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Margrethe Tungesvik

Abstract

Scale build up is one of the leading reasons for production decline in oilfields worldwide. Scale can be formed whenever water is produced; either by direct precipitation from the water that occurs naturally in the reservoir rocks, or as a result of produced water becoming oversaturated with scale components when two incompatible waters are mixed downhole. The two most common scales formed in an oilfield are calcium carbonate and barium sulfate. Scale can be found in the reservoir, along the wellbore and in the surface process system. There are various methods for controlling scale. The methods shall either prevent scale formation or remove scale that has already occurred. Scale inhibition and choosing the correct injection fluid are two methods for preventing scale formation. Removal of scale can be divided into chemical dissolution and mechanical removal. For chemical dissolution, the alternative is to bullhead the well with chemicals to remove the scale. Mechanical removal includes the use of different equipment e.g. brushes, broaches, string shots and milling.

This thesis focuses especially on mechanical wireline milling for removal of scale. Due to this, the wireline rig-up equipment for both platforms and riserless well intervention vessels, has been presented. Wireline milling is a mechanical method which uses a special tool string with a milling bit in the end, to remove scale.

Four scale milling case histories from the Smørbukk field in the Norwegian Sea has been studied. They were all performed from a riserless well intervention vessel. Different plots with measurements from one of the case histories, taken during the milling operation have been looked into. The plots contain different measurements such as head tension, current and wireline tension and are plotted against time. The objective of the thesis has been trying to locate parts of the execution of scale milling operations that can be improved. Some of the key findings were:

- When carrying out a scale milling operation; as much as possible information about the scale, and other well conditions, should be obtained before the scale milling start. This can be information about the scale type, where it is located, and the length and thickness of the scale restrictions. Other important information is temperature, pressure and fluid in the well. This information can make the choice of equipment easier and reduce the risk for something going wrong during the operation. To obtain information about the scale restrictions, a caliper can be run in well.
- The weight on bit should be controlled carefully throughout the milling operation. The correct weight on bit is crucial to avoid stalling out with the bit. The consequence of stalling

with the bit is no progress in the scale milling, and maybe the need for pulling out of hole with the tool string.

- The removal of scale cuttings is very important during a milling operation. If the cuttings are not sufficiently removed, there will be an accumulation of cuttings around the mill bit and no progress in the milling.
- Real time measurement taken during the scale milling is important for having optimal control over the operation.
- In wells with challenging well conditions, like high temperature and high pressure, pre-testing of equipment for real well conditions, may be important for optimizing the scale milling operation. This can be a good measure to prevent equipment failures and short circuits during the milling operation and decrease the need for tripping in and out of hole more than planned for.
- The effect that acid has on scale is difficult to conclude based on these case histories and should be further investigated.
- The overall experience from the scale milling operations emphasizes the need for a detailed planning of milling operations. Experience, equipment limitations and the different aspects of a milling operation should be thoroughly addressed before one start to mill the scale. This may help to reduce the number of problems during the milling operation.

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Abbreviations

BHA	*Bottom hole assembly*
BOP	*Blowout preventer*
CCL	*Casing collar locator*
CT	*Coiled tubing*
DHSV	*Down hole safety valve*
DTPA	*Diethylene-triamine-penta-acetic acid*
EDTA	*Ethylene-diamine-tetra-acetic acid*
HCl	*Hydrochloric acid*
HO	*Hole opener*
HTHP	*High temperature high pressure*
HUD	*Hold up depth*
ID	*Inner diameter*
K_{sp}	*Solubility product*
LLP	*Lower lubricator package*
LPM	*Liter per minute*
LS	*Lubricator section*
LT	*Lubricator tubular*
LUB	*Lubricator*
LWI	*Light well intervention*
MD	*Measured depth*
MEG	*Mono ethylene glycol*
MIC	*Minimum inhibitor concentration*
OD	*Outer diameter*
PCH	*Pressure control head*
POOH	*Pull out of hole*
RIH	*Run in hole*
PLT	*Production logging tool*
PSI	*Pounds per square inch*
PUW	Pick up weight
RLWI	*Riserless light well intervention*
RPM	*Revolutions per minute*
SCSSV	*Surface-controlled subsurface safety valve*
SR	*Saturation ratio*
SRP	*Sulfate removal plant*
TUB	*Tubular*
ULP	*Upper lubricator package*
USD	*United states dollar*
WCP	*Well control package*
WOB	*Weight on bit*
Xmas tree	*Christmas tree*

1 Introduction

Oilfield scaling is a serious problem for the oil and gas industry. Every year problems with scale costs the industry millions of dollars in damage and lost production. Scale is one of the leading causes of worldwide production decline. In the North Sea area 28% of decline in production are related to formation of scale (figure 1-1) [1]. Scale is probably one of the three biggest water-related production problems, next to corrosion and gas hydrates [2].

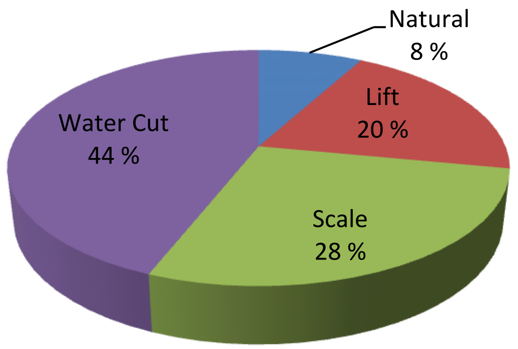

Figure 1-1 Impact of scale in the North Sea area; percentage of loss of production from each process [1].

The global cost of scale has been estimated to be more than USD 4 billion every year [1]. Scale control can for some fields be the single biggest operational cost [2]. The economic consequence of scale is estimated to have the highest impact on fields in North America and South America, and in the North Sea (figure 1-2). In the coming years it is expected that these scale costs will increase as more reservoirs becomes mature and requires pressure maintenance by water flooding to increase recovery.

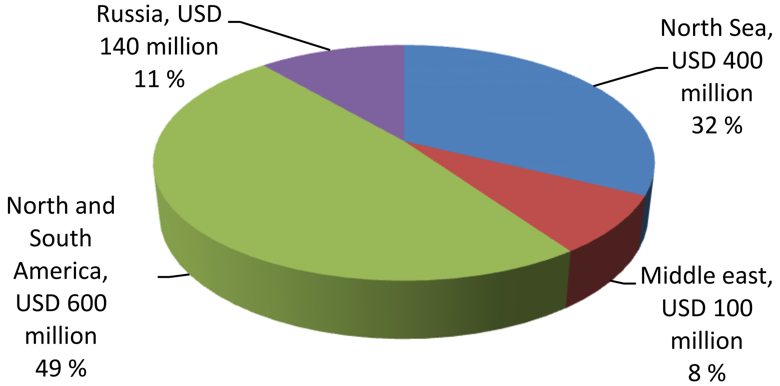

Figure 1-2 Estimated global cost of scale [1].

For the past ten years the trend for subsea wells has increased [3]. Consequently the number of subsea well interventions has also increased and the need for new and efficient intervention service is higher. Traditionally intervention work such as scale milling in subsea wells has been performed with semi-submersible rigs and heavy intervention equipment as snubbing or coiled tubing [4]. But the semi-submersible rigs are expensive due to the requirements of equipment and personnel to operate them and the availability of the rigs are also limited. Today more and more intervention jobs are being performed from riserless light well intervention (RLWI) vessels in combination with wireline. This has been seen as a more cost efficient alternative to the rigs when coiled tubing or snubbing is not needed. The wireline tractor has made it possible to use wireline in more deviated and horizontal wells where gravity itself is not enough to reach the required depth with the wireline bottom hole assembly (BHA). Analyse

This thesis will first describe scale as a phenomenon. The most common scale types will be described both on how they are formed and where they normally are formed in a well. Further, different methods for handling scale will be presented. This includes both methods for reducing scale potential and methods for removing scale deposits that has already formed. The thesis will have a special focus on mechanical removal of scale with the use of milling equipment on wireline. The wireline rig up equipment will therefore be presented before a closer look on milling in combination with a wireline tractor. The thesis will also analyse well data from completed well intervention operations, to see if it’s possible to extract some information about what are the most optimal technical solutions when milling scale.

2 The Scale problem

The possibility for scale to form is present whenever a hydrocarbon well produces water or water is injected into a reservoir to enhance recovery. The greater the volume of water produced, the greater the potential volume of scale that could be deposited.

Scale is an assemblage of deposits which occurs either in the reservoir, in the perforation interval, along the well bore including the surface-controlled subsurface safety valve (SCSSV) or in the surface process system. In some cases, the effect of scale can be dramatic and immediate, the production can fall to zero in a few hours and the treatment cost can be massive [5].

Scale in the formation pores restricts the flow of fluid through the formation which results in a reduced porosity and permeability (figure 2-1) [6]. Scale can also block fluid flow by clogging the perforations or by forming a thick layer in the wellbore tubular which reduces the diameter of the production tubing and chokes the production from the reservoir. This can lead to a drastic increase in pressure drop and thus a decrease in the production. Access to lower parts of the well with equipment is also more difficult when the diameter in the well is reduced due to scale build up. Scale can coat and damage downhole completion equipment and valves like the SCSSV and gas lift mandrels.

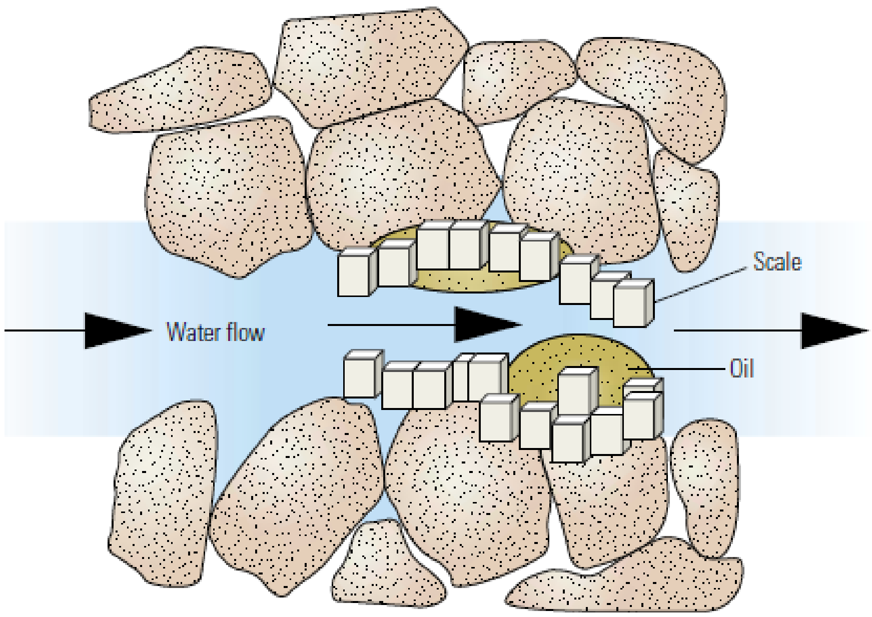

Figure 2-1 Scale deposition restricts the flow of fluid through the formation, resulting in a loss of permeability [6]

2.1. Formation of Scale

In a hydrocarbon reservoir, before a well is drilled and completed, the fluids in the formation is saturated with dissolved salt from the reservoir rock and in equilibrium with the surroundings. After the well is drilled and starts to produce, the fluids are no longer in equilibrium and salts may start to precipitate. This means that scale begins to form when the state of any natural fluid is disturbed, such that the solubility limit for one or more components is exceeded [1].

The formation of scale depends on various parameters, such as change in pressure and temperature, degree of agitation/turbulence during formation of crystals, size and number of seed crystals, degree of super-saturation and change in pH of solution.

$$SR = \frac{[M^{z+}][X^{z-}]}{K_{sp}} \qquad \textbf{Equation 2-1}$$

The saturation ratio (SR) (equation 2-1) measures the degree of supersaturation for salts. M^{z+} and X^{z-} represent the salts where M being the cation with a positive charge and X is the anion with a negative charge. K_{sp} is called the solubility product and is the equilibrium constant for the dissolution of the salt. The solubility product is a measure of how many moles of ions per unit volume of solvent there can be in a system before a salt precipitates out [7]. If the saturation ratio equals 1.0 the solution is saturated and neither precipitation nor dissolution of the salts will occur. When the SR is less than 1.0 the solution is undersaturated and precipitation will not occur. When the SR is greater than 1.0 the solution is oversaturated and precipitation of the salts may occur. This will, however, depend on the kinetics of the precipitation reaction. Some salt do not start spontaneous precipitation even if they are many hundred times super-saturated [8, 9].

Equation 2-2 shows an example of the saturation ratio formula used on the salt barium sulfate, which consist of the Ba^{2+} cation and the SO_4^{2-} anion.

$$SR = \frac{[Ba^{2+}][{SO_4}^{2-}]}{K_{sp}} \qquad \textbf{Equation 2-2}$$

Produced water that goes through a pH shift, a temperature or pressure change or are in contact with incompatible water, do not always produce scale, even though the produced water has become oversaturated. This is because scale must grow from solution to form. The process is called nucleation and is the first stage in forming scale. Nucleation is the creation of a sub particle or ion cluster consisting of several individual scaling ions. There are two different nucleation processes called homogeneous nucleation and heterogeneous nucleation [1, 6, 10].

Homogeneous nucleation is a process where scale growth starts in a supersaturated solution with ion pairs forming single crystals in solution (figure 2-2). Heterogeneous nucleation is a process where scale crystals start to grow on substrates like metallic surfaces, sand grains or on pre-existing surface defects (figure 2-2) [6].

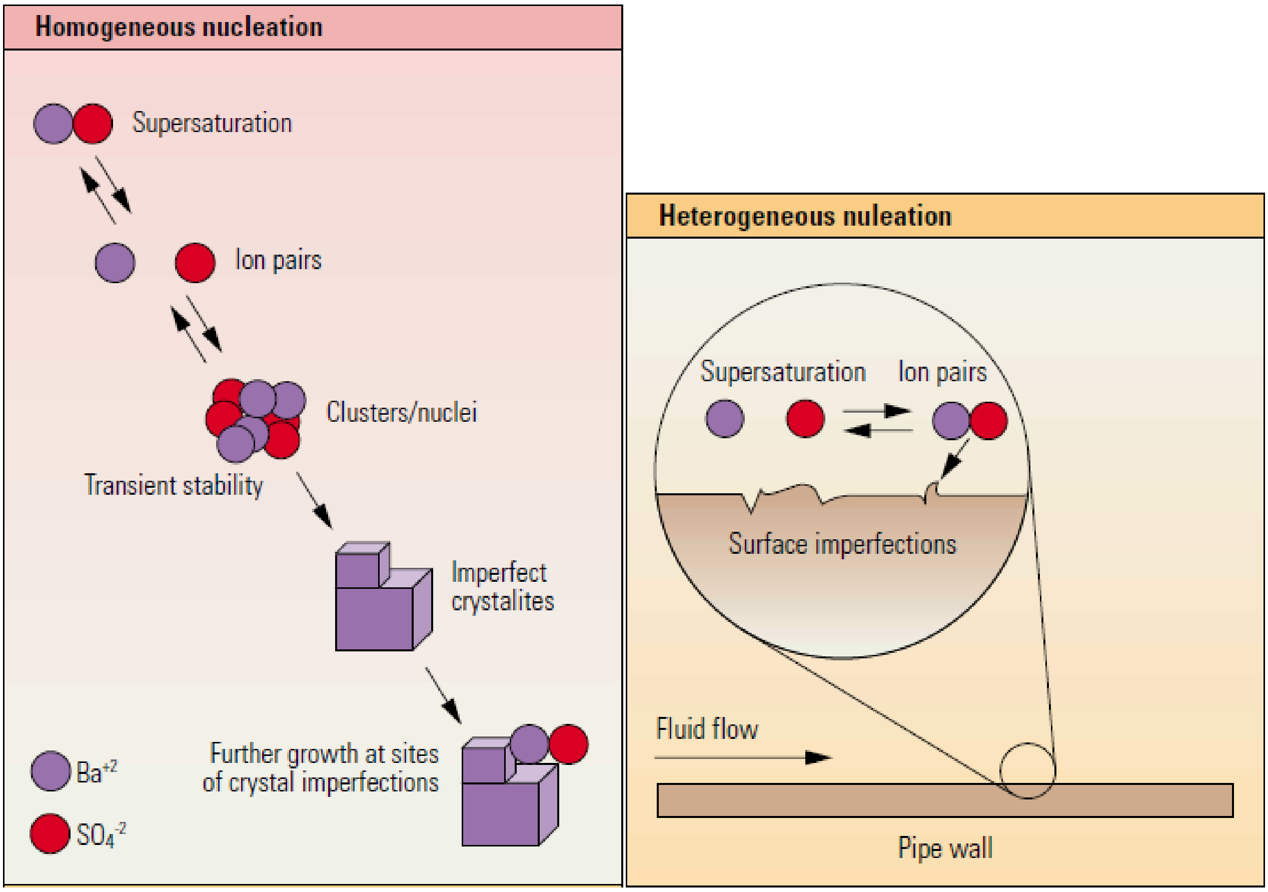

Figure 2-2 Homogeneous nucleation and Heterogeneous nucleation[6]

There are three common ways for scale to form in an oil field. These are autoscaling, incompatible mixing and evaporation-induced scale.

