition. Drilling through over-pressured formations the mud weight is the main clue. This parameter has to be carefully controlled in order to balance formation pressure. The 36” diameter was drilled with sea water with 1.30 sg. Around 133 m of liquid column in 24” section was displaced for 1.10 sg mud, but after came back to heavier fluid. One of the characteristic composes of the WBM is lubricant. This helps to reduce friction between moving surfaces. Based on water properties, shale and corrosion inhibitors are often added. Deeper units were washed with oil-base mud. After running 13⅝” casing, the displacement of fluids took place. To gain the mass of the mud, it is practical to use high-density solids. It should be in the attention, that additive cannot cause any reactions and thoroughly change the properties. From the safety and environment side, it has to be nontoxic. Barite is the most common used extender. That was done in the well J-4H. Successively weighing agents were added and final weight was 1.5 sg. Brygge, Tare and Tang formations had tendency to be unstable. The weight was increased up to 1.54 sg before entrance Brygge Fm. From that moment it was maintained to keep this density. Speek formation was disclosing high pore pressure. To drill without any accidents, drilling mud was weighted up to 1.59 sg. Admittedly, this prevented seepage losses to sandstone formations during drilling and following cement job. Based on this finding, it seems that formations under Speek were treated with high weight mud. There were used lost circulation materials. Calcium carbonate worked well in this situation. This OBM were kept until Tilje section. Other significant extras on OBM are emulsifiers, lime and organic fluid loss substances. However, losses of mud were observed. The volume of lost liquid was bigger, than predicted. Side track was entered with the same mud. The last section 8½” distinguished lower pore pressured. The mud weight was decreased to 1.30 sg. Meanwhile, mud had good fluid loos properties and was able to inhibit mud cake build. [20,21]

6.1.3 Fishing in J-4 H

The main issue on this event was impossibility to rotate, but ability to circulate drilling fluid. Cutting, pulling, setting cement plug, side tracking the well and running the casing are complex processes. Based on findings, it seemed that the results gathered from the study seem to be consistent with research and fishing performance was required. Conversely, the only reasonable solution was wellbore abandonment.

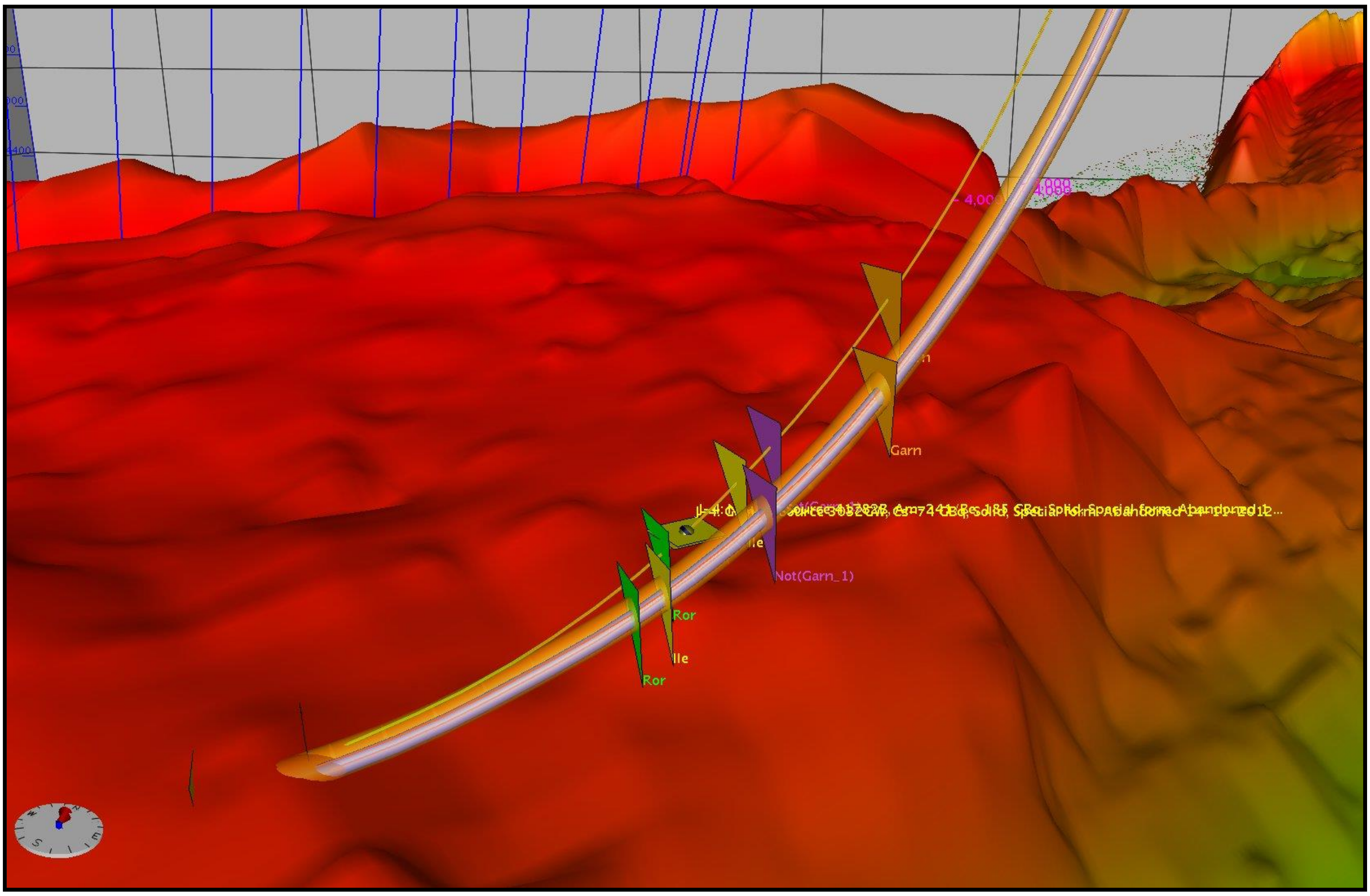


Figure 18. Fishing operation in the well. [13]

Figure 18. shows the trajectories of the wellbore, which was fished and new path. The top of Tilie is colored by depth. The fish was done between Ile and Ror formations. It was necessary to be as close as possible to planned trajectory. The new path, which was planned, is represented in purple. The actual drilled well is in orange. The diameter was smaller for planned well bore. All in all, the target is achieved at the point.