Autoscaling

Autoscaling or self-scaling happens when the natural water in the reservoir undergoes a change in pressure and/or temperature when it is produced. Normally, an increase in temperature tends to increase the water solubility of a mineral. This means that more ions are dissolved at high temperatures. Similarly, a decrease in pressure tends to decrease the water solubility of minerals [6]. The temperature trend is not valid for all minerals. Calcium Carbonate ($CaCO_3$) has an inverse trend with increasing water solubility with decreasing temperature.

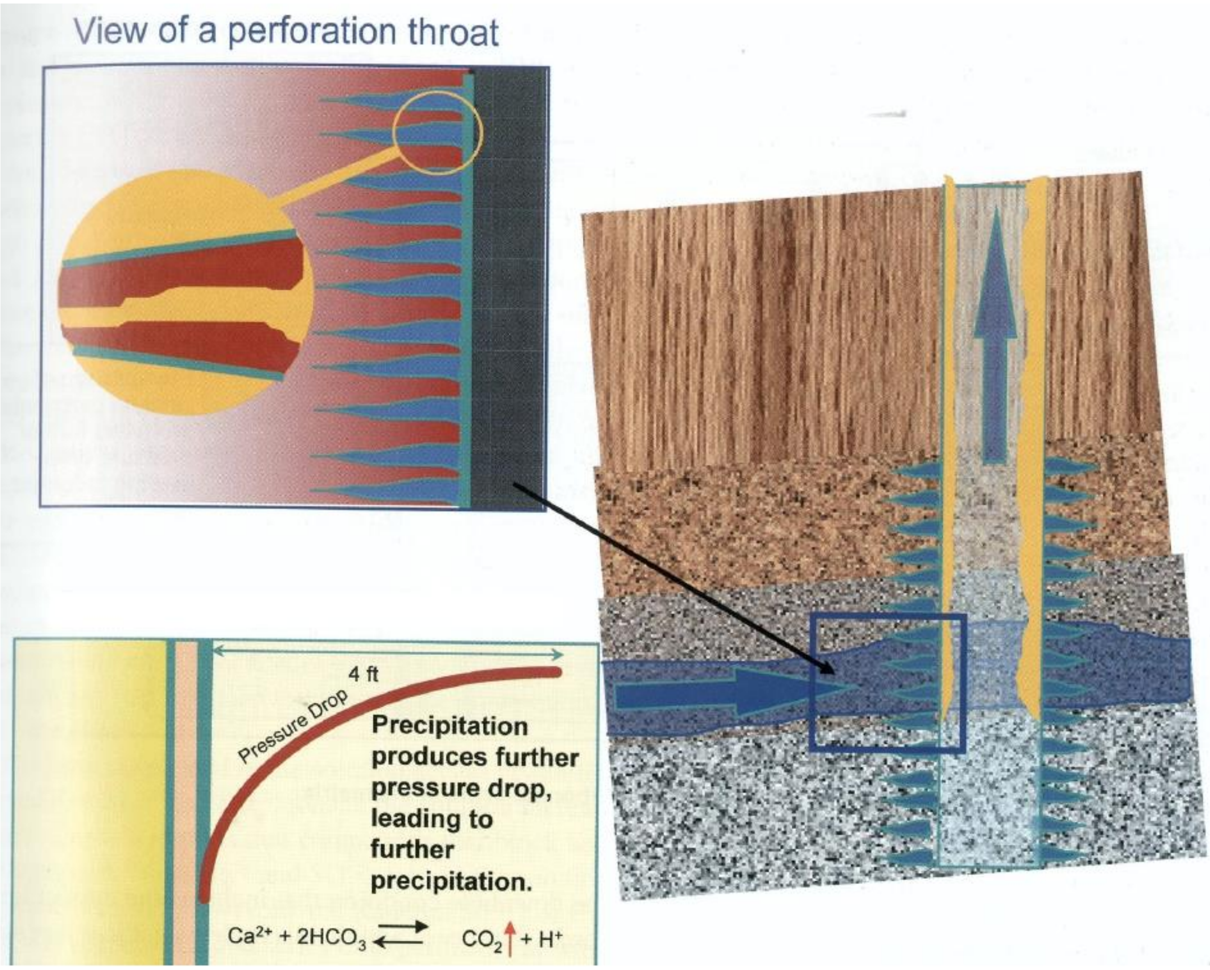

Figure 2-3 Autoscaling of calcium carbonate in a well [1].

Incompatible mixing

Scale from incompatible mixing occurs when two incompatible waters like injected seawater and formation water gets mixed downhole. The produced water then gets oversaturated with scale components. This happens because seawater has a high content of sulfate (SO_4^{2-}) and formation water is rich in ions such as calcium (Ca^{2+}) and barium (Ba^{2+}). Mixing of these two waters leads to precipitation of sulfate scales, such as $BaSO_4$ [11]. Figure 2-4 shows this occurrence.

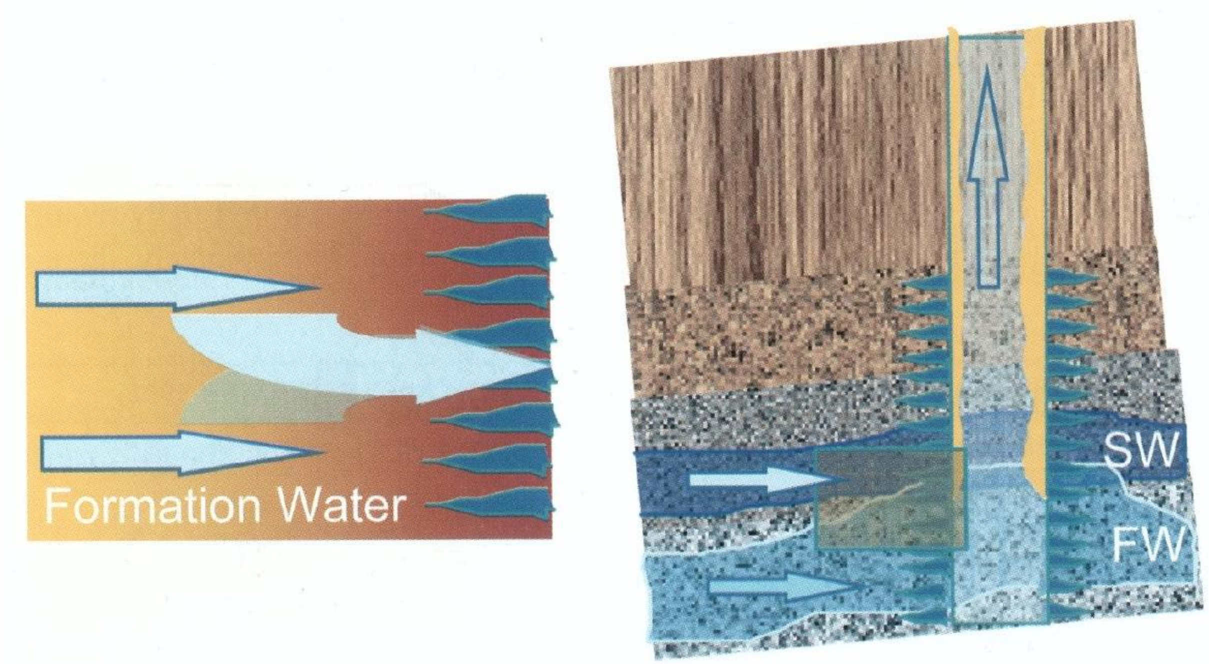

Figure 2-4 Seawater mixing with formation water [1]

Evaporation

When a mixture of hydrocarbon gas and formation water is produced simultaneous, evaporation-induced scale may occur. A pressure drop caused by reduced hydrostatic pressure leads to an expansion of the hydrocarbon gas and the hot brine phase evaporates. The salt concentration will then increase above the solubility limit and salt will precipitate. Halite (NaCl) scale in high temperature, high pressure (HTHP) wells is the most common scale type to be formed this way [1, 6].

2.2. Different types of scale

The most common scales types to be encountered in an oilfield are in order of prevalence listed in table 1 [2, 12]. The various forms of calcium carbonate ($CaCO_3$) scales differ only in crystal structure [1].

Table 1 Most common oilfield scales

	Name	**Chemical formula**
Carbonate scales	Calcium carbonate *-Calcite* *-Aragonite* *-Vaterite*	$CaCO_3$ $CaCO_3$ $CaCO_3$
Sulfate scales	Calcium sulfate *-Gypsum* Barium sulfate *-Barite*	$CaSO_4$ $BaSO_4$
Sulfide scales	Iron sulfide *-pyrite*	FeS_2
Sodium chloride Scale	Salt *-Halite*	NaCl

Further there follows a description of how and where carbonate and sulfate scale occurs in a well. The reason for presenting these scale types is that they are the two most common oilfield scales and because they represent two different mechanisms for scale to form.

2.2.1. Carbonate scales

Carbonate scale may form during production of formation water or when re-injecting produced water and/or aquifer water. All systems, containing carbon dioxide (CO_2) and scale ions like calcium (Ca^{2+}) and magnesium (Mg^{2+}), can form carbonate scale. Calcite, aragonite, vaterite and magnesite are some of the carbonate scales which occurs in production wells, where calcite (calcium carbonate, $CaCO_3$) being the most common one. Calcium ions, bicarbonate (HCO_3^-) and/or carbonate ions (CO_3^{2-}) are ions that can be found in formation water and must be present for calcium carbonate to form. In a carbonate and calcite-cemented sandstone reservoir the water usually contains a high level of calcium ions. The most common place for carbonate scale to deposit is in the upper completion, in the area around the downhole safety valve (DHSV), and in the surface facilities [8].

For calcium carbonate scales to occur, the saturation limit for dissolving the ions in the produced water must be reduced. Pressure, temperature, pH and ionic strength are all factors that affect the water solubility.

Pressure

Calcium carbonate scale formation is normally a consequence of the pressure drop that comes with production. When the pressure is reduced to less than the carbon dioxide (CO_2) bubble point, the CO_2 is released from solution into the gas phase. This causes $CaCO_3$ to precipitate.

pH

When the fluid pressure drops and CO_2 is lost from solution, the pH of water increases, which leads to a reduction in the solubility of $CaCO_3$ and thus increase scale deposits [13, 14].

Temperature

Unlike the behavior of most minerals, calcium carbonate becomes less soluble as temperature rises. This means that an increasing temperature gives a higher $CaCO_3$ scaling potential [14].

Ionic strength

Ionic strength of a solution is a function of the concentration of all ions present in the solution [14]. The ionic strength of calcium carbonate will increase the higher the concentration of e.g. Na^+ and Cl^- is. This means that more carbonate and calcium ions can be dissolved without precipitating calcium carbonate. In contrast a reduced ionic strength will increase the probability for $CaCO_3$ to precipitate [14].

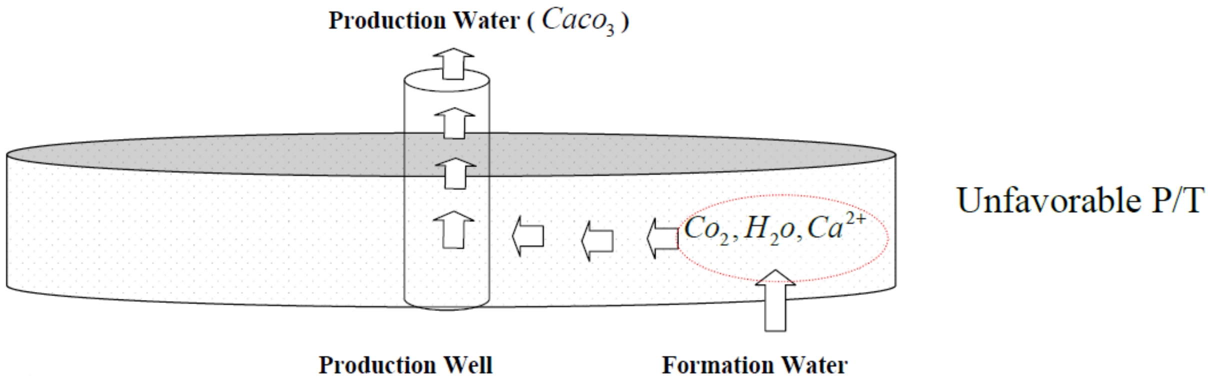

Figure 2-5 Precipitation of calcium carbonate due to change in different factors like pressure and temperature [15]

Most behavior of the calcium carbonate equilibrium can be predicted from Le Chatelier's equilibrium principle [7].The Le Chatelier's equilibrium principle states that a chemical system at equilibrium will always try to counteract any imposed change in concentration, temperature, pressure or volume.

When the pressure drop in a well is high enough the saturation limit for carbon dioxide (CO_2) may be exceeded. The CO_2 can no longer go into solution and is given off [14]. The CO_2 reacts with water and forms carbonic acid (equation 2-3).

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \qquad \textbf{Equation 2-3}$$

Further the carbonic acid dissociates to bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) (equation 2-4 & equation 2-5).

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \qquad \textbf{Equation 2-4}$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-} \qquad \textbf{Equation 2-5}$$

The bicarbonate and carbonate ions then react with calcium ions and forms calcium carbonate ($CaCO_3$) (equation 2-6 & equation 2-7).

<u>From bicarbonate:</u>

$$Ca^{2+} + 2HCO_3^- \leftrightarrow Ca(HCO_3)_2 \qquad \textbf{Equation 2-6}$$

<u>From carbonate:</u>

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3 \qquad \textbf{Equation 2-7}$$

The overall effect of this process is seen from equation 2-8.

$$Ca^{2+} + 2HCO^{3-} \leftrightarrow CaCO_3 + H_2O + CO_2 \qquad \textbf{Equation 2-8}$$

Figure 2-6 shows a producing well where $CaCO_3$ scale is formed as pressure in the well decreases.

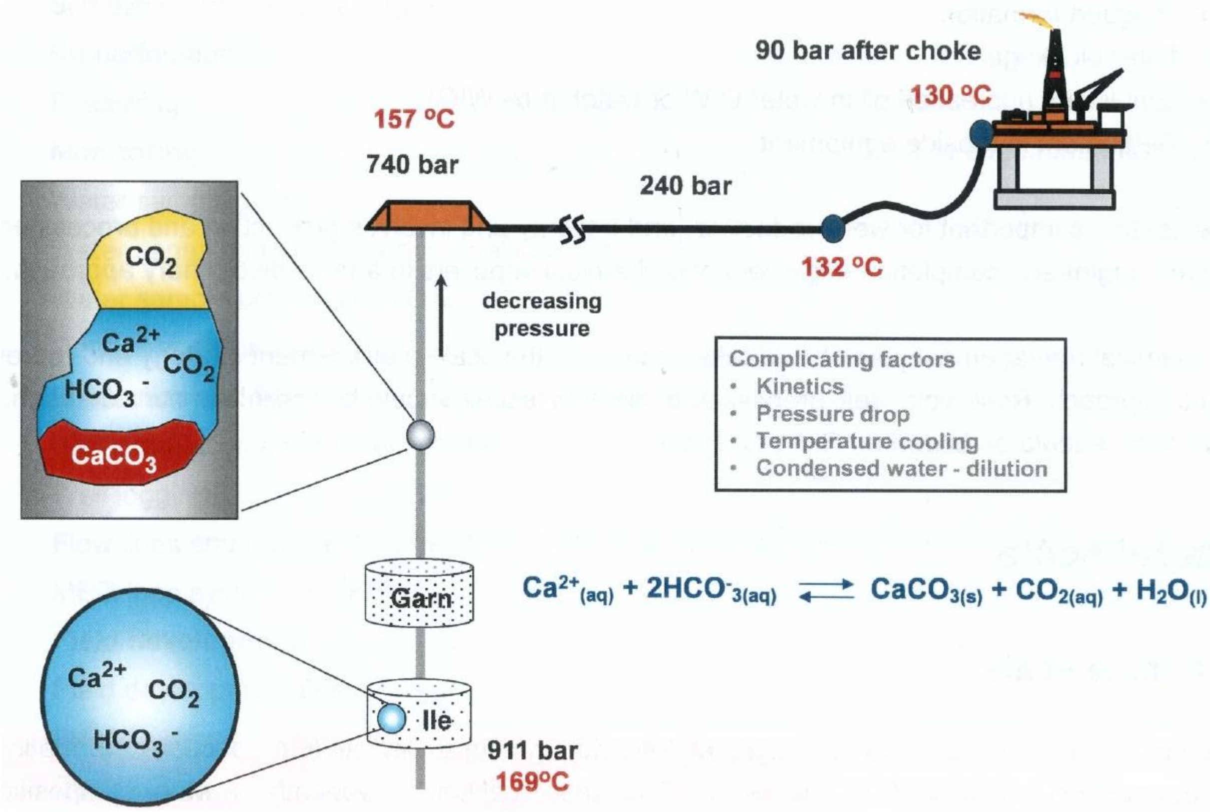

Figure 2-6 Mechanisms causing $CaCO_3$ scaling in produced water [8]

2.2.2. Sulfate scales

Figure 2-7 Calcium sulfate in a production tubing

Usually, sulfate scales are formed when formation water and sulfate containing water, e.g. injected seawater, is mixed (figure 2-8). Formation water normally contain barium (Ba^{2+}), strontium (Sr^{2+}) and calcium (Ca^{2+}) ions, while seawater has a high concentration of sulfate (SO_4^{2-}) ions. This means that mixing of incompatible waters often leads to formation of strontium, calcium and barium sulfate scales. Barium sulfate ($BaSO_4$) (equation 2-9) and strontium sulfate ($SrSO_4$) (equation 2-10) scales form in sandstone formations, and calcium sulfate ($CaSO_4$) (equation 2-11) scale forms in limestone formations.

$$Ba^{2+} + {SO_4}^{2-} = BaSO_4$$ **Equation 2-9**

$$Sr^{2+} + {SO_4}^{2-} = SrSO_4$$ **Equation 2-10**

$$Ca^{2+} + {SO_4}^{2-} = CaSO_4$$ **Equation 2-11**

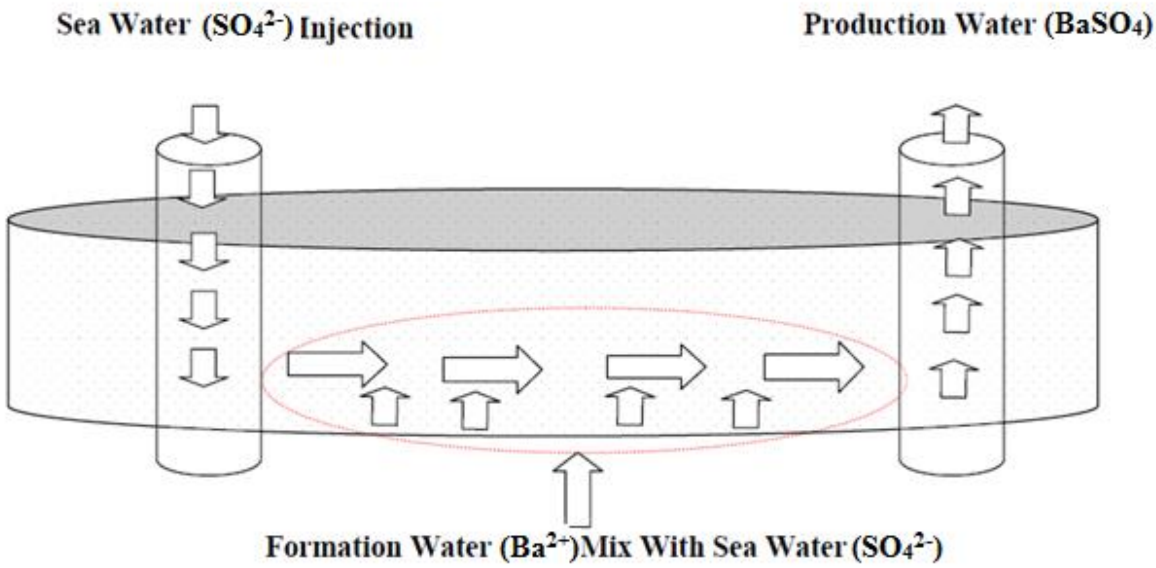

Figure 2-8 Mixing of seawater with formation water [15]

The degree of precipitation and deposition of sulfate scale will wary over the field lifetime and depends on the formation water composition, water production rates and the fraction of seawater in the produced water. Also other factors are important for sulfate scale to form or not. Low temperatures will generate more sulfate scale while the pH in the system will have no or little effect on sulfate scaling [8].

Sulfate scale may form through the whole production system depending on where the seawater and formation water mix [8].

In [16] Bader list where scale deposits could take place in a production system with water injection:

Case 1: At the surface water injection facility where incompatible sources of waters are mixed prior to injection.

Case 2: In injection wells where the injected water starts to mix with the reservoir formation water.

Case 3: Downhole in the reservoir where the injected water displaces reservoir formation water.

Case 4: Downhole in the reservoir where the mixed injected water and formation water are about to reach the range of producing wells.

Case5: Downhole in the reservoir where the mixed waters are within the range of producing wells.

Case 6: At the connection of a branched zone where each branch produces different water.

Case 7: At the manifold of a producing zone where water is produced from different blocks within the same producing zone.

Case8: At topside facility where produced fluids are mixed from different zones to separate oil and gas from produced waters, or in pipelines that transport produced fluids to on-shore processing facilities.

Case 9: And if applicable in disposal wells where produced water is injected for final disposal.

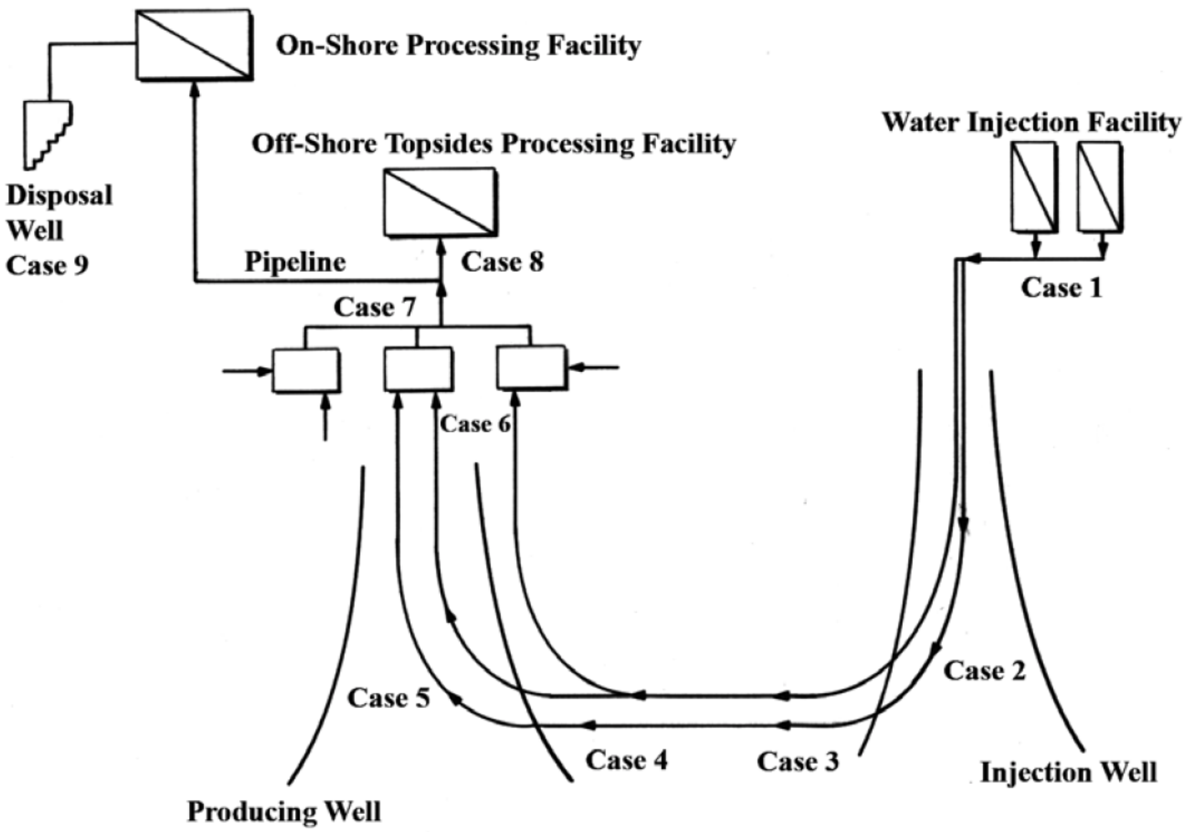

Figure 2-9 Possible locations for scale deposit [16]

2.3. Problems caused by Scale

The formation of scale may occur in the reservoir, in the wellbore or in the surface facilities.

Scale deposits may cause [8]:

- Formation damage by blocking pore throats.
- Flow restriction by blocking flow lines and tubing.
- Completion damage by plugging perforations, screens, advanced completions, and gravel packs.
- Choke and safety valve failure
- Pump wear
- Flow meter and instrumental failure
- Corrosion underneath scale deposits.

Suspended solids can cause [8, 17]:

- Plugged formation
- Plugged filtration equipment
- Reduce oil/water separator efficiency
- Settlement in topside equipment

3 Scale control methods

3.1. Reduce scale potential

3.1.1. Selection of injection fluid

Over time the pressure in a producing well will decline and the production will go down. To meet this problem water is injected to maintain pressure in the reservoir and to sweep oil from the reservoir, and push the hydrocarbons towards production. Normally, the choice of injection water depends on available water and an evaluation of the scale risk within the reservoir and the well.

Seawater is a convenient source for offshore production facilities. But the seawater has a high content of sulfate ions which increases the risk of forming different sulfate scales in the well. To meet this, a sulfate removal plant (SRP) can be used to desulfate seawater before it is injected into a well. Desulfation of injected seawater is a method that will only prevent sulfate and sulfide scales. The SRP uses a membrane nano-filtration technology which removes the sulfate from the seawater, while leaving other salts substantially unaffected [18]. This reduces the sulfate scaling potential in wells with high barium concentration in the formation water. Not all the sulfate ions can be removed in the SRP, but enough to reduce sulfate and sulfide scale problems considerably. The sulfate concentration in seawater is reduced from approximately 2700 ppm to 40-100 ppm in the SRP [2]. The use of SRP is a considerable high capital investment but can be the best option for large fields with severe predicted sulfate scale formation.

Aquifer water and produced water are other water types that can be injected to avoid the risk of sulfate scaling. Both of them have a sulfate content less than 20 mg/l, which are negligible when it comes to potential for sulfate scaling [8]. A risk of carbonate scale formation may occur if the injected aquifer water has a high content of calcium ions (Ca^{2+}), while the formation water has a high content of bicarbonate (HCO_3^-).

Another method that may reduce the scale potential is a good well production strategy. This could be to produce the well carefully, to avoid large pressure drops, or by choking back wells that produce water which may lead to mixing of incompatible waters [2, 8, 18].

3.1.2. Scale Inhibition

Scale inhibition is a chemical treatment used to control or prevent scale from forming in a producing well. Scale inhibitors are water-soluble chemicals that are designed to prevent or retard the nucleation and the crystal growth of inorganic scales. They can reduce the rate of scale formation to almost zero.

For a scale inhibitor to be considered as a good inhibitor it must be [10]:

- Stable: it must be sufficiently stable under the conditions imposed.
- Compatible: it must not interfere with the action of other oilfield chemicals, nor be affected itself by them. It must be compatible with the chemical injection system under operating conditions.
- Efficient: i.e. it must be able to inhibit the scale in question, irrespective of the mechanisms operating.

Choosing the right inhibitor and having the ability to place the chemicals properly are important for getting the best inhibition. To choose the right inhibitor and the right dosage of it, the water in the well must be tested to find the type and concentration of scale forming compounds present in the water. For calcium carbonate and sulfate scale, which are the main concern of production operators, there are two types of scale inhibitors that are most common in the oil industry. These are phosphonates and polymeric inhibitors. Phosphonates have the ability to slow or prevent scale-nucleation/crystal growth processes and are stable over a wide range of conditions such as temperature and pressure [19]. Polymers are also good nucleation inhibitors and dispersants. The polymers adsorb onto the crystal surfaces and are consumed in the lattice, when scale crystallization occurs, and thereby slowing growth when tested below their threshold levels [1, 2, 10].

The main alternatives for applying and placing scale inhibitors are squeeze treatments, continuous injection and solid, slow-release scale inhibitor composition. Squeeze treatment is the standard method for application of scale-retarding solutions. Figure 3-1 show this scale inhibitor squeeze treatment. The first stage is to pre-flush the well with injection water or a brine. The second stage is to squeeze a volume of the scale inhibitor into the well above the formation pressure whereby the solution will be pushed into the near-well formation rock-pores. The third stage is to over-flush the well with injection water or brine so the scale inhibitor gets pushed further in. The squeeze treatment should protect the well from scale formation and formation damage downhole, but also continue to work above wellhead. The fourth stage is to shut in the well for some hours so the scale inhibitor gets adsorbed onto the formation rock. The fifth and last stage is to return the well to production. When the well starts to produce again, the chemicals will slowly be released as water is produced with the hydrocarbons. The water should, because of this treatment, contain enough scale inhibitor to prevent scale deposition. The well should be re-squeezed when the concentration of the inhibitor falls below the minimum inhibitor concentration (MIC) which prevents scale deposition [1, 2, 6].

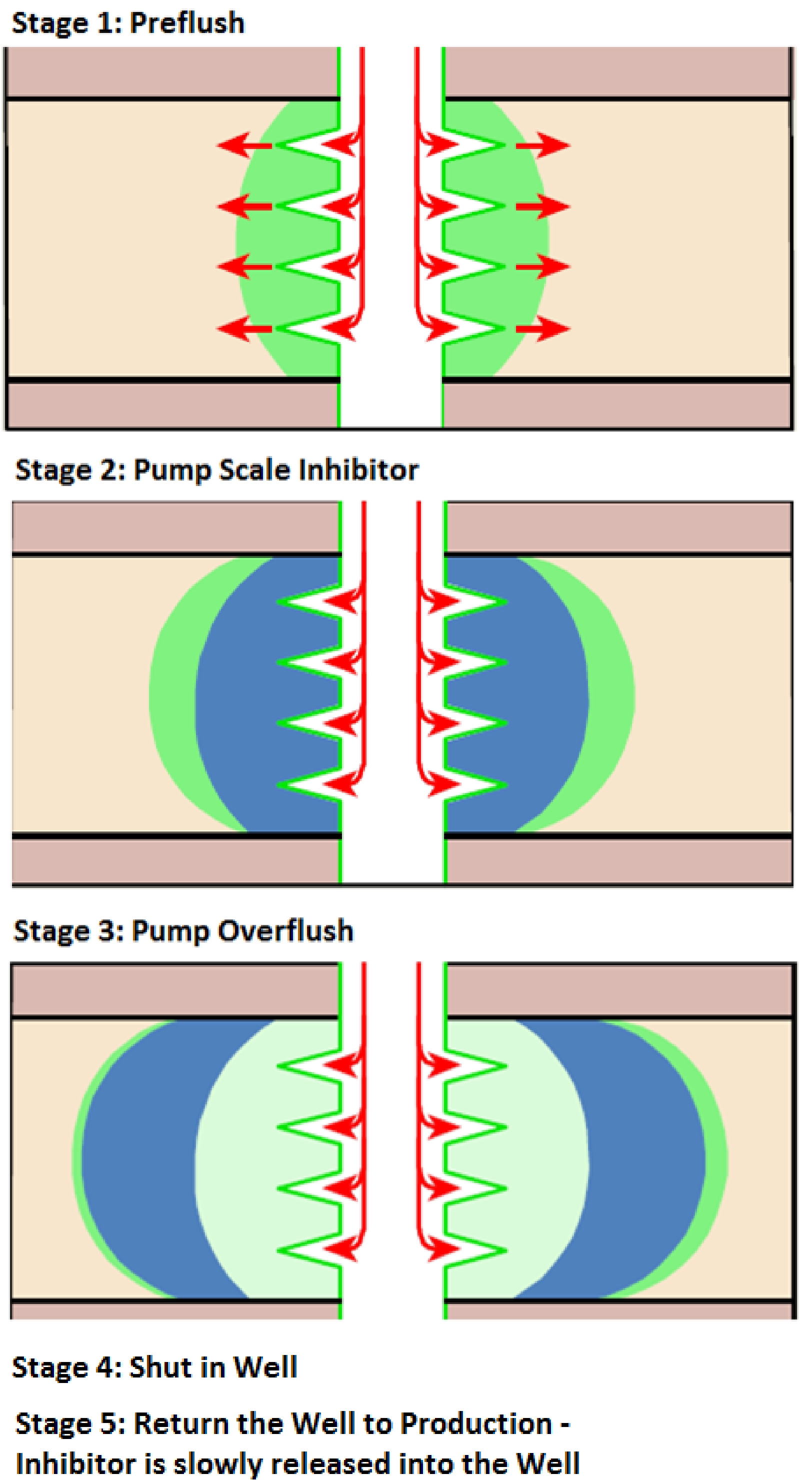

Figure 3-1 Scale Inhibitor Squeeze Treatment [20]

3.2. Scale removal technologies and intervention approaches

Deposition of scale in a well may occur even if a well has gone through different scale reducing methods such as scale inhibition treatment. If a production well is not sufficiently protected against scale, the production in the well may decrease because of flow restriction caused by scale. When this happens the scale must be removed by the use of different scale removal technologies. Choosing the best scale removal technique is important for getting the most effective removal of scale. Knowing the type and quantity of the scale and its physical composition, are important factors for the choice of technique. The techniques must be quick, non-damaging to the wellbore, tubing and the formation, and prevent re-precipitation [6]. The two primary methods for removal of scale are chemical dissolution and mechanical removal. Both methods can be used separately or in combination.

Wireline, coiled tubing (CT) and snubbing are three well-intervention methods that can be used in live wells and are used to remove scale. CT and snubbing can be used for chemical dissolution of scale by pumping the chemicals directly into the scale affected area through their pipe strings. In wireline operations this is not possible, but instead a type of pumping called bullheading can be used to place the chemicals in the scale affected area. Bullheading will be explained in more detail in chapter 3.2.1.1. For mechanical scale removal all of the tree well-intervention methods can be used. Some of the tools used for mechanical removal will be explained in chapter 3.2.2.