One of the cardinal actions was to evaluate the situation. Engineers had to investigate which size of pipe was stuck, and check the depth of it. Quick decision was made after well records and field history had been analyzed. It was decided to run explosives and disconnect steel with shots. Unfortunately it was unable to shoot of drilling pipe with wireline explosives. Then the decision was made to cement the annulus around BHA. The cement plug was set with thickness 148 m. To prepare fishing operation it was vital to land LMRP on BOP. On wireline cutter assembly was RIH. The drill string was cut and POOH as a free pipe. For safety and security reasons BSR was closed, to provide isolation and sealing of the wellbore. The 5 ½'' pipe was pulled out from the well above LMRP. Forecast showed bad weather conditions for next three days and second step of intervention was delay. Camera was run with the ROV for BOP inspection and testing operation. Check-up of visual checks were done with good effects. In order to perform fishing operation on the well, special fishing tools were employed. One week after stuck affair BSR was opened and the milling BHA was run in the hole. Top of the fish was tagged from the depth 341 m MD. Downhole milling tool was run in to the hole and started to crush TOF. It was milled 0.6 m of top of fish/drill pipe. At this stage it is very important to clean wellbore properly. When the well was cleaned, the ID of the string was suitable to run on wireline tool string and tried to latch the fish. Run in the hole overshot tool, grappled the fish and shoot off pipe. On the next trip the 11 ¾'' overshot was run with extension BHA. Latching operation was made several times. Stuck pipe was severed after the 4th attempt at the depth 3263 m. The three previous runs were unable to free pipe, but indications of explosives fired positive. Drilling string was not 100% parted. The broken tubular was run out of hole and hole was preparing for side tracking. [7, 8]

6.1.4 Side-track operation

Side tracking was performed to initiate directional drilling and to help guide the drilling bit in the desired direction. When the pipe was retrieved, crew started the preparation for placing balanced plug. This placement method is the most common operation to plug and abandonment the well. In this particular drilling operation, the remaining stuck pipe might have been sidetracked for economic reasons. There were defined three main risk during drilling the junk section: differential sticking while drilling in Garn/Ile Fm, poor hole cleaning, low leak off test, weather dependency for bulk off loading and skips handling, and last but not least drilling through faults.

5 ½'' tubing was run into the hole to the desired depth. As a plug base the high viscous fluid was used. For proper cement job, two CST were set, which are the insurance

of good cementing job. The next step was cement squeezing. Spacer fluid was pumped after the cement. It is a high density mix of drilling water and different chemicals, and it helps to avoid contamination with the mud. Those fluids have different properties and can cause serious problems. The worst scenario is leakage from the wellbore. Cement evaluation job is the final activity of setting the plug. Spacer fluid follows the cement slurry. The main bore was plugged are ready to drill the patch. Drilling operation could be started after the BOP pressure test. The plug was set from 3190 m to 3025 m. The side-track was initiated. From the kick of point started to make 12¼'' hole, but it was unable to continue. The most probable reason was not satisfactory quality of the plug. Consequently the abandonment operation was continued.

The cement string was picked up again and like the previous time, the balanced plug was set. The barrier was located between 3137 m and 2965 m. The second try with the OD 12 ¼'' BHA was organized to create the path at the depth 3005 m. At this time the kick off was successful.

The pore pressure was estimated to be 1.30 sg at kick off point. In Lysing/Lange Fm the pressure increases to 1.50 sg just above the top of Spekk, before decreasing to 1.11sg at the top of Garn Fm and decreasing further to 1.06 sg in Tilje. There were not recorded any losses to formation. Cavings were not seen during drilling of this section and no connection gases were recorded. Unplanned deviation was continued without any unpredicted situations. However, affair of pipe stuck cost 15 days of reparation and without progress on drilling. [7, 14]