There is an increasing trend to use RLWI vessels instead of semi-submersible rigs to perform intervention operations on subsea wells. Today wireline is the only well-intervention method available from these vessels.

Wireline

Normally, wireline is referred to as a cabling technology that lowers and raises equipment with cable in a well, by the use of an electro-hydraulic or diesel driven winch. Wireline operations are operated on both fixed platform and on floating units. Traditionally, there are three types of cable systems in use, these are slickline, braided line and electric line (figure 3-2). Slickline is a thin single strand cable which is used only for mechanical operations like deployment or retrieval of gas lift valves and plugs, or to clean a well by the use of e.g. a broach. A braided line is a type of multistrand cable which is stronger than a slickline and can thus do heavier mechanical work. The electric line is a type of multistrand cable consisting of individual steel strands woven around one or more electrical conductors. It is used in operations which needs electrical signal e.g. milling and logging [21].

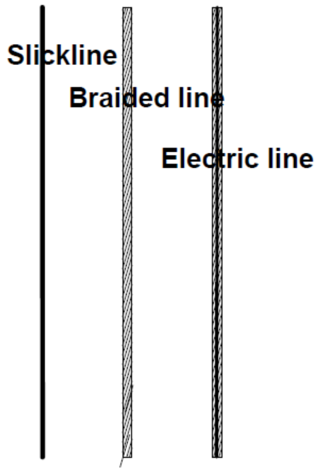

Figure 3-2 Types of wireline cables [21]

Coiled tubing

Coiled tubing (CT) is a piece of continuous, flexible tubing that is stored on a rotating drum called a reel [22]. The flexible tubing is run in and out of the well to perform various well servicing and to circulate fluids. CT normally performs operations similar to wireline. The main benefits over wireline are that CT has the ability to pump chemicals through the tubing and the ability to push the bottom hole assembly (BHA) into the hole rather than relying on gravity. [23]. This means that CT can perform heavier work than wireline.

Figure 3-3 Coiled tubing on a reel [24].

Snubbing

Snubbing is a type of heavy well intervention which involves running the BHA on a pipe string using a hydraulic workover rig. The pipe with joint sections is not spooled up on a drum like in wireline and coiled tubing, but made up while being pushed into the well against wellbore pressure [25]. Snubbing is only used for the most demanding operations when lighter intervention techniques like wireline and CT do not offer the strength and durability needed.

3.2.1. Chemical

Scale can be divided into two categories with regards to their solubility. These are scales which are soluble in acid and scale which are insoluble in acid. Different carbonates scales like calcium carbonate (calcite; $CaCO_3$) and iron carbonate (siderite; $FeCO_3$) are examples of scales which are soluble in acid. Carbonate scale can be dissolved in both organic acid (e.g. citric or formic acid) or in inorganic acids (e.g. hydrochloric acid). Hydrochloric acid (HCl) is the cheapest and easiest acid to use, but the disadvantage is that the acid is very corrosive. This means that a corrosion inhibitor often must be added to the acid solution when being used [2, 8].

Equation 3-1 shows the reaction between HCl and calcium carbonate which forms calcium chloride ($CaCl_2$), carbon dioxide (CO_2) and water (H_2O).

$$2HCl(aq) + CaCO_3(s) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l) \quad \textbf{Equation 3-1}$$

Sulfate scales are scales which are insoluble in acid. Barium sulfate (barite; $BaSO_4$) and calcium sulfate (anhydrite; $CaSO_4$) are examples of this. Insoluble scale can be removed by the use of different scale dissolver chemicals. These are chelate agents such as ethylene-diamine-tetra-acetic acid (EDTA) or diethylene-triamine-penta-acetic acid (DTPA). A chelating agent is a complex molecule which breaks up the scale by isolating and tying up the metallic ions in the scale [7]. The application of these dissolvers is time consuming and is dependent on high temperatures and circulation for optimum effect. Calcium sulfates are soluble in many chelate dissolvers and is therefore the easiest sulfate scale to handle. In contrast, barium sulfate is more difficult to handle, being very hard [2, 5, 8].

3.2.1.1. Bullheading/pumping

A chemical scale removal method is to pump down chemicals to the scale affected area in the well. A volume of the chemical is pumped into the well and displaced with a volume of another fluid to position the chemicals in the right area. The displacement fluid needs to be lighter than the chemical so it stays over the chemical. Diesel can be an example of this. The amount of fluid and chemicals used in the operation is calculated from the volume in the well. The well is then shut in and the chemical stays for a certain time in the well before it is produced out. How long the chemicals can stay in the well is dependent on how corrosive the chemicals are. If the chemical stays too long in the well, parts of the completion equipment may start to corrode.

3.2.2. Mechanical

3.2.2.1. Brush/scratcher

A brush is a downhole tool which is used to loosen and remove scale deposits from critical components, like downhole safety valves and gas lift mandrels/valves. To remove scale from the affected area the brush can be pulled multiple times over the area, or the brush can be driven as a rotary brush by the tractor. Brushing in combination with chemical scale dissolvers are also common [8].

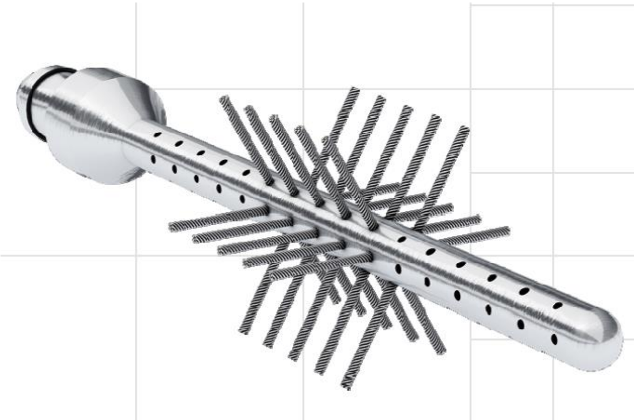

Figure 3-4 PowerTrac Brush, courtesy of Aker Well Service [26]

3.2.2.2. Broach

A broach is normally run on mechanical wireline and is a downhole tool used to remove scale in upper parts of the production tubing to increase the inner diameter and re-establish wireline access to the deeper parts of the well [8]. The broach is jarred up and down to remove scale build up on the tubing wall. The operation has to be repeated with increasing outer diameter broaches, to remove all of the scale.

Figure 3-5 Broach [21]

3.2.2.3. Explosives - string shots

String shots are explosives that are run on an electric line and are detonated in the tubing/liner to "rattle" the pipe to remove scale layers from the pipe wall. Multiple runs are often needed to remove all of the scale [8, 20].


Figure 3-6 String shots and a detonating cord taped to a steel bar [27]

3.2.2.4. Milling

Milling is a mechanical method which uses a special tool string with a milling bit in the end to remove scale. Milling can be deployed by coiled tubing, snubbing or wireline and its purpose is to remove scale buildup and retrieve well access. CT and snubbing are normally used on heavier operations where you have large amounts of scale, while wireline milling is preferred on shorter scale bridges/restrictions. Milling will be explained further and in more detail in chapter 5 "Mechanical wireline milling with tractor".

4 Wireline equipment for mechanical removal of scale

4.1. Wireline rig-up equipment

Wireline operations are generally carried out by positive wellhead pressure [21]. To control the pressure from the well bore different pressure control equipment needs to be installed on top of the Xmas tree. The pressure control equipment must be rated over the expected well pressure and normal ratings for the equipment are 5000, 1000 and 15000 psi [28].

The main functions that the pressure control equipment needs to handle is according to Harestad [21]:

a) Seal around area surrounding the wire under both static and dynamic condition.
b) Keep sealed against any maximum wellhead pressure.
c) Allow the tool string safely set and pulled out of the well by the mean of a lubricator long enough to cover the tool string length.
d) Allow the lubricator to be leak tested against any maximum wellhead pressure before opening the well, and that the pressure can be adjusted to wellhead pressure before the main valve is opened.

4.1.1. Wireline rig up - Platform

Figure 4-1 shows the basic surface rig up equipment for wireline operations with slickline and braided line/electric line on platforms with Xmas tree on deck.

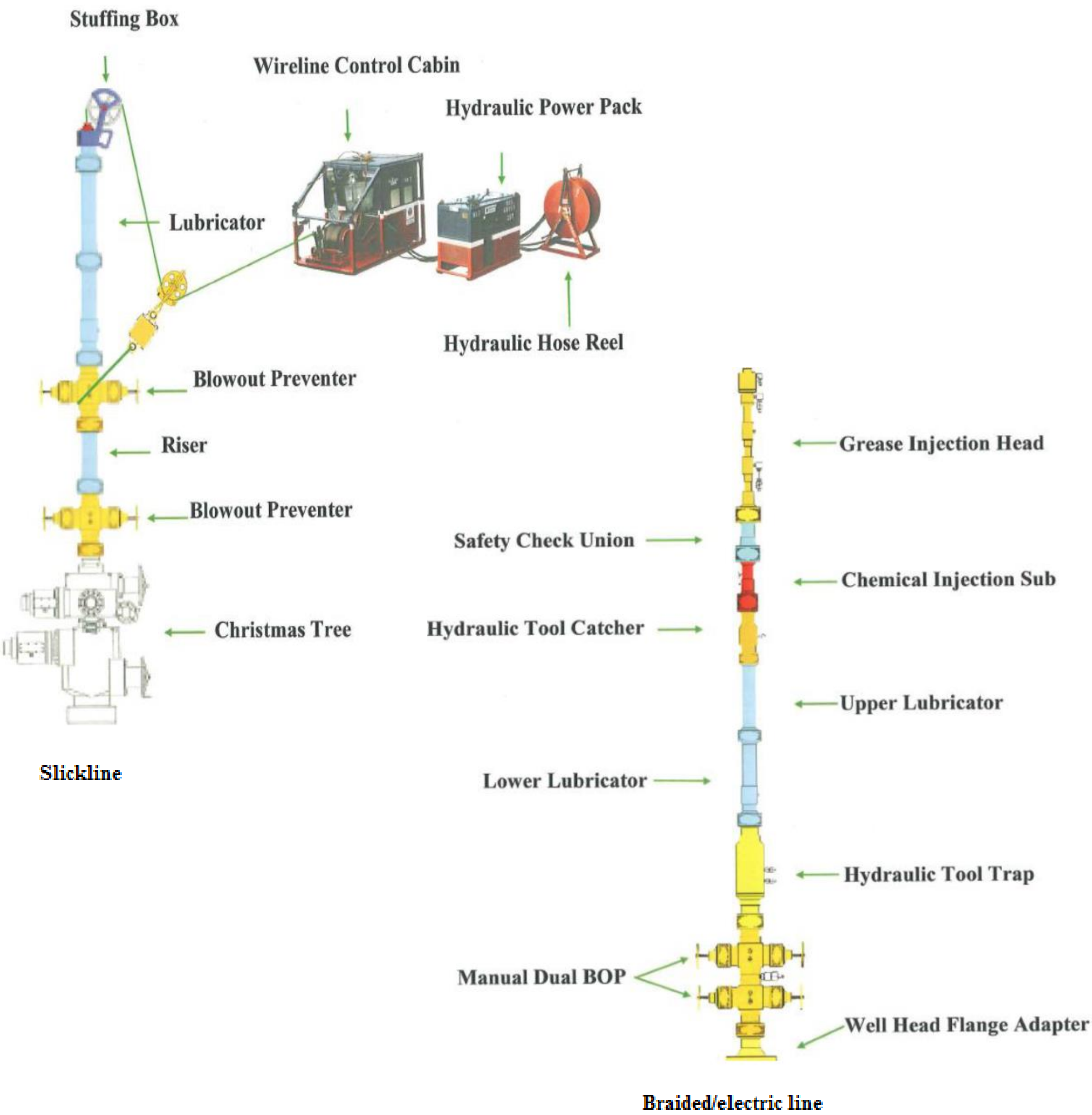

Figure 4-1 Surface rig up equipment for slickline and braided line/electric line [21]

Stuffing box

For an operation with slickline the primary barrier element that seal around the wire is the stuffing box. The stuffing box consists of rubber packers which seal around the slickline to confine wellbore fluids and gases within the surface pressure equipment. The well pressure forces the rubber packers together and additional hydraulic pressure can be applied if leakages occur.

Grease injection head

The primary barrier element for braided/electric line is the grease injection head. Its function is to contain well pressure whilst running braided/electric cable into or out of well. Inside the grease injection head is a certain number of flowtubes which the cable is tread trough. How many flowtubes that are required will depend on the well pressure [21]. The grease is continuously pumped around the cable and fills the annular space between the inner wall of the flowtubes and the outside surface of the wireline. This forms a liquid seal that seals against well pressure. The grease is injected with a pressure that is approximately 70 bars larger than the well pressure under normal conditions.

Blow out preventer

The secondary barrier element in the wireline rig up for operations with slickline or braided/electric line is a blowout preventer (BOP). The BOP is installed just above the Xmas tree. Its function is to seal around the cable when there is a leakage in the components above or when maintenance of the equipment at top of the lubricator is needed (e.g. shifting packers within the stuffing box) [21]. The number of rams in the BOP depends on the cable in use. A slickline only need a single BOP with just one ram while braided/electric line needs a double BOP with two rams. This is because the braided/electric line needs grease injection between the rams to seal around the wire. The most common BOP for wireline operations is the combo BOP. This is a BOP which can be used for both slickline and braided/electric line.

Lubricator

A lubricator is a series of steels pipes which are used to lubricate the tools string in to the pressurized well. The maximum lengths of the tool string which can be run in hole are limited by the lubricator length.

Tool catcher

A tool catcher is a hydraulic driven tool which is installed on top of the lubricator below the stuffing box or the grease injection head. It will catch the tool string before it hits the top of the lubricator. This prevents the wireline to snap and prevent the tool string from inadvertently dropping down the hole if the wireline weak point breaks when pulling tool string into the lubricator.

Chemical injection sub

A chemical injection sub is mounted just below the stuffing box or grease injection head. It allows injection of either an inhibitor to prevent H_2S/CO_2 corrosion or a de-icing agent (i.e. Methanol or Glycol) to prevent gas hydrates [21].

Check valve union

A check valve union is designed to seal off well pressure in the event of the wireline parting from the tool string. A steel ball is forced against the seat by the well pressure preventing flow from below [21].

4.1.2. Wireline rig up - Riser Less Wireline Intervention (RLWI) Vessel

Figure 4-2 shows one type of system configuration for a riser less wireline intervention on a subsea well from a dynamic positioned monohull vessel.

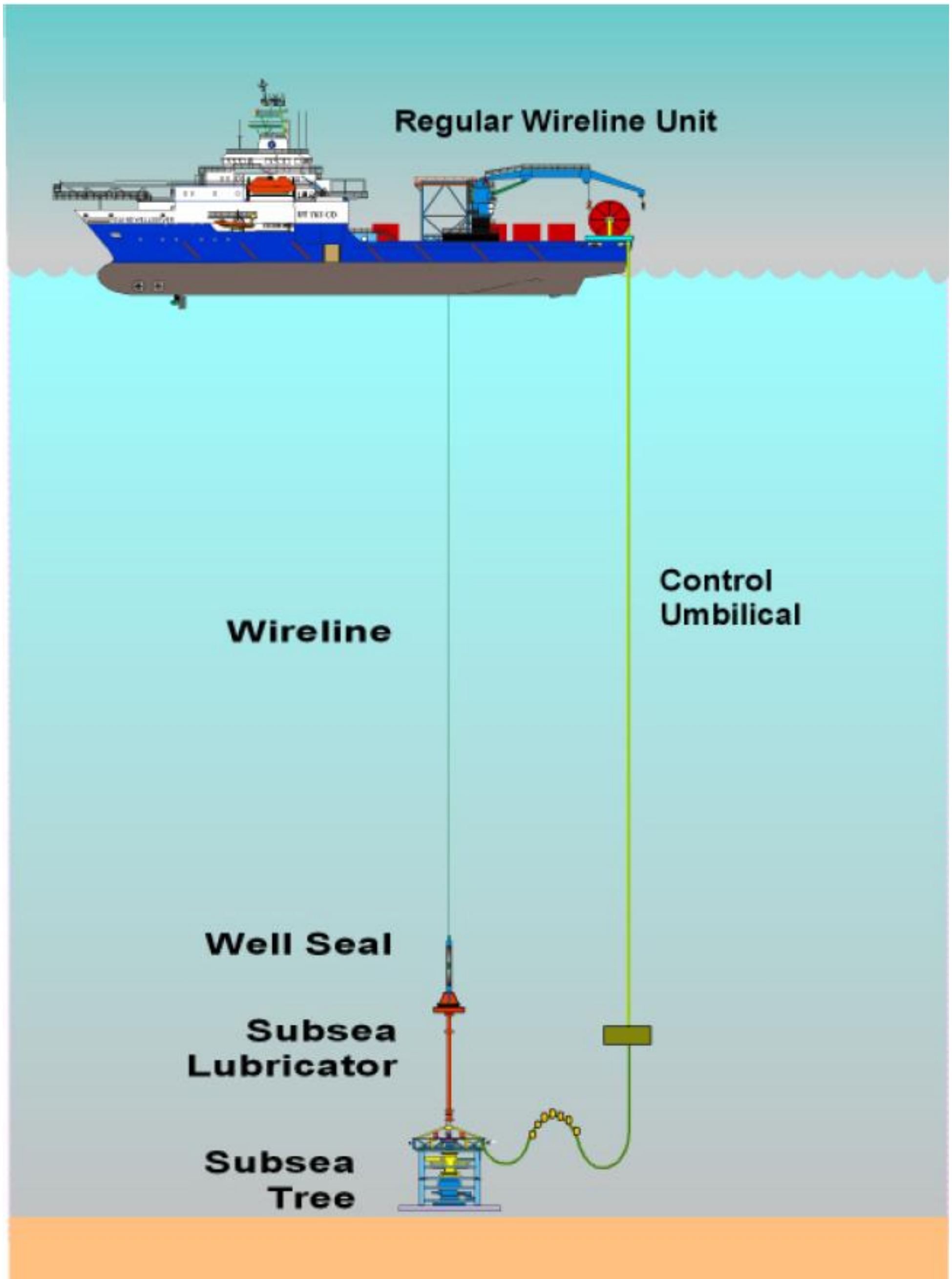

Figure 4-2 Standard configuration for wireline operations [29]

Figure 4-3 shows a RLWI system which is installed on top of the subsea Xmas tree during wireline intervention on a subsea well.