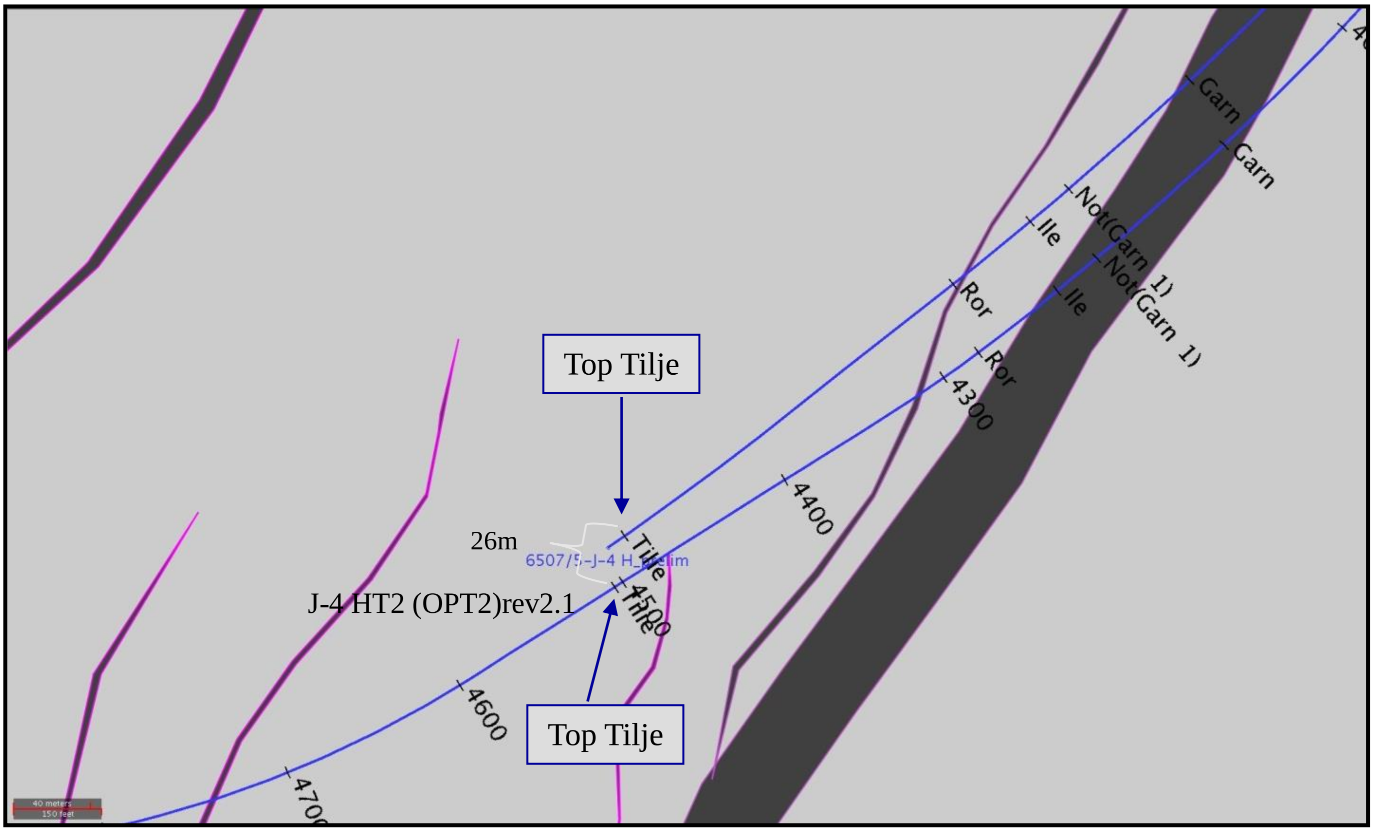


Figure 19. View from the top at the trajectories with stuck point. [14]

Figure 19. shows the part of two trajectories. It is seen at which moment the main bore was finished. The top of Tile formation was relatively passed. Branched section achieved tops of formations on different depth, and then was expected in the planning process. The trajectories are parallel. Distance between the tops of Tilje formation in both wells is 26 m.

6.2 Estimation situation between J-1H and J-4H

Part of the investigation was survey of the obstacle in the well J-4H. Going further with the studies well J-1H was taken into consideration.

6.2.1 Obstacles in J-1H well

In this object the main problem was well integrity. The danger was uncontrolled flow of the hydrocarbons to the surface and between formations. A common problem corresponds with over-pressured formation is cross flow after cementing. Failure of the cement is the most widespread reason of fluid migration. Good quality of bonding is related to following factors: type of cement, additives, mud and cement density, contamination incidence, temperature, pressure, mud cake film, pumping pressure, centralization, movements of casing string, cement filtration. Over-pressured formation is more challenging for the casing and cementing job. During the drilling in the J-1H well overbalanced was recorded. High mud weight with high circulation rate around permeable zones, with low pressure, high porous encourages fractures and wash outs. It makes cementing more difficult. The hole should be clean (no cuttings, no drilling fluid), clear of filter cake, and in gauge before cementing. [3]

6.2.2 Job failure

The problem has arisen during cementing 9⅞’’ x 10¾’’casing. The value of critical pumping pressure was overstepped and as a result formation has been fractured, and meaning volume of mud has been lost. Reason for this accident is not defined. The relevant trouble has occurred during activity of displacing the cement slurry with drilling water. From the DDRs it is not possible to get direct reason for cementing job failure.

Very similar situation took place in both wells with pressure measurements. There were three failed measurements carried with TesTrack™ tool in J-1H. That was taken into consideration during logging the other well. [5, 6]

6.2.3 Correlations between wells

Following the sentence “No two wells are alike”, it is possible to discuss about failures and compare them. Well J-1H was drilled before well J-4H. It was the same goal for both wells: oil horizontal producer in Tilje section. J-1H was located on relevant distance from fault. Owning to collected data it was possible to evaluate reservoir properties and unit thicknesses. The gradient of pore pressure in J-4H was expected to be the same as found on J-1H. Measurements were done to confirm these suggestions. The common lithology and conditions gave the same hazards during the drilling. The well was penetrated Tilje with faults.

J-4H has the same well design as well J-1H. Casing string 9⅞’’ x 10¾’’ is approximately 300 m longer in J-4H and it is the longest string run on Skarv. There are some differences in design between wells in Garn and Ile formations. Both wells are linked to the same template. The wells were drilled form the same template, so in theory the drilling conditions should be very similar, but in practice was different. Preceding wells did not display any well stability problems. The only issue was fluid losses in to formation and migration. Experience which had been gotten from well J-1H had impact on drilling design of J-4H. In the J-4 H well were set oil swellable packer, which are not in the other well. This informs about probability of oil flow in the J-4H. Those types of packers swell in condensate and gas. By dint of quick decisions and following the procedures both wells were done with success

6.3 Comparison between main bore and branch

6.3.1 Horizontal wells, well paths

Directional drilling gives opportunities to reach a target which is complicated to achieve. Different obstacles can be skipped. It is applied when fault drilling is necessary and the salt dome drilling takes place. [39]

Nowadays directional drilling technology is dynamically evolving. Contemporary drilling motors, tools, and MWD allow drilling wells more efficiently, placing precisely in the reservoir, and evaluating the formation adjacent to the wellbore accurately. It is very significant to develop drilling optimization. From the other hand, this solution has economic and environmental impact. Offshore drilling possibilities are very limited. Wells have to be drilled from one drilling unit. [48]

Horizontal well is a deviated well with an inclination angle. Drilling technology of horizontal wells on the NCS is known from early 90's. Referring to the definition, we can call the wellbore horizontal when inclination is higher than 80°. It is more complicated and risky, but it has many benefits. It can help to avoid drilling into unwanted formations. It is popular to get the thin reservoir zone. Very important merit is bigger drainage area of the well in the reservoir and the lateral surface area of the well bore. This gives higher values of hydrocarbon production rate. The basin with high dip angles can be easily crossed. This selection has been created to maintain drilling operations and follow the hydrocarbon reservoir requirements. [38]

To drill horizontal well, rotation parameter is a very important element. There are two ways to initiate drill bit rotation. It can be inducted at the surface (drilling unit) or at the bottom, using different types of downhole motors. The angle in the deviated well is built owning to rotation induced at surface. The part of the drilling string is in contact with wall of the wellbore and it creates friction torque. Torque and drag due to friction forces increases when the angle is increasing. In the horizontal length the total weight of the drill string causes friction torque and drag, and this gives unwelcome situations. This explains why sticking event is problematic for drilling progress. Downward force on drill bit and circulation are two more significant. They are four methods of horizontal drilling.