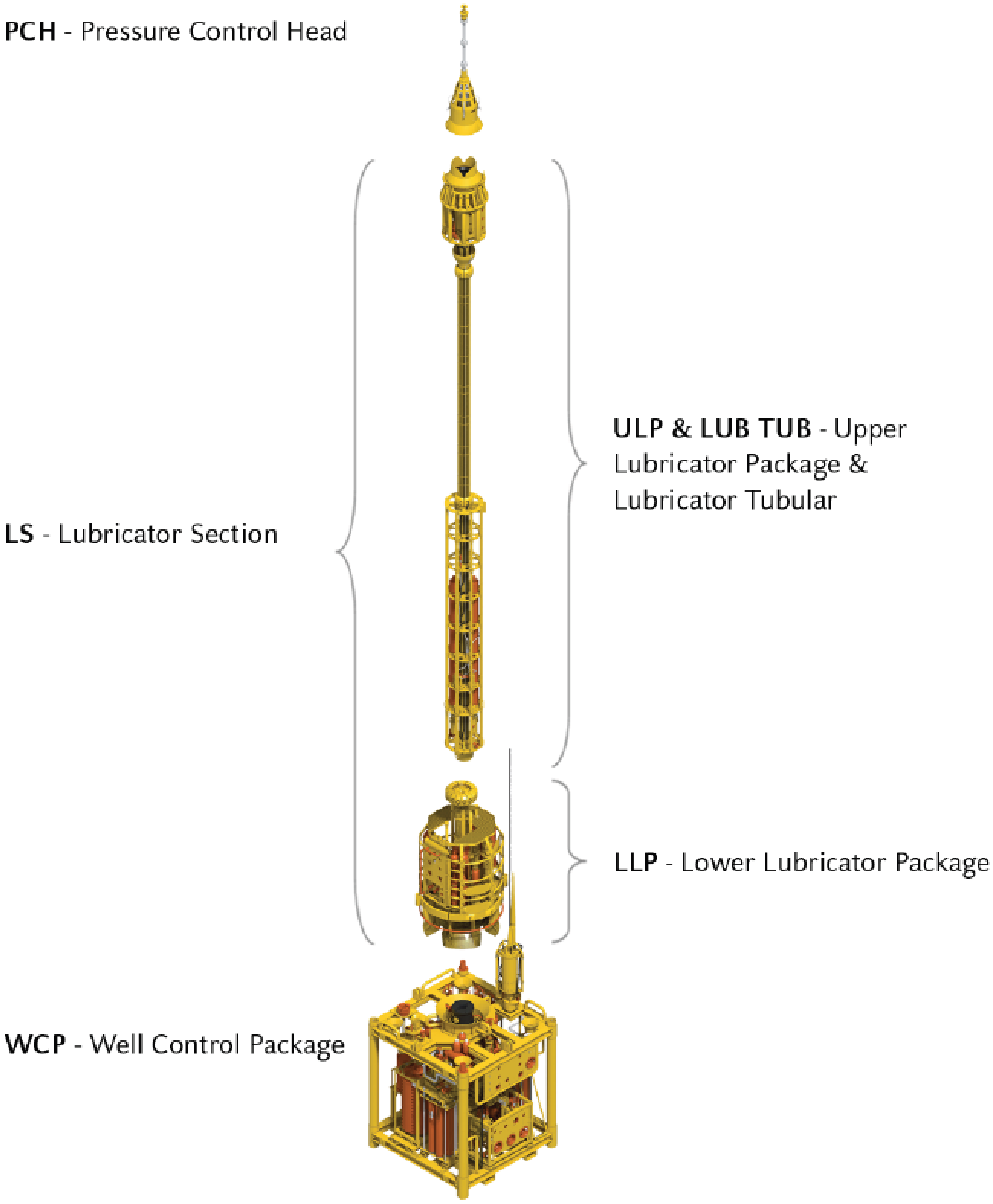

Figure 4-3 Riserless Light Well Intervention system, courtesy of FMC [30]

Well control package

The Well control package (WCP) is installed on top of the Xmas tree and consists of a shear/seal ram and an upper and a lower valve block. The sear/seal ram can cut wireline, coiled tubing and certain wireline tool string. The Well control package is the secondary barrier element when wireline is in hole.

Lubricator section

The lubricator section is connected towards the WCP and is designed to bend if stack sees excessive forces. The length of the tool string is limited by the length of the lubricator section. The lubricator section (LS) consists of the upper lubricator package (ULP), the lubricator tubular (LT) and the lower lubricator package (LLP). The LT is mounted on top of the LLP and carries grease reservoirs and high-pressure injection pumps. The ULP is mounted on top of the LT and consists of a wireline cutting ball valve, a circulation outlet and a connector hub towards the PCH.

Pressure control head

The Pressure control head (PCH) is connected on top of the ULP. It is the primary barrier element during operation and consists of flowtubes and emergency packing elements for wireline [31].

While the well control package and the lubricator section stands on top of the Xmas tree during the whole wireline operation the PCH and the tool string is deployed in parallel through the open sea for every wireline run, and gets locked on to the lubricator. Before pulling the PCH and wireline tool string to deck and unlocking the PCH from the lubricator, all hydrocarbons are flushed towards the well to avoid wellbore fluids spill to sea. The overall system is operated and controlled from surface via an umbilical connected to the WCP [31].

5 Mechanical wireline milling with tractor

5.1. Wireline milling

In a wireline milling operation the main parts of the tool string is normally a tractor, a rotation assembly and a milling bit. For a milling tool string to operate properly on wireline, there are two physical principles that need to be dealt with [32]. These are weight on bit (WOB) and torque. WOB is the amount of downward force placed on the bit while torque is the force that causes the bit to rotate.

In a milling operation it is important to hold a constant and controllable WOB so the bit won't stall out. When the tool stalls out the bit becomes stuck and doesn't rotate. This happens when the WOB applied increases to a point where the available torque is not high enough to rotate the bit.

When the mill bit rotates the tool string and the cable above the mill bit experience an equal force in the opposite direction called reactive torque. This reactive torque causes the tool string and the cable to rotate which is undesirable because it can damage the cable an eventually lead to the loss of the tool string in the well [33]. To prevent rotation of the tool string an electrical wireline tractor is used in milling operations (figure 5-1). The tractor can push the tool string into highly deviated and horizontal wells where gravity is insufficient. When the tractor is activated an electrical motor drives a hydraulic pump which squeezes out wheels against the wellbore and drives the tool string down the hole. The tractor provides a constant pushing force against the object being milled, by adjusting its driving force, which reduces the risk of stalling [33]. It also prevents the tool string and cable from rotating because of the contact between the wheels against the wellbore which provides an anchoring mechanism. This anchoring mechanism is maintained even if the milling motor stalls.

Figure 5-1 Well tractor with wheels deployed against the wellbore [7]

Between the tractor and the milling bit sits the rotation assembly which provides torque and rotation to the mill bit. It consists of a motor which provides torque that drives the bit and a gearbox which adjust the revolutions per minute (RPM).

Milling bits comes in different sizes and shapes (figure 5-2 and figure 5-3). Selecting the right bit for different milling operations depends upon expected target material and well bore restrictions [34]. It is also important to take in to consideration the WOB created from the tractor, the torque output from the hydraulic motor and the cuttings removal when choosing the right bit.

Figure 5-2 Milling bits, courtesy of Welltec [35]

Figure 5-3 Mill bit; ConeCrusher, courtesy of Aker Well Service [30]

5.2. Surface readout parameters during a milling operation

During a milling operation different parameters get measured to have control over the operation. The measurements are provided to the operator, by transmitting data from the tool string to surface, through the electrical wireline cable.

Head tension

Head tension is measured in a device installed on top of the tool string and it shows the tension/WOB applied on the bit. The WOB is provided from the weight of the tool string where gravity acts as a downward force on the bit and from the tractor which applies force on the bit. In a horizontal well the force from the tractor is the only source of WOB.

Temperature

The temperature sensor shows the internal temperature in the tool string. In high temperature wells it is crucial to control this parameter because the different tools used in a milling operation (e.g. the tractor) are only rated for limited temperatures. If the tools experience a higher temperature than rated for, the tool may work for a shorter time and eventually stop working.

Current

Knowing the amount of current used while milling can give an indication if the mill bit is milling or only stalling out. If the bit is milling the current curve would most likely be flat and even. But if the bit is stalling out the current will increase rapidly and high peaks would be seen on the current curve. This is because when the bit is stuck more current is used to try rotating the bit.

Wireline tension

Wireline tension is an important parameter to measure because it indicates how much tension is applied on the cable. The wireline cable can only tolerate a certain amount of tension before it breaks. Because of this regular pick up weights are taken to verify that the cable can pull the tool string out of hole without exceeding the cable limitations and leaving fish in hole.

Depth

While running the cable in hole, a depth counter counts the amount of cable which are spooled out. The wireline depth can give an indication of how far down the tool string is in the well. But the depth can also be misleading because if the tool string stops in the hole, due to an obstruction in the well, the cable can still be spooled out and show a deeper depth than what is the actual depth. To make sure that the tool string hasn't stopped the wireline tension needs to be monitored to see if the tension increases or decreases. To obtain a more correct depth when running in hole, the depth must be correlated by running a CCL (Casing Collar Locator) in the well. The CCL is an electrical logging tool that operates on Faraday's law of Induction. Two magnets are separated by a coil of copper wire. As the CCL passes a casing joint, or collar, the difference in metal thickness across the two magnets induces a current spike in the coil. The signal is transmitted to surface equipment that provides a screen display and printed log enabling the output to be correlated with previous logs and known casing features such as pup joints installed for correlation purposes [36].

5.2.1. Plots from a wireline milling operation

The figures 5-4, 5-5, 5-6 and 5-7 show plots with parameters measured during a scale milling operation. The data is from a scale operation performed in 2012 on the well "Statoil well A" located in the Smørbukk field. The actual milling operation will be explained in detail in section 7.2.

Figure 5-4 shows the first part of a milling run with a 4.7" scale milling bit. It shows the voltage and current used and also the head tension and the internal temperature in the tools. From the plot it is seen that the parameters increased quickly in the start (1), when the milling tool was activated. The milling seemed to go fine in the beginning, because the curves were fairly stable. After 5 minutes the current and voltage curves suddenly increased, which most likely indicates stalling of the mill bit because more current is needed then (2). Attempts at milling further are shown from the two peaks, which indicate that the bit was still stalling when trying to mill the scale (3).

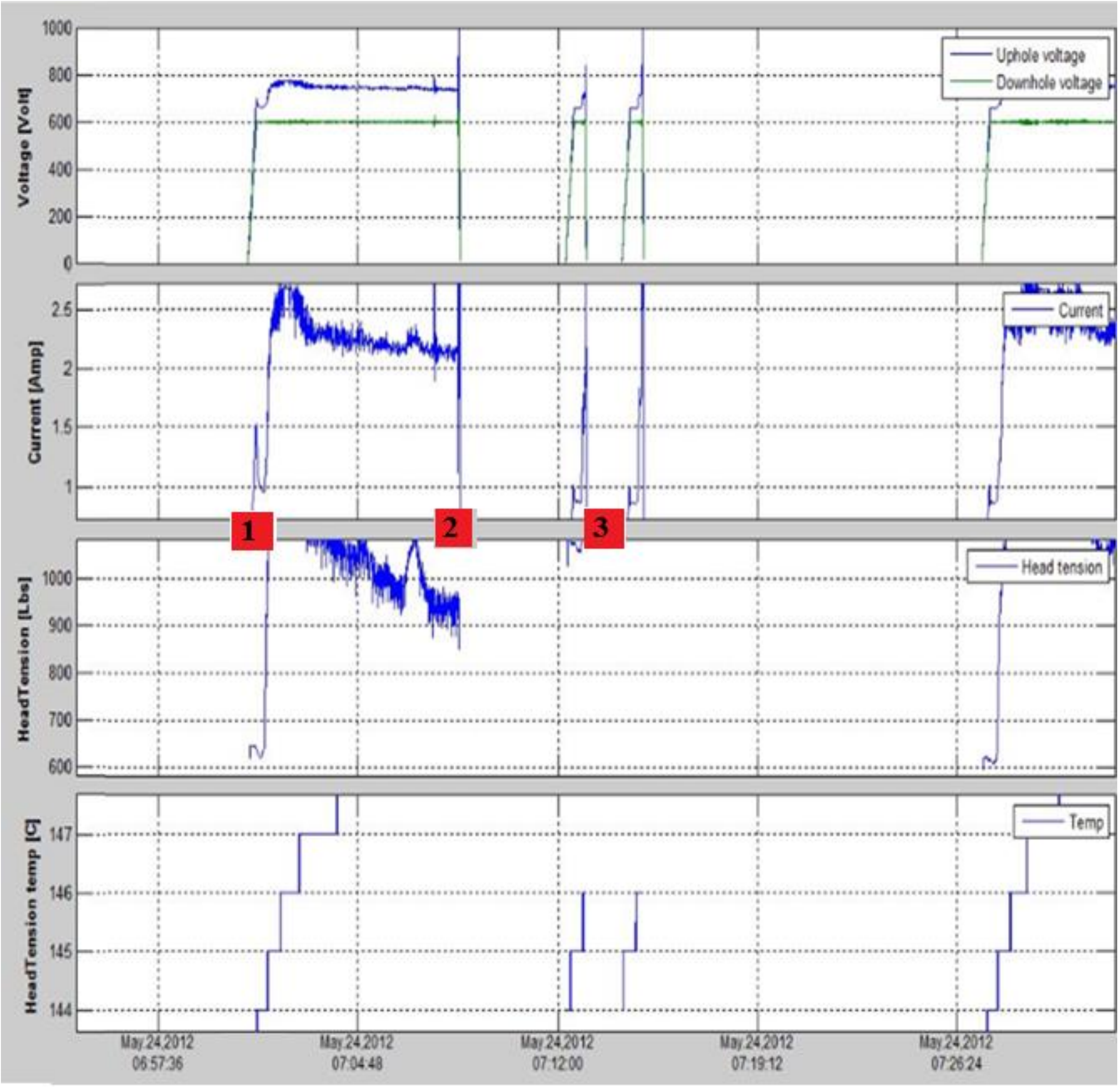

Figure 5-4 Measurement plot #1

Figure 5-5 shows the same parameters as in figure 5-4 and the tool string is the same. As the milling started, the curves increased and the milling seemed to go fine for 20 minutes due to stable voltage and current curves. The milling was then stopped for a short period to cool down the tools due to high internal heat generation during the milling load (1). Too high internal temperature in the tools can stop them from working properly.

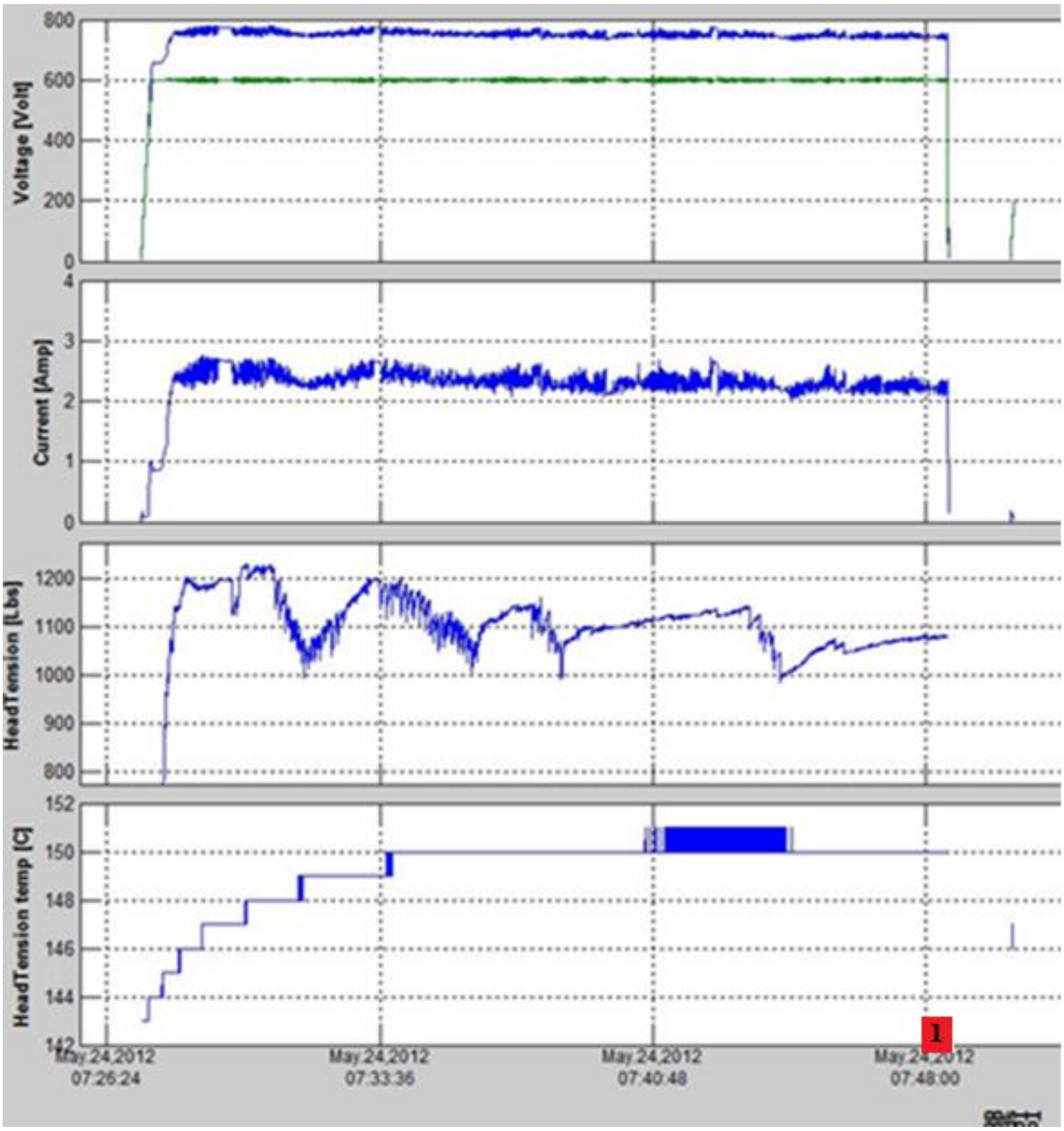

Figure 5-5 Measurement plot #2

In figure 5-6 the milling started again after the cool down period in figure 5-5. The head tension temperature curve showed that the temperature was less than before the cool down period. The milling continued for 20 minutes before it stopped due to a short circuit in the tool string (1).

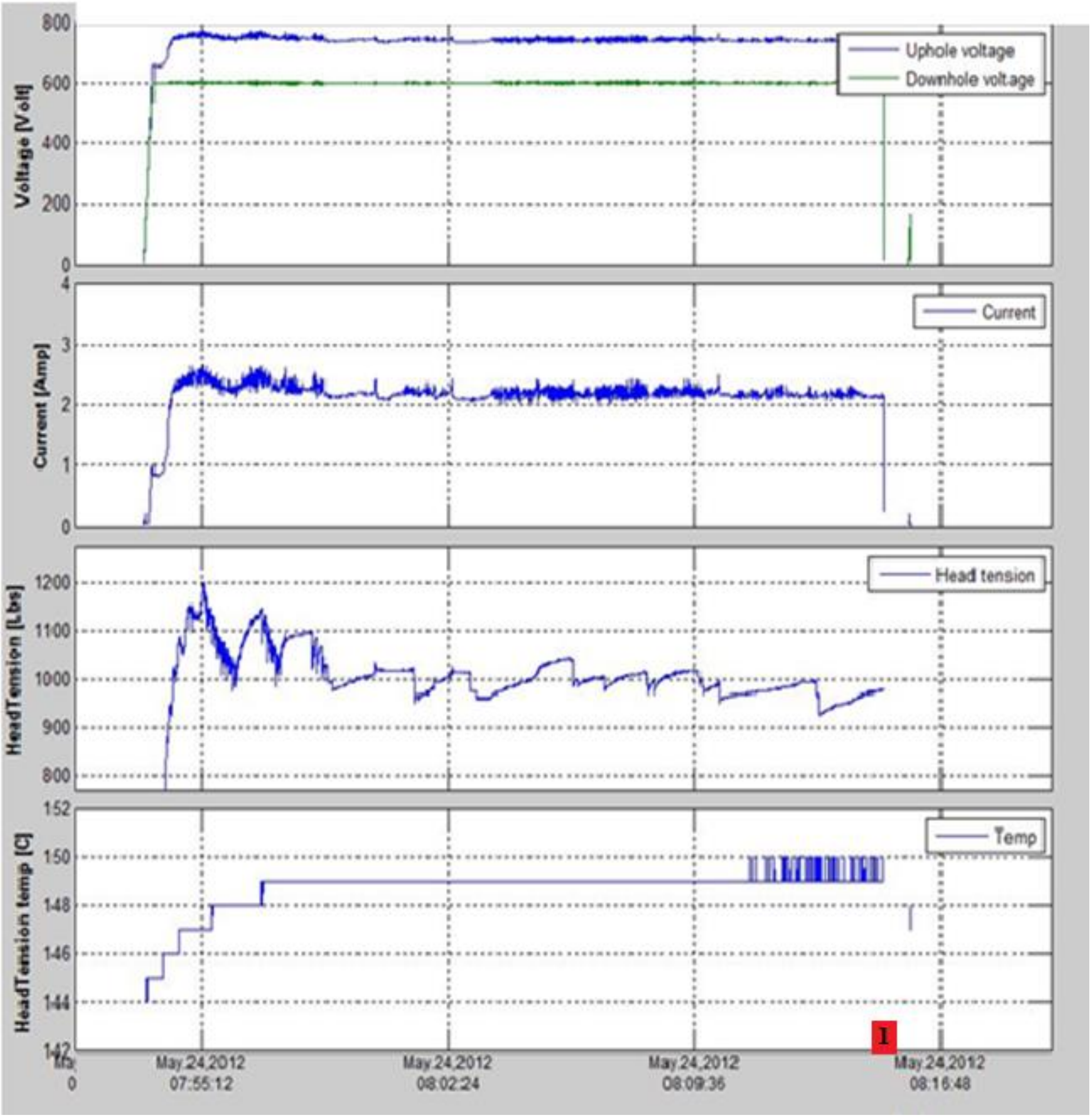

Figure 5-6 Measurement plot #3

Figure 5-7 shows a plot of the voltage and current curve while milling with a 5.7" scale milling bit. Due to a failure in the tool the head tension measurement was not detected. This made the milling more difficult because it is harder to hold an even WOB when the head tension is unknown. From the plot it is seen that the stable periods with milling were shorter than in the previous plots (1). There were also high peaks in between these stable periods, which indicate that the milling bit was stalling out (2). In the last part of the plot it was seen several high peaks which can indicate attempts on pulling free due to mill bit being stuck (3).

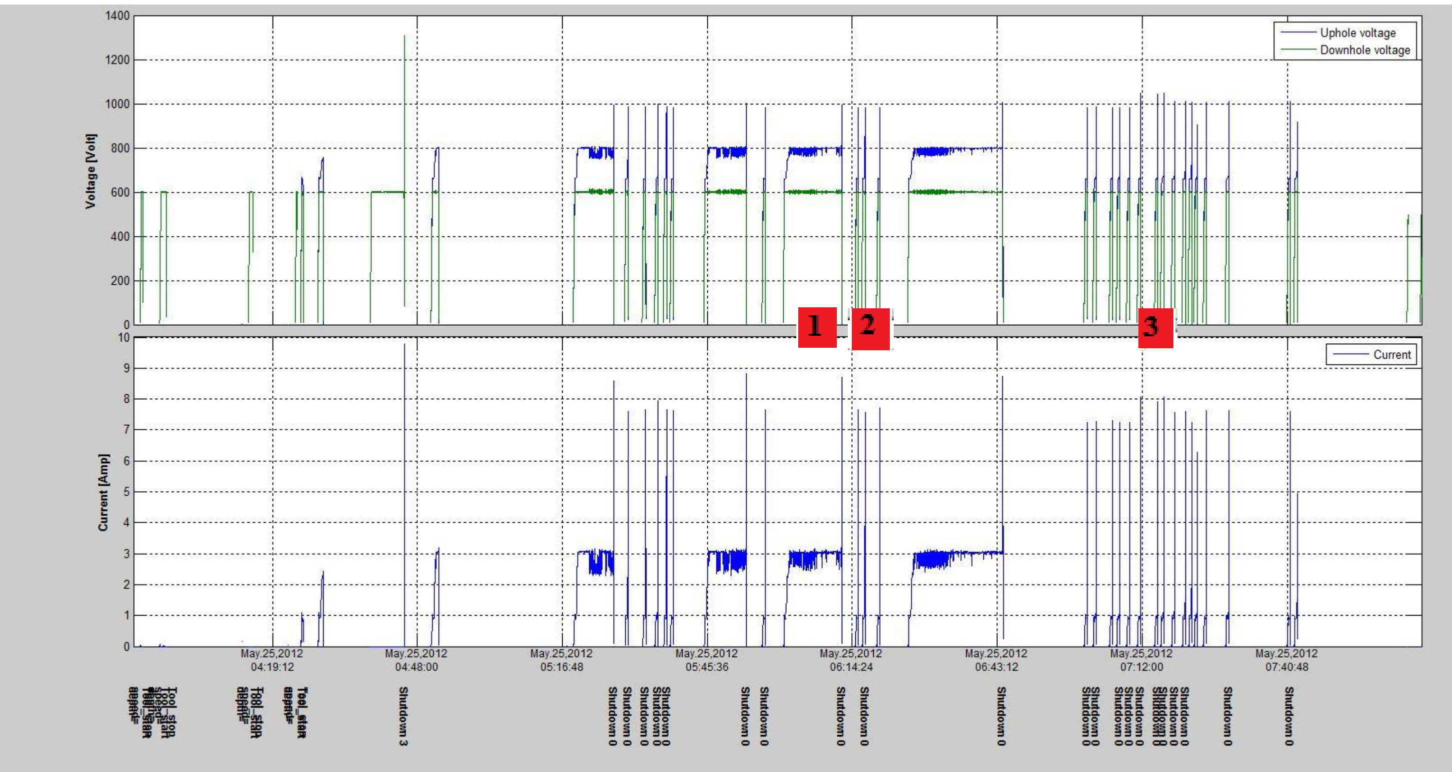

Figure 5-7 Measurement plot #4

The figures 5-8, 5-9 and 5-10 show plots with wireline depth, wireline speed and wireline tension plotted against time.

A positive wireline speed indicates that the tool string is lowered down in the well, while a negative wireline speed indicates that the tool string is pulled upward. The opposite happens with the wireline tension. The wireline tension is increasing when the tool string is pulled upward, due to friction, and decreasing when lowered into the hole. This is seen from the measurement plots. Between point A and B in figure 5-8 it is seen that the tool string was lowered into the well because the wireline depth increased. At the same time the wireline speed was positive while the wireline tension was decreasing rapidly. This is seen between point A and B in figure 5-9 and 5-10. The opposite effect is shown between point C and D as the tool string was pulled upward. The wireline depth in figure 5-8 was decreasing and at the same time the wireline speed was negative in figure 5-9. The wireline tension increased between point C and D in figure 5-10 as the tool string was pulled upward.

Figure 5-8 Wireline depth plotted against time

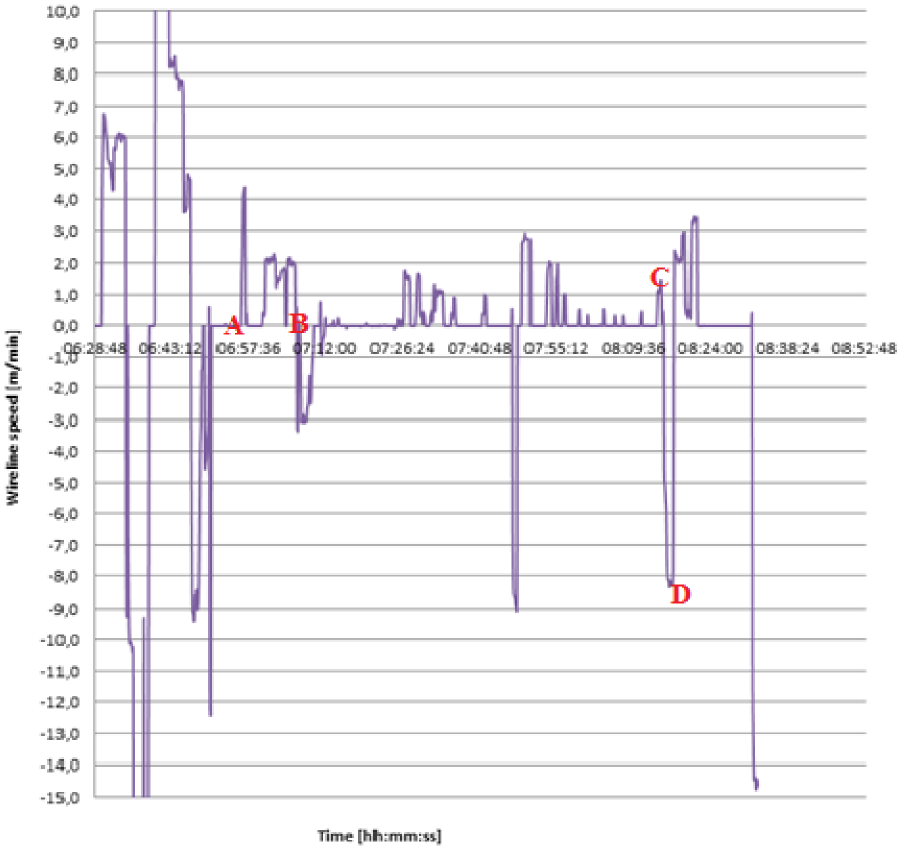

Figure 5-9 Wireline speed plotted against time

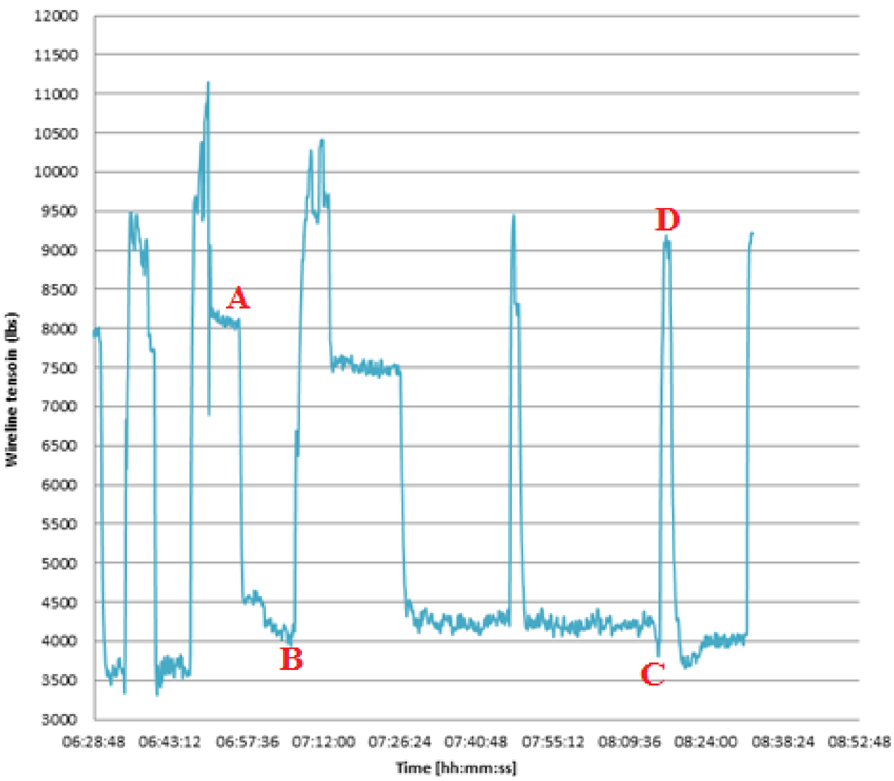

Figure 5-10 Wireline tension plotted against time

6 Case Histories

In this chapter relevant case histories from intervention performed on wells with a scale problem will be presented. The case histories have in common that all the wells are located in the Smørbukk field in the Åsgard development. The four operations are all performed from the light well intervention vessel Island Wellserver [37]. The main focus will be on the scale removal part of the operation. The information about the operations comes from well programs, daily drilling reports and final well reports.