Long radius (LR) method was chosen to design J-4H. There were taken into consideration following factors:

- Costs
- Location of template
- Characteristics of rocks
- Production method
- Problems during the drilling
- Type of completion

LR method is characterized with small build rate and high build radius. Drilling method can be rotary or steerable motor systems for curved and horizontal section. Choice of this trajectory could have effect on location and number of collars. The long turn radius is a drilling method with at least one section has been deviated at a build rate 1-6°/30,48 m. It is the most evolved method in offshore locations. Drilling system includes BHA and steerable system. BHA software is applied to optimize, predict and accurate information, especially on anomalies in formation. Steerable systems with MWD tool can be more cost effective compare to conventional BHA. This can cut time to get truly stuck. [4]

As a general rule, that more advanced technology costs money and can be described with the equation: [39]

EQ. 9

$$Cost\ \$ = location + casing + mud + tool\ rental + directional + rig\ rental + drilling\ time + logging$$

Sidetracking from an existing wellbore is a type of directional drilling. The reason can be several to make a path. In the J-4H well it was done to bypass an obstruction in the main bore. [33]

6.3.2 TesTrack^{TM} tool

Appropriate data from drilling operation is a clue to understand the conditions of the well and reservoir. The management and strategy is based on the real-time information. Each well project involves measurements of different parameters: resistivity, gamma ray, density, etc. The most important is pressure specifics. Those inputs can warn dangerous situation and quickly mobilize engineers to make a decision in hazardous situation. Closer to the reservoir formation, the value is more significant.

On the J-4H well was determined to use TesTrack^{TM} tool. It is an implement which gates real-time formation pressure mobility data. Logging while drilling supplies incurrence and control on drilling operation. After stuck event in the main bore, it was a big risk to collect pressure points in the sidetrack section. The most complicated task on how to obtain good pressure measurements with the tool took the focus away from the most important objective of a job. The intention was avoid to get stuck again. [48]

In the Rig Action Plan can be found, that in the beginning of work the pressure points wanted to be collected in the 12 ¼” section. It was required to discuss pressure points with geologists and get their recommendations. The suggestions were Lange sandstones and Gråsel formation. There is no limitation of getting pressure points, but should be enough to confirm pressure gradient. The impact has also sand thickness and presence of oil-water contact.

The lack of details about pressure is caused by risk of drill string stuck event. The procedure for TesTrack^{TM} is applied when directional driller contacts rig floor crew. The tool is run in to the hole. When a formation pressure test is performed the drill string has to be stationary and the torque worked out. This moment is suitable for differential sticking. Typically this will be done after the stand is drilled down and a survey is taken. A log pass may be performed to determine pipe stretch. It is critical that the string it kept stationary during the test. A downlink has to be sent to start the pressure measurement. Driller need to be informed about the test depth. When in position and a formation pressure test is started, drill string will have to be held stationary for several minutes. After testing is over, pumps have to be cycled before drilling can be continued. The results are transmitted to the surface.

7. Fault tree analyses

7.1 Theoretical background

Fault tree analysis (FTA) is a method for characterizing a single unwanted event. It develops engineering reliability establishing all probable reasons that could provoke that incident to occur. This mechanism takes a top-down way to estimate failure consequences. The evaluated event is a top event of the fault tree diagram and generally performs a whole failure of an incident or a product. One of the possibilities is identification of product safety matters. It is very good type of combined effects of simultaneous interpretation. In the drilling operations it helps to identify potential design defects and root causes for an observed failure. When the changes are implemented in project, the potential corrective actions and impact can be discussed.

The best time to apply FTA is at the design phase. Main obligations are knowledge and reliability data for perceptible evaluation. The prime infliction is to define the fault. After defining the error, the subsequent consequent faults leading to this one are to be determined. It is demanding that each event should be qualified individually and clearly. Each branch has to be finished down before starting another. The analysis is complete at the same moment when all basic levels are not able to be further split up. [46]

Of course FTA does not have to be inconvenient and protracted process. It is feasible to use reliability engineering software. The biggest purpose is to explain why hazard can take place. All next steps are put in logic gates. The top event answers the questions: What the system failure is, where it is observed, and when it can take place?

It handles two types of logic gates. The gate *OR* is when one or more input events occur. The gate *AND* exists when all the basic events are at the same time. [46]

7.2 Graphical layout

As a first step, problem and boundary conditions should be defined. The substep is an explanation of critical accident. The analyzed problem is a drill string stuck. This is the TOP event. To specify the description, three questions have to be answered:

- What: type of event - drill string stuck
- Where: where the event occurs - well J-4H
- When: when the event occurs - drilling through the over-pressured formations

In this evaluation the TOP event is “ Drill string stuck in the J-4H well during drilling through the over-pressured formations.”

There are several limited conditions. One of them is physical border of the system. Special equipment, geology and wellbore conditions are the parts and should be included in the analysis. The initial conditions are very important. In my opinion it was not the full capacity of the operation. From the DDRs, drilling rates were reasonable. The operation was done in pursuance of the plan. Earthquake, weather, crew and economic are the conditions with respect to external stress. Frequency and probability of presence is low, but they have to be put into consideration. Last but not least is the level of resolution. The detailedness in the fault tree is comparable to the amount of the available data. The FTA does not present the causes of all failures or accidents for stuck event. It shows only the specified failure. [40]

The figure below (Figure 24) is the FTA of the failure in the well J-4H. There are presented fault tree symbols. The OR-gate indicated that the out-put event occurs if any of the input events occur (Figure 20). The AND-gate is when all the inputs are present at the same time (Figure 21).

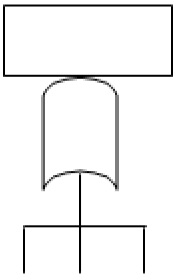


Figure 21. OR- gate.

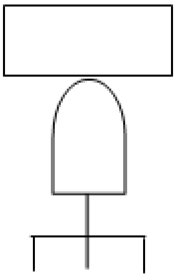


Figure 20. AND-gate.

There were used input events and a transfer symbol. The basic event is a fundamental failure that does not need any further development. Supplementary information is located in the comment rectangle (Figure 22). Transfer symbols indicates that FTA is developed further (Figure 23). [40]

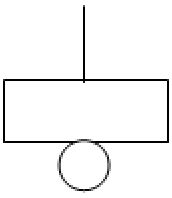


Figure 23. Basic event

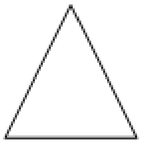
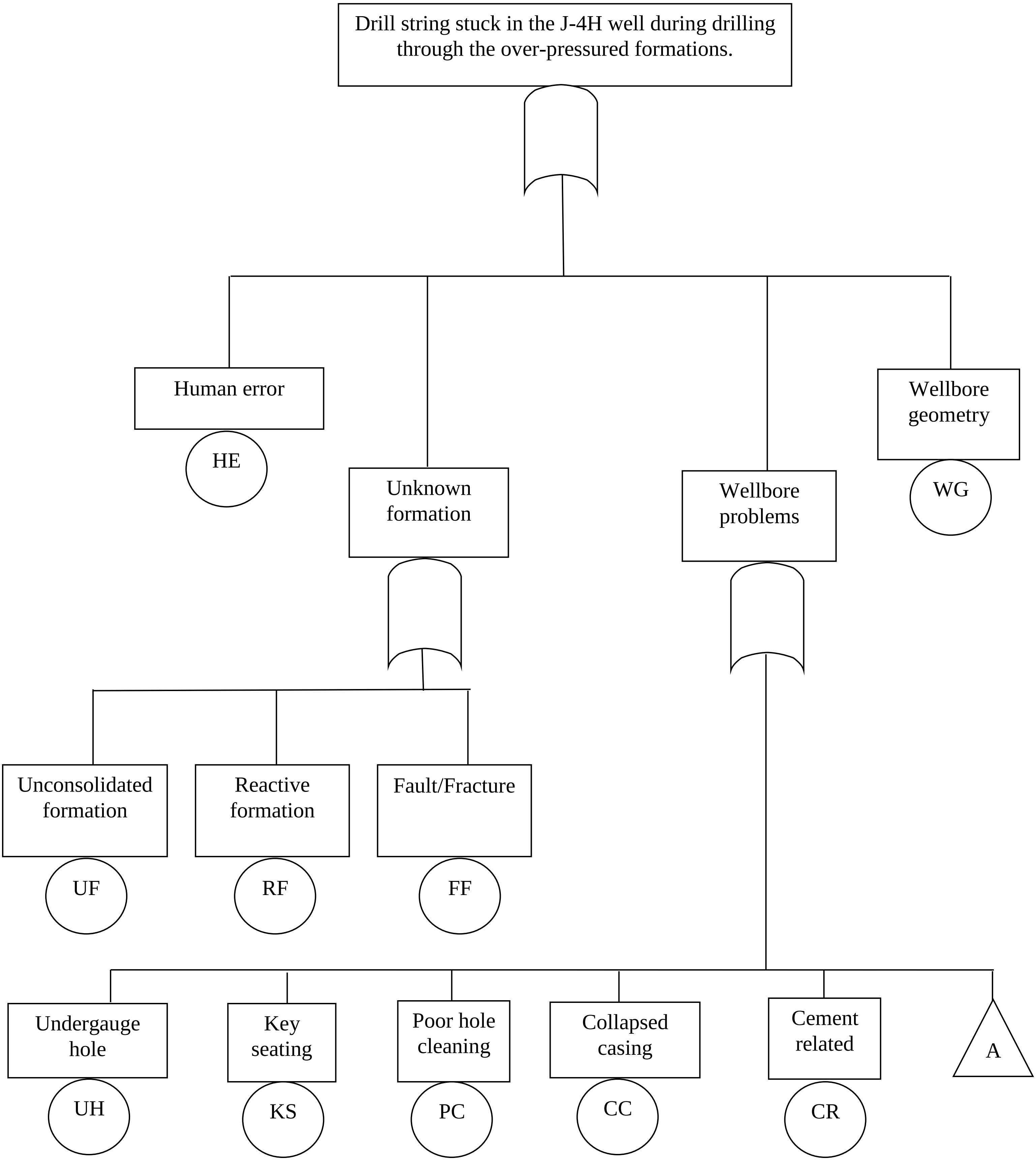


Figure 22. Transfer symbol.

The logic gate below (Figure 24) was made for the probability of drill string stuck in the well J-4H. There are listed all possible combinations of different influential events for top incident. Most of them take place without influence of each other. Just differential sticking can occur when overbalance of the mud connected with differential pressure and mud cake on the wall are presented in the well. Mud circulation is also an agent, but it was decided not put it on the FTA. More important is no rotation movements of the drill pipe. Presented FTA can be the origin for more advanced problem. It can be easily extended for others steps with transfers symbols. This technique helps to provide more safe work on the next wells. Created top event includes the general topic of over-pressured formations and specific example of the well. Failure inspection can be transferred for others incidents. All presented causes are independent from each other. Any of this failure can happen if the previous input occurs. Triangle is a transmission. This helps to make the tree more visible and readable.


Drill string stuck in the J-4H well during drilling through the over-pressured formations.
Human error
HE
Unknown formation
Wellbore problems
Wellbore geometry
WG
Unconsolidated formation
UF
Reactive formation
RF
Fault/Fracture
FF
Undergauge hole
UH
Key seating
KS
Poor hole cleaning
PC
Collapsed casing
CC
Cement related
CR
A

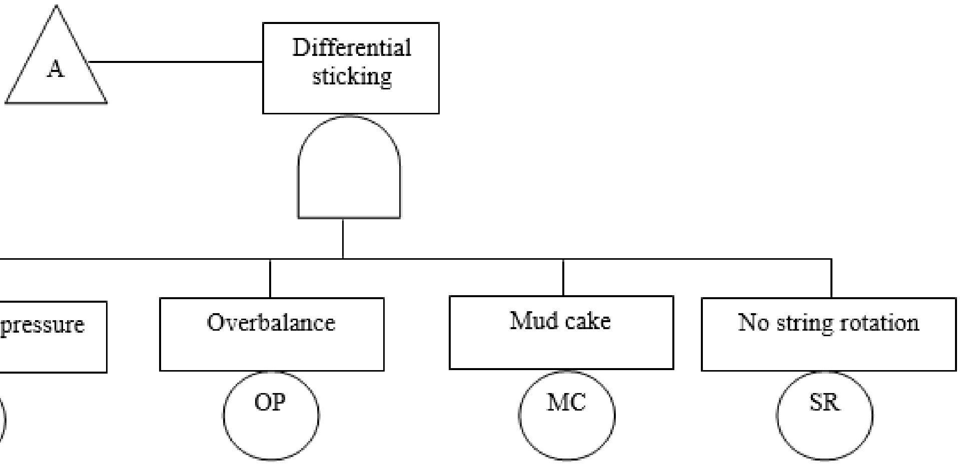


Figure 24. Fault tree analyses of the well J-4H.

The transfer symbol in the picture above shows complex branches for differential sticking. Here the AND-gate was used. It means that all of the presented caused have to happen, to create differential sticking. There are strongly interdependent. All four factors have to appear.