6.1. Introduction

Figure 6-1 Location of the Åsgard development [38]

The Åsgard development is located about 200 km off Mid-Norway in the Halten Bank area in the Norwegian Sea (figure 6-1). It consists of three independent discoveries -Smørbukk, Smørbukk Sør (South) and Midgard [38]. Åsgard is operated by Statoil ASA and started to produce in May 1999. It is developed with subsea completed wells which are tied back to two floating productions installations (Åsgard A and Åsgard B) and a condensate storage vessel (Åsgard C) (figure 6-2). It is among the largest developments on the Norwegian Continental shelf, embracing a total of 52 wells drilled through 16 seabed templates [38]. Carbonate scale deposition has been identified in some of the wells in Åsgard and is most likely the most common scale in the field. There is no water injection in the field so barium sulfate is not likely to occur.

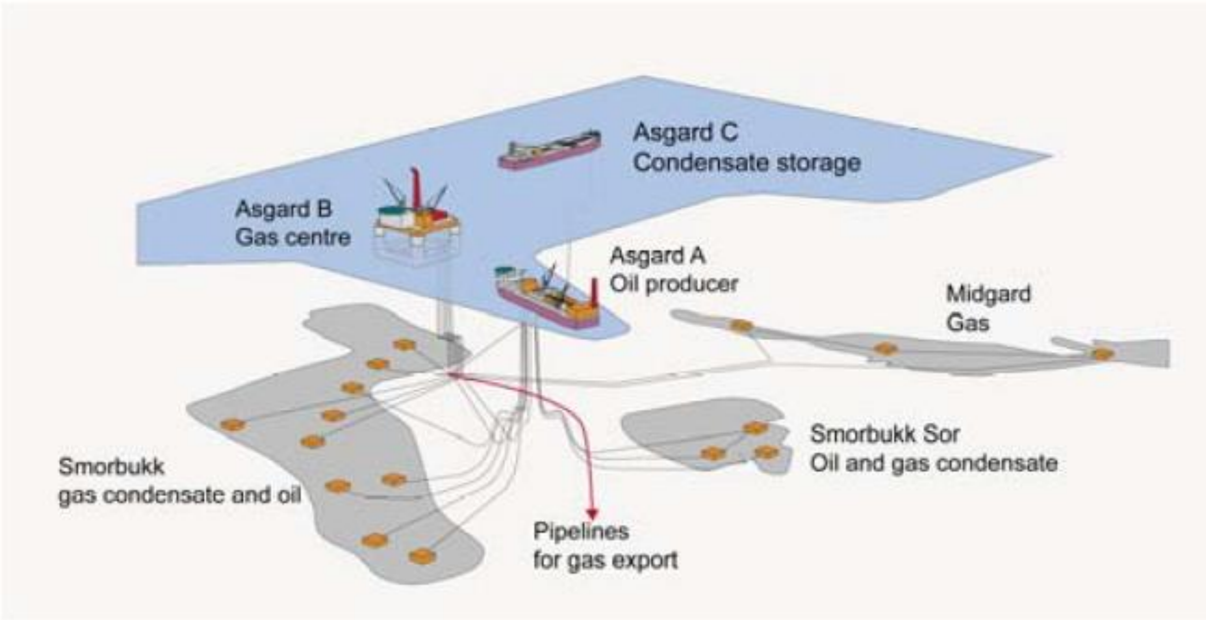

Figure 6-2 Åsgard field installations [39]

Smørbukk is a high temperature (temperature over 150°C [40]) gas condensate field including an oil rim and consists of the five independent reservoirs Garn, Ile, Tofte, Tilje and Åre (figure 6-3). The temperature in the field is up to 165°C and the initial pressure is up to 500 bar [41]. The wells are completed with 7” production tubing and 7“ cemented and perforated liner [4]. The field is partly produced by pressure depletion and partly by gas injection.

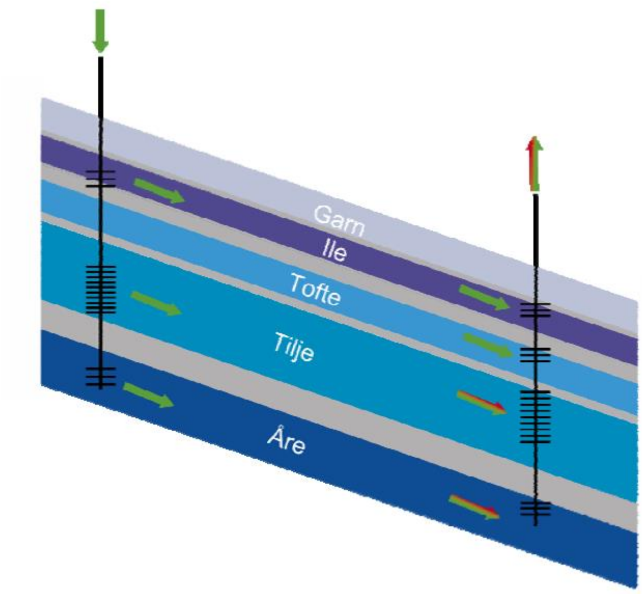

Figure 6-3 Smørbukk reservoirs [39]

6.2. Case History "Statoil Well A"

A LWI operation was carried out on "Statoil well A", a gas condensate producer, in 2012. The main objective for the operation was to re-perforate the Tilje formation. A caliper log from an intervention job performed in 2009 showed restrictions in the liner around the Tilje formation (figure 6-5). The scale restrictions were seen at 5690 m MD and 5692 m MD and were expected to be around one meter each. To get access to the perforation area it was decided to mill the scale restrictions. Furthermore the plan was to use a bailer[1] to get access to the Åre formation and then re-perforate the formation. Finally a production logging tool (PLT) was planned to be run for data acquisition.

Several types of milling assemblies from two suppliers were mobilized to try to find the best solution for these types of milling/bailing operation.

A total of five milling runs were performed to try mill through the scale bridges. The tool string consisted of a wireline tractor, rotation assembly and a mill bit in every run, but the type of mill bit varied in the different runs. The well was flowed during the milling part of the operation.

The figure below (figure 6-4) shows how far down the tool string came in each of the five milling run and which bit size used. The red part on the lines indicates where scale was milled. The numbers in the figures indicate each milling run which will be explained further.

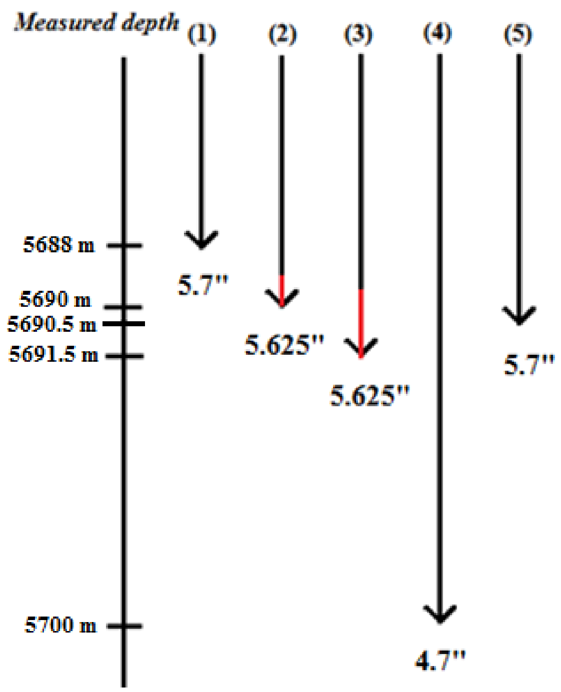

Figure 6-4 Lines showing how deep the tool string went in the well for each run, "Statoil Well A"

[1] A wireline tool generally used to remove of sand or similar small particles.

(1) In the first run a tool string with a 5.7” scale mill bit was run in hole (RIH) on a 7/16” monoconductor wireline cable. After milling for only a short while, the milling assembly got short circuit and was pulled out of hole (POOH).
(2) In the second run a new tools string with a 5.625” scale mill bit were RIH. The interval from 5689 to 5690 m MD got milled before the bit motor failed, due to short circuit in the rotation assembly.
(3) In the third run the same tool string as in run two was RIH. The milling assembly tagged scale at 5690 m MD and milled the interval from 5690-5691.5 m MD. Thereafter the bit stalled out and no milling progress was made.

Due to the slow progress with the large mill bits, it was decided to run a smaller bit to make a smaller hole first, prior to making another attempt with the large mill bit.

(4) A tool string with a 4.7” scale mill bit was made up for run number four. The tool string was RIH to 5699 m MD before it started to mill and milled for 20 minutes. The tools were then cooled down for a short period, due to high internal temperature in them. When the milling started again the tools experienced a short circuit and it got POOH.
(5) In milling run number five a tool string with a 5.7” scale mill bit was RIH. Head tension measurements were not available but the tool string was still RIH. The tool string tagged the restriction at 5690.5 m MD and started to mill. The mill stalled out several times and got stuck. Fourteen attempts on pulling free the tool string was needed before the tool string was finally free and POOH.

Because of several short circuits in the tools and lack of progress when milling, it was decided to abort further milling. Instead a bailer was run in hole to remove debris and then a perforation gun where run in hole to try removing the scale, but without success. In the end of the operation a PLT with a caliper was RIH (figure 6-5 (2012)). The milling part of the operation was only seen as partly successful due to some scale left in the well, and the rest of the scope had to be done with smaller OD guns as a large enough hole was not achieved with the milling attempt.

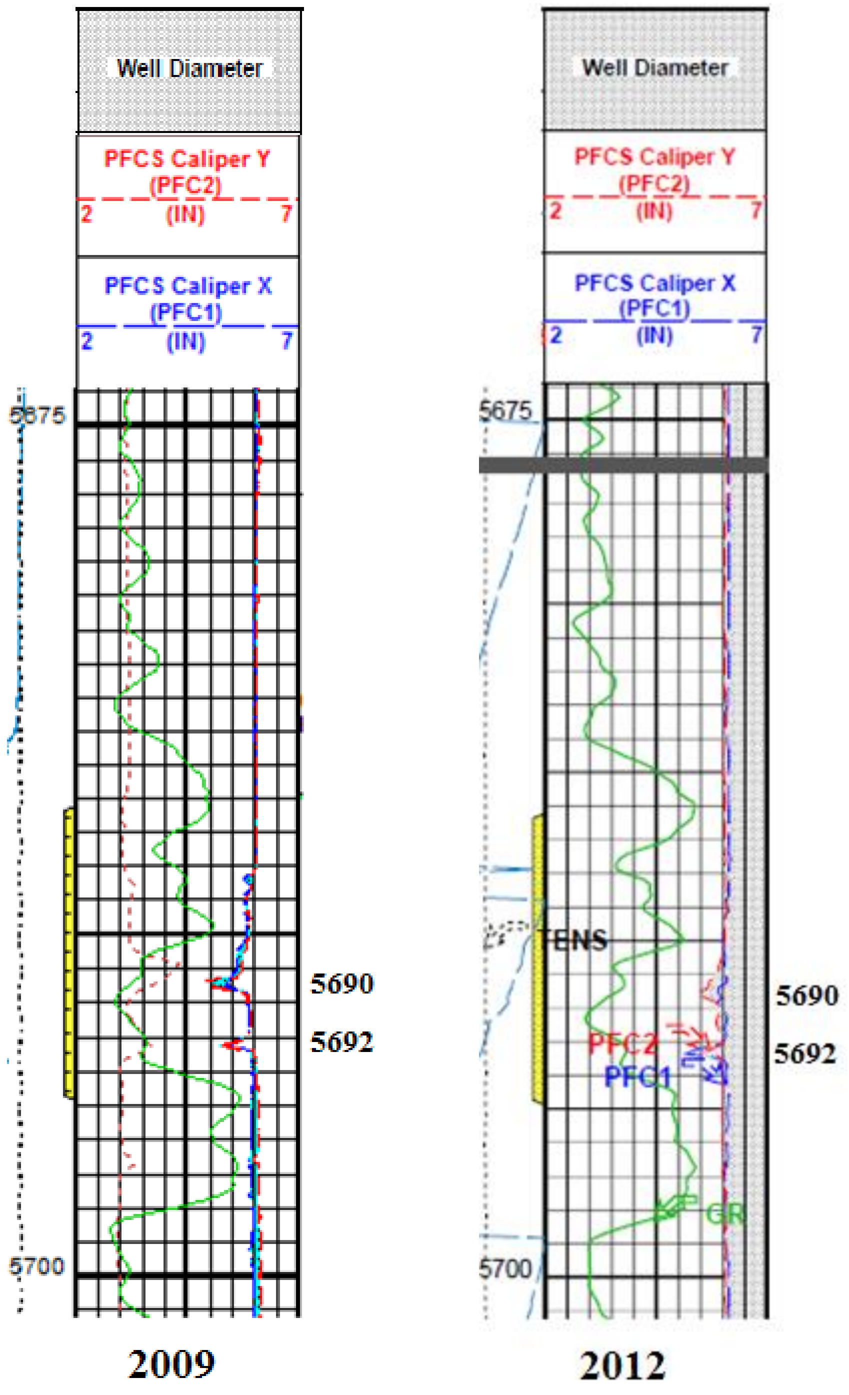

Figure 6-5 Caliper logs from PLT in 2009 and 2012 [42]

The caliper log from the PLT run in 2009 (figure 6-5) showed restriction at 5690 m MD and 5692 m MD. The log showed that the minimum ID at the restriction seemed to be around 4.8" and that the restrictions were around one meter long each. The caliper log from the PLT run after the milling part of the operation in 2012 shows that ID at 5690 m increased from 4.8" to 5.5"while the ID at 5692 m MD was unchanged.

6.3. Case History "Statoil Well B"

In 2012 an LWI operation was performed on "Statoil well B", a gas condensate producer. The main objective for the operation was to perforate the Tilje formation and gather productivity data. A light well intervention operation performed in 2007 showed carbonate scale restrictions in the Tilje and Tofte formations. Based on this the plan was to run a caliper to verify the scale restrictions before milling the scale restrictions to access the perforation area. After milling and perforating the Tilje formation the objective was to run a PLT for data acquisition and to install a straddle to isolate the water producing zone Garn.

The caliper which where RIH to verify the scale bridges before milling, showed that there were scale bridges from 4560 m down to 4760 (figure 6-6) and that the minimum ID in the well was less than 4".

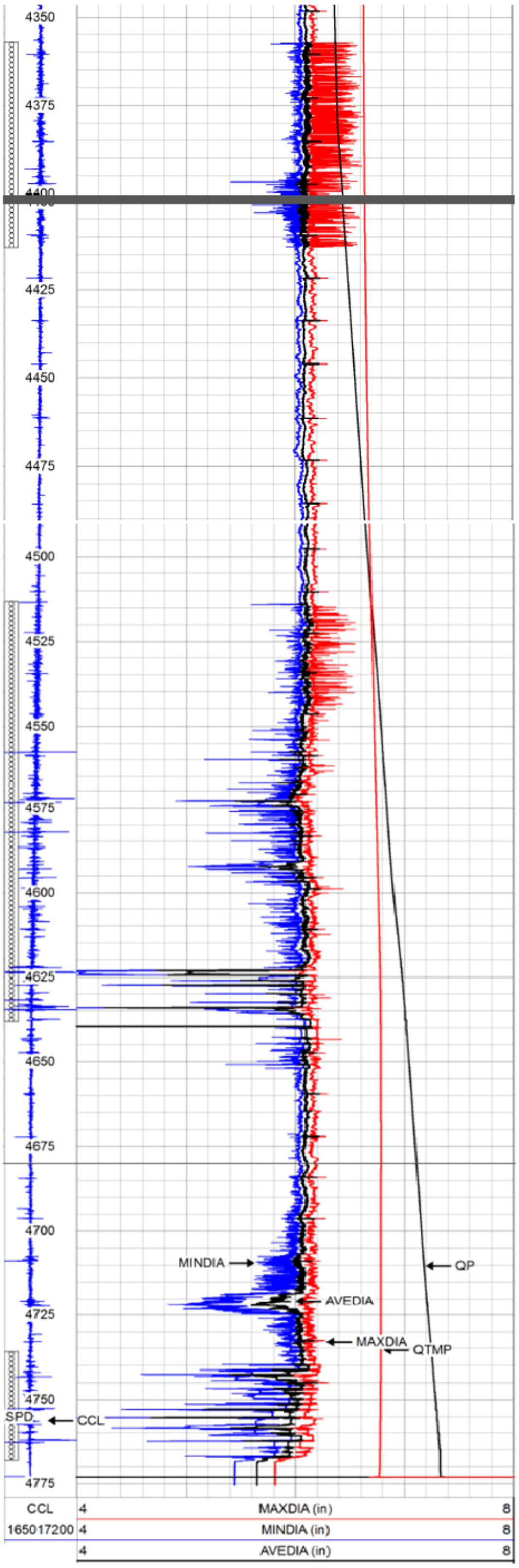

Figure 6-6 Caliper log "Statoil well B" [42]

The figure below (figure 6-7) shows how far down the tool string went in each of the four milling run and which bit size used. The red part on the lines indicates where scale was milled.