8. Results and discussion

The well J-4H was drilled with the detailed prepared plan. It was necessary to emphasize on the main risks:

- Zonal isolation between reservoirs.
- Running casing over c.340 mMD of significantly overbalanced reservoir section.
- Gråsel & Upper Lange sand in 12¼” section – zonal isolation with casing / cement.
- Losses on cement job for 9⅞” casing when setting shoe in Tilje.
- Stability problems during drilling A600 fault at acute angle.

Those five hazards mentioned above were listed during project stage. Close consideration was put on them. There were used appropriate precautions to prevent those accidents. They were selected, basing on risk factors from past performances. Experience which was gotten form previous jobs, the 12¼” section on J-4H was the most difficult to be drilled on Skarv field, with high overbalance, big faults and quite long section. Engineers were involved on the project and had knowledge about over-pressure affair. They designed the BHA to reduce possibility of getting stuck in Garn, Ile and Tilje. The collars were needed and it was resolved by placing a total of 7 stabilizers in the string. This practice is mildly speaking uncommon. This movement was done to avoid differential sticking. Four stabilizers were located above the jar. The once below jar were in fault area.

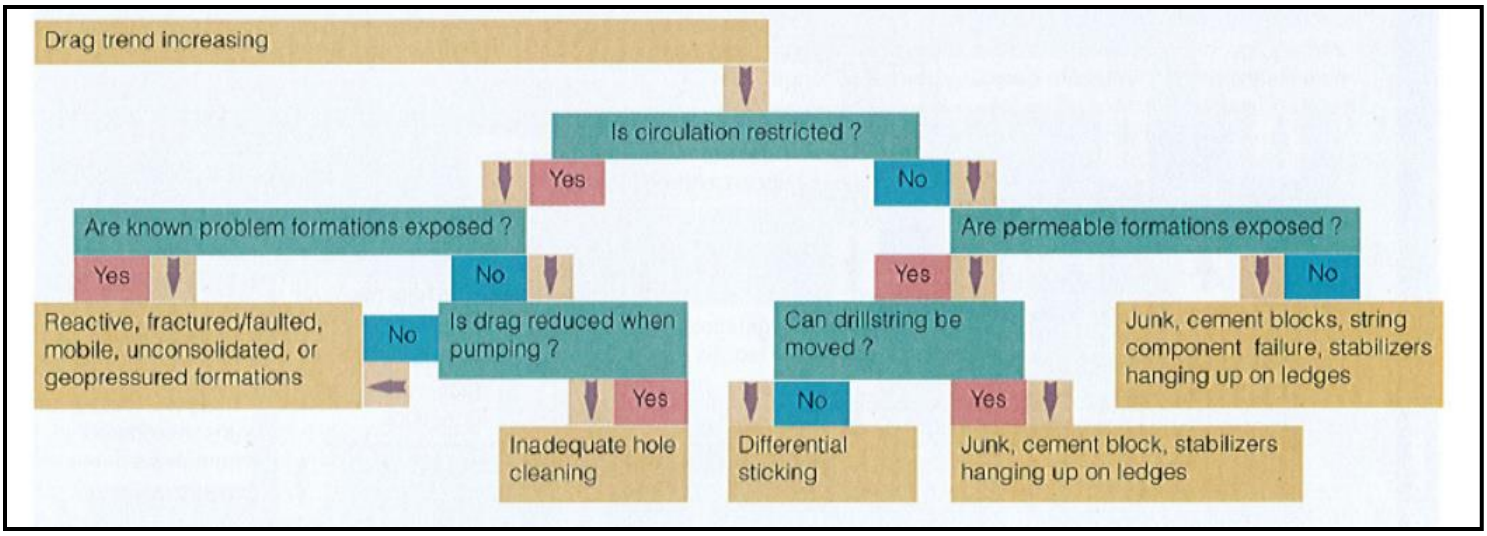


Figure 25. Decision diagram of moving drill pipe from static. [43]

Going deeper in to the documentations, it can be deducted that differential sticking had place. Poor and thick filter cake gave a chance surround BHA. The answer can be given after following the flow diagram for diagnosing the cause of stuck when encountering overpull after moving pipe from a static position (Figure 25). Is can be seen on the visual scheme, the drag increasing trend is the first sign. From the DDRs, circulation was registered. Next move is to explosion in permeable formations. In these formations it was impossible to move the drill string. As a final result, quick decision from cause to reason gives the differential sticking setback. The effect of the pipe stuck was most probable overbalance. Daily drilling reports and pressure curves are the most precious data to draw conclusions. Due to high mud weight in the over-pressured formation the effect was high density in layers with lower pore pressured. Therefore 184 bar overbalanced was recorded. The drill pipe was not able to rotate after stuck affair. The station status gave a chance to develop filter cake around zone and drill string. The whole accident took money and time. Delay on work could be avoided. Days to reach total depth included spent time on plug setting, kick off, and re-drill. In the other hand, in about 90% side-tracking is successful. For J-4H well this was the best reason to achieve the goal. This shows how important are studies of the origin of over-pressured zones.

Every well structure is unique and drilling operations are unrepeatable, even in the same reservoir and geological structure. If one the hazards was predicted it does not mean that

it will not appear in near distance. That was show on the chapter 6.3 the comparison with the J -1H well.
Moreover, drilling project and well design are significant. Engineers create reliable plan for over a dozen years of well and reservoirs lives. Most of the operations have different kinds of risks. The goal is to minimize unwanted hindrances and be experienced to react quickly.

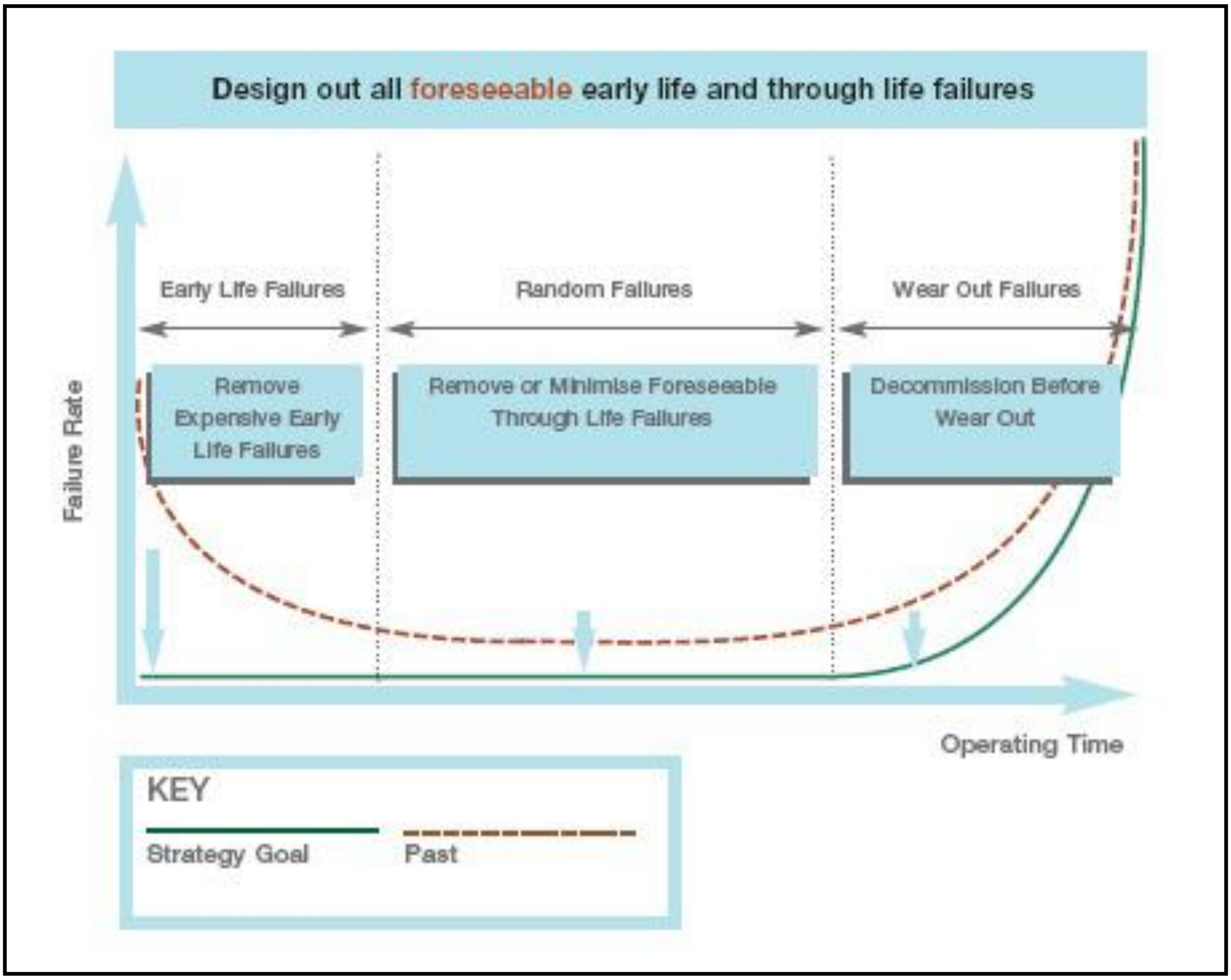


Figure 26. The bathtub curve. [30]

The bathtub curve (Figure 26) how failure rate is changing over the operating time. Red dashed line represents all foreseeable failures which take place on the typical well. This trend was observed on the J-4H well. Green solid line is the effect which has to be achieved. In the beginning of well time life (evaluation, modelling, drilling, completion) usually there are many difficulties. The aim is to decrease them to almost zero. For the thesis, just this part of curve is the most considerable. From the technical point of view, workovers and well interventions are involved very often. They consume time and money. Amount of spent budget on those actions shall be lower than plugging and abandonment activities. As it is shown above, killing procedures are the most costly on the whole well lifecycle. Reliability can be improved, without significant additional costs. The best scenario is when OPEX is higher than CAPEX. Operator invests more in the beginning (drilling state), put more attention on hazards. Improved reliability benefits companies. This situation was on the well. Costs were taken into account on the drilling stage. In the future, familiarity with over-pressures will make drilling operation safer and will give the occasion to reduce costs. In next projects drill string evaluation must be transformed into time and budget. Inspection of a drill string with BHA during drilling one month costs around $ 15 000. Price for fishing operation is $ 20 000, including lost rig time and fishing expanse. To summarize all reflections, the scope is to decrease failures as much as it is possible. From the start of planning process all possible incidents have to be covered. In the end of the well life, collected benefits should be invested for perfect abandonment job.

9. Conclusions

This kind of accident is less common nowadays than twenty years ago, but still frequent enough. The stuck event was unpredictable. Drilling area was known as risky, because of high pore pressure. During drilling in Spekk, Melke and Garn formations any warning signs did not appear. After stopped the rotation of BHA and pressure measurements the pipe stuck happened. From available data and investigation after the accident it was determined that it was a human error. Fault tree analyses explains the human error as the reason of the failure. This even is a fundamental reason. Driller and mud logger need to keep an eye on pump pressure and torque. The drillers were requested to keep the drill pipe moving at all the time, to the extent possible. It was not enough attention after POOH logging tool and run in hole BHA again. Stationary time while doing connection should always be minimized. This was proximate reason for later consequences. One more thing is, that warning signs were not recorded. Significant mud overbalance had influence for this event, but it was not put in a consideration.

In the well J-4H pore pressure was not higher then mud weight. This says that differential pipe sticking was due to overbalance and it is called positive differential sticking. It was a consequence of feckless movement. It has to be detected by drag on connections. As far as I am concerned, closer look should been given into BHA configuration, location and position of stabilizers. The attention should be paid on equipment connections that everything is ready, and if any delay prior or under connection. It is not recognized as good practice to place stabilizers close to each other. As a lecture for the future the length of BHA should be as short as possible. Appropriate placement of the stabilizer will avoid pipe-well contact. This means that design of the assembly has to be done carefully. It is important to check the equipment which will be run in to the hole. The sum of different unplanned, but probable operations, including consideration of success ratio (risk), have to be used in an economic comparison.

The most significant is the solution for discussed subject. The main focus is put in the drilling mud. The solution is to reduce overbalance to cautions level. Pipe did not move on the Garn formation. This layer is mainly built of sandstones, which are conductive to create filter cake. Exchange the mud after the over-pressure formation for lighter fluid. This will avoid the overbalance and prevent the differential pressure. However, this dilution is very expensive, but can be more effective than side track affair after pipe stuck. Furthermore, intermediate casing has to be set on the bottom of Spekk formation (over-pressured). After cementing job, drilling fluid can be replaced with low density mud. What is more, the drilling operation can be continued without any time losses and changes from the project. Basically, over-pressured formation has often higher porosity and weaker grain cementation, which means fluid losses. The second proposition is to reduce overbalance with adding to the drilling mud a chemical, which reduces mud weight. Choose of the most suitable additive in the begging of the drilling phase, can be cost and time effective. The volume of low density fluid can be easily calculated, when the density is known. After drilling over-pressured formations, the weight of mud can be have again. Critical notice is to not change others parameters of the mud. To use lighter fluid in deeper section, the mud can became a gas (foam). It will still withstand formation pressure. Based on gas, cuttings are removed by a high velocity stream of air or natural gas. Foaming agents can have the same task as OBM. Mud was in excellent shape, so density changes can be a success. It can be taken into consideration to drilling in overbalanced conditions with hydraulic motor. Higher velocity can clan the well more efficiency and gives power to rotate the lowest part of the BHA. This keep all the time the assembly in rotation. Those all factors: overpressure, pressure differential, string non-rotation and mud cake and collected in one specific essential factor- drilling mud.