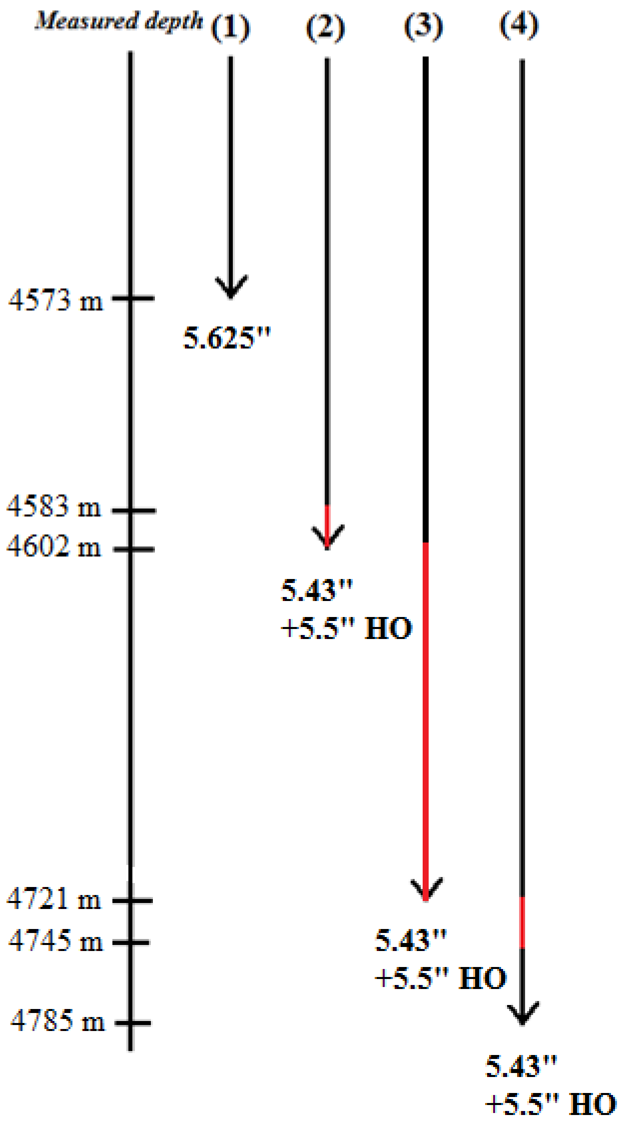

Figure 6-7 Lines showing how deep the tool string went in the well for each run, "Statoil Well B"

(1) In the first milling run the tool string which consisted of a wireline tractor, a rotation assembly and a 5.625" scale mill bit was run on a 7/16" monoconductor cable. The tool string hung up on several small scale bridges in the area from 4396 m MD to 4560 m MD (see figure 6-8) while running in hole before hold up depth (HUD)[2] was tagged at 4573 m MD. At this depth milling were attempted but it was not possible to get sufficient WOB. The tool string experienced short circuit and was therefore POOH.

[2] The point or depth at which a tool or drift of a specific size can no longer pass through the wellbore

(2) In the second milling run a 5.430" scale mill bit and a 5.5" hole opener[3] were RIH and tagged hold up depth at 4583 m MD. The tool milled from 4583 m MD to 4602 m MD (19 m) in 7.5 hours. After this the tool string started stalling out and there were no further progress.

(3) A new identical tool string was then RIH and milled scale bridges between the intervals from 4602 m MD to 4721 m MD (119 m) during 16 hours. At 4721 m the mill stalled out and was unable to go further.

(4) In the fourth milling run, a new and identical tool string as in milling run two and tree, milled scale bridges in the intervals between 4721-4745 m MD (24 m) during 14 hours. Further the tool string was run in hole from 4745 m MD and tagged hold up depth at 4785 m MD.

The well was cleaned up after the milling by flowing the well to try to remove the scale cuttings.

Overall the milling part of the operation was considered as successful. The tool string with a scale mill bit and a hole opener managed to mill scale bridges without major problems in a relatively short amount of time.

[3] A hole opener is an equipment that makes the hole more straight after milling and helps to stabilize the mill bit.

6.4. Case History "Statoil Well C"

In early 2010 an LWI operation was carried out on the gas condensate producer, "Statoil Well C". The objective was to run a PLT for data acquisition from the Åre formation to get valuable information for reservoir modeling and further development of the well. Another objective was to perforate the Ile formation to increase condensate recovery.

But the objectives were only partly met. When the PLT was RIH, it stopped at 4582 m MD due to a restriction which prevented access to the well below. A new PLT was RIH and logged above restriction. Further, it was decided to try to mill the restriction and tractor milling equipment was mobilized to the vessel.

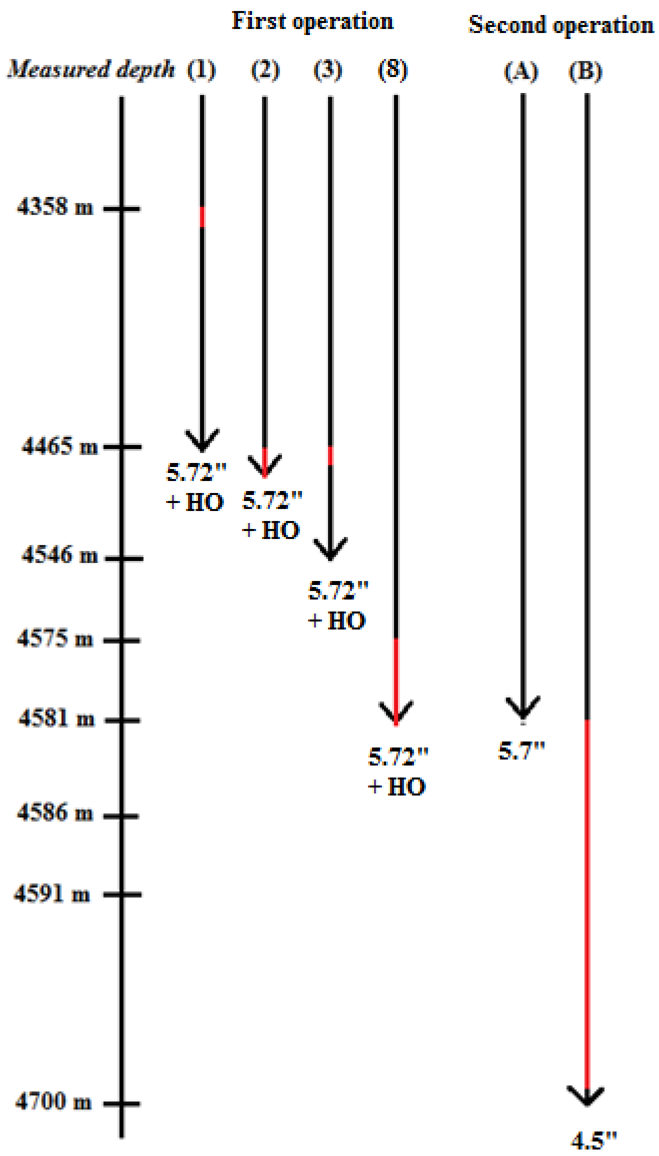

Figure 6-8 Lines showing how deep the tool string went in the well for each run, "Statoil Well C"

First operation

(1) In milling run number one a tool string with a wireline tractor, a rotation assembly and a 5.72” scale mill bit and hole opener was RIH. The mill bit tagged restriction at 4358 m MD and milled through it. A new restriction was tagged at 4465 m MD but the mill stalled out when trying to mill it and the milling tool was POOH. Errors were found in the milling tool when it was inspected on deck.

(2) A new milling tool string with the same OD was RIH. The tool tagged the scale at 4465 m MD and milled two meter in six hours before power on the tractor was lost due to gas influx in the tractor.

(3) In milling run number three an identical tool string as in run one and two started to mill scale at 4465 m MD and milled through a one meter restriction. Further the tool string was run down to 4546 m MD before the tractor failed and the tool string was POOH.

In milling run number four, five, six and seven different equipment failed and no scale milling was carried out.

(8) In milling run number eight a tool string with a 5.72” scale mill bit and a hole opener milled scale from 4575 m MD to 4581 m MD before the motor stalled out several times.

When the tool string was retrieved to deck it was discovered that parts of the tool string was left in hole. Fishing equipment was mobilized and two attempts were needed before the tool string left in hole was fished out. It was then decided to abort the rest of the operation and return to the well at a later stage, to finish the planned activities.

Later in 2010 a new RLWI operation was planned for the well. The plan was to remove the scale restriction with both milling and acid treatment before completing the initial objectives from the earlier LWI operation in 2010.

Second operation

(A) In the first milling run a wireline tractor, a rotation assembly and a 5.720” scale mill bit was RIH on a 7/16” monoconductor cable and scale was tagged at 4581 m MD. The tool started to mill and meanwhile 4m^3 acetic acid was injected into the well. There was no progress in milling at 4581 m MD and the tool string got stuck. Another 10m^3 with acetic acid was then injected with 55 lpm (liter per minute) and the tool string got worked up and down several times before the tool string finally was free.

Next a caliper was RIH and tagged restriction at 4582 m MD.

(B) A tool string with a 4.5" scale mill bit was RIH for mill run number two. The tractor got activated and the sections 4581-4585 m MD and 4585-4589 m MD were milled. Regular pick up weights (PUW) was taken to check that the tool string was free upwards. The section 4581-4586 m MD got milled again several times. The mill had problems getting past 4586 m, but after two attempts the tool milled the section 4586-4591 m. The tool milled further down to 4599 before the tool was RIH down to 4700 m. After POOH it was seen scale on the tool string and four teeths on the mill was damaged.

A tool string with a 5.72" scale mill bit was then RIH. Due to high PUW compared with max safe pull it was decided to stop further milling with the 5.72" mill bit.

Further, 5m^3 acetic acid was pumped into the well. Afterwards a PLT was RIH. The PLT string was coated with scale when the tool came to surface. It was therefore decided to flow the well for clean-up prior to further PLT logging. Finally a new PLT string was RIH and logged the well.

Samples from scale coated on the tool string showed that it was $CaCO_3$ in the well.

Figure 6-9 shows the caliper log from the last PLT run after milling the scale restrictions. From the log it can be seen that there is still scale bridges in the well between 4581-4591 m MD with a minimum ID in the well of 4.5".

Finding scale in the well in the first operation was unexpected, because scale was not seen as likely to occur in the well.

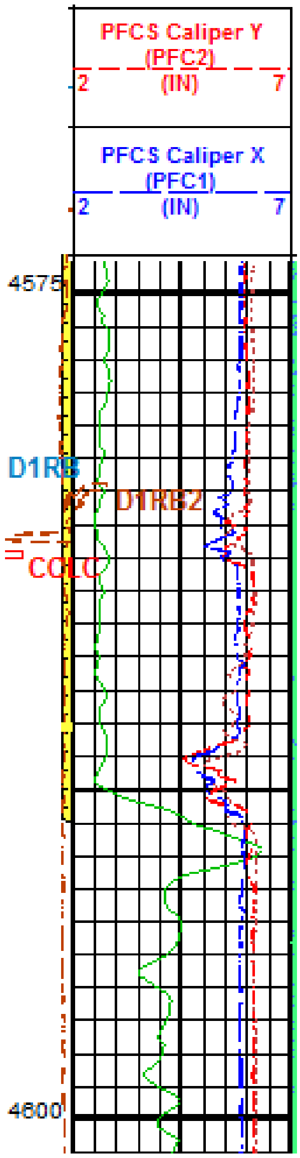

Figure 6-9 caliper log [42]

6.5. Case History "Statoil Well D"

An LWI operation was in 2009 carried out on an oil/gas producer, "Statoil well D". The well had an increase in water production and the main objective for the operation was data acquisition to find out where the water production came from. If the water production came from Åre, the option was to plug it back. A PLT operation performed in 2007 showed a restriction in Tilje at 5197 m MD. Therefore, prior to the data acquisition, the objective was to remove the scale restriction with milling.

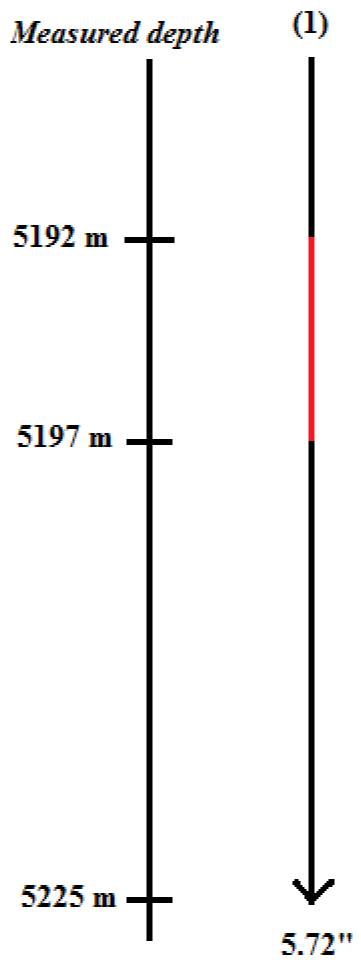

Figure 6-10 Line showing how deep the tool string went in the well, "Statoil Well D"

(1) The milling tool string with a tractor, a rotation assembly and a 5.720" scale mill bit was RIH and milled the scale restriction from 5192-5197 m MD in 7,5 hours. During the milling, a rate of 15 lpm with MEG was injected. The milling assembly was run in hole to 5225 m MD to verify no scale below the expected scale depth.

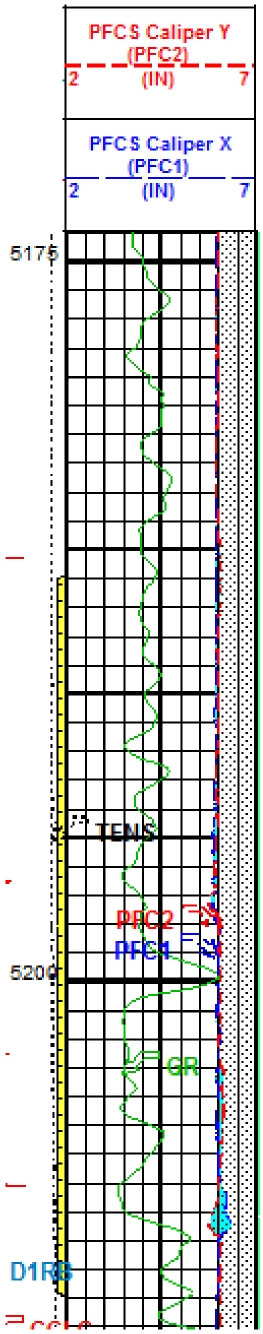

Figure 6-11 caliper log [42]

The figure above (figure 6-11) shows the caliper log from the PLT run carried out for data acquisition after the scale milling job. It shows that the restriction between 5192-5197 got removed. The operation was therefore considered as successful.

7 Discussion and analysis of the case histories

In this chapter different aspect of planning and carrying out a scale milling operation will be discussed. Also the scale milling operations presented in the case histories in chapter 6 will be compared and analyzed. The aim is to see if it is possible to draw something out of the operations and see if there is an optimal way of performing a scale milling job.

Knowing where the scale is located in the well and the thickness and length of the scale restrictions, is important when planning a scale milling job. The length of the scale restriction indicates if there are only small scale bridges in the well or if there are long scale restrictions, where continuous milling is needed for several meters down the well. If the scale restriction in a well is relatively long, the need for a hole opener may arise. The hole opener is used to avoid a spiral shape of the milled hole and to remove the scale that the mill bit may not take. The hole opener can also be used if the wanted mill bit size is not available. Knowing the minimum inner diameter (ID) at the scale restrictions helps deciding if the ID is big enough to produce or inject fluid through, for removal of scale cuttings, or if the ID is too small and a bailer is needed instead. The minimum ID in the well is also an important factor when it comes to choosing the correct size of mill bit to use. A too small outer diameter (OD) of the mill bit will lead to that the mill bit will not be in sufficient contact with the scale restriction. All of this information can make the planning easier and the scale removal approach better. The information can be gathered by running a caliper in the well. A caliper is a logging tool that measures the internal diameter of the pipe and can thereby indicate where the scale has deposited.

When it comes to the choice of tool string setup there are many elements to consider. The tool string should have an OD that gives a sufficient passageway for the cuttings around it. The optimal choice of OD should also decrease the risk of clogging of scale around the tool string. If the passage between the tool string and the tubing wall is too small, there is a risk that the scale cuttings accumulates around the tool string and thereby stops further milling. What type and size of mill bit that is chosen are dependent on the minimum ID in the well and the expected type of scale. The WOB delivered from the tractor and the torque from the rotation assembly should also be taken into consideration when choosing the right mill bit. The same type of mill bit can in principle be used for both hard scales like barium sulfate and for softer scales like calcium carbonate. But the difference is that more WOB and torque is needed on the mill bit in a barium sulfate scale milling job than in a calcium carbonate scale milling job, to achieve the same progress.

The highest risk while milling is usually the risk for getting stuck with the milling bit. The WOB should always be controlled and regulated to minimize the risk of stalling out with the bit. Too much WOB will only make the bit stall out while too little WOB will not give any milling effect. The WOB is seen from the head tension measurement. The milling bit stalls out if the WOB gets too high and the maximum torque available is not large enough to rotate the bit. One of the disadvantages with wireline milling is that it delivers much less torque, RPM and pulling strength than CT or snubbing can deliver in a milling operation.

Taking measurements during the scale milling job is also crucial for optimizing the operation. Some of the important measurements taken are head tension, internal temperature in the tool string, tension on cable and the current used. The head tension is important for controlling the WOB and preventing stalling of the bit, to get a more efficient milling operation. The internal temperature in the tools should be controlled to avoid the tools getting hotter