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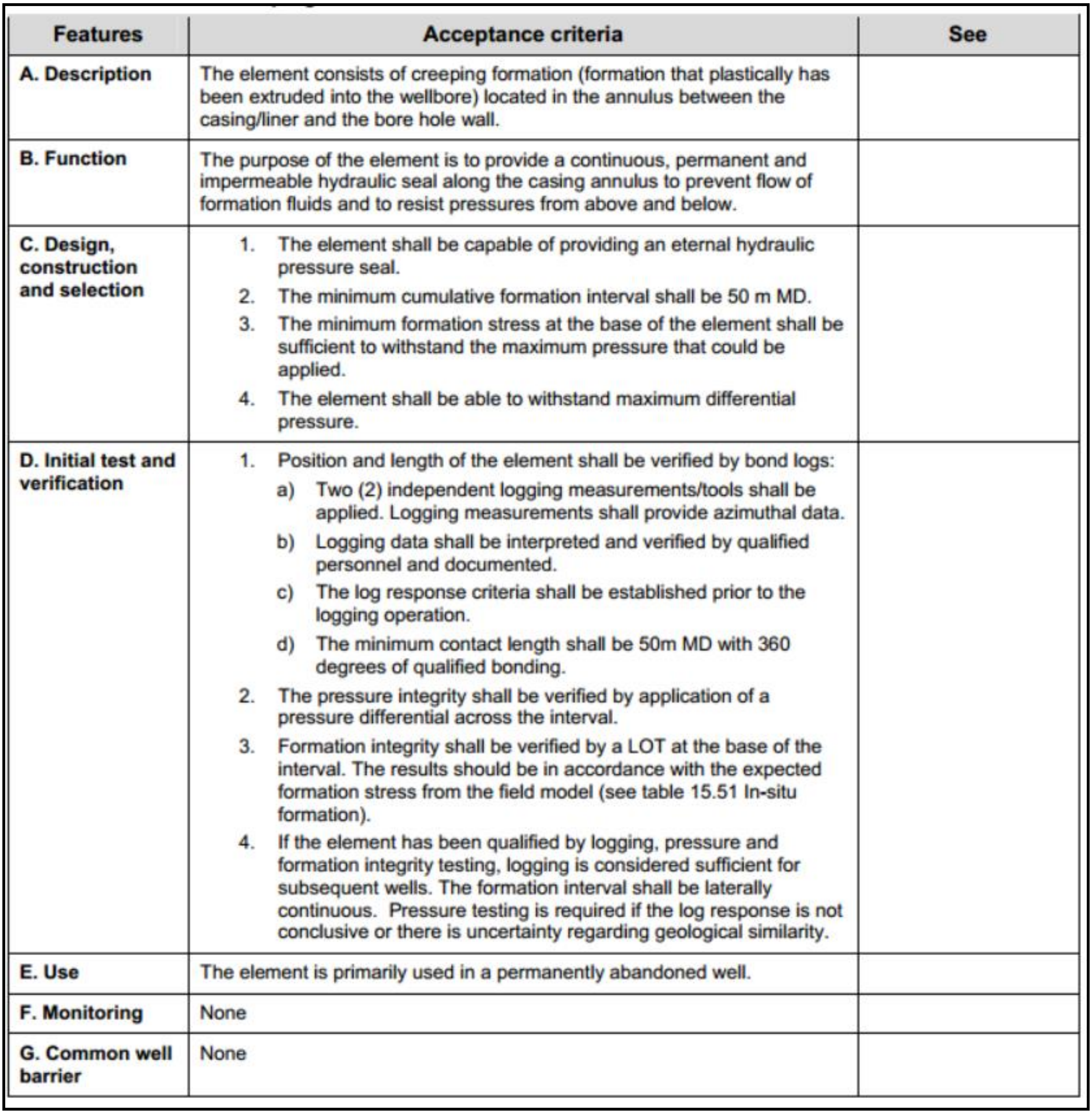
VII. APPENDIX A

Acceptance criteria-creeping formation. [37]



Features	Acceptance criteria	See
A. Description	The element consists of creeping formation (formation that plastically has been extruded into the wellbore) located in the annulus between the casing/liner and the bore hole wall.	
B. Function	The purpose of the element is to provide a continuous, permanent and impermeable hydraulic seal along the casing annulus to prevent flow of formation fluids and to resist pressures from above and below.	
C. Design, construction and selection	1. The element shall be capable of providing an eternal hydraulic pressure seal. 2. The minimum cumulative formation interval shall be 50 m MD. 3. The minimum formation stress at the base of the element shall be sufficient to withstand the maximum pressure that could be applied. 4. The element shall be able to withstand maximum differential pressure.	
D. Initial test and verification	1. Position and length of the element shall be verified by bond logs: a) Two (2) independent logging measurements/tools shall be applied. Logging measurements shall provide azimuthal data. b) Logging data shall be interpreted and verified by qualified personnel and documented. c) The log response criteria shall be established prior to the logging operation. d) The minimum contact length shall be 50m MD with 360 degrees of qualified bonding. 2. The pressure integrity shall be verified by application of a pressure differential across the interval. 3. Formation integrity shall be verified by a LOT at the base of the interval. The results should be in accordance with the expected formation stress from the field model (see table 15.51 In-situ formation). 4. If the element has been qualified by logging, pressure and formation integrity testing, logging is considered sufficient for subsequent wells. The formation interval shall be laterally continuous. Pressure testing is required if the log response is not conclusive or there is uncertainty regarding geological similarity.	
E. Use	The element is primarily used in a permanently abandoned well.	
F. Monitoring	None	
G. Common well barrier	None	

VIII. APPENDIX B

Intersection of reservoir with the whole well trajectory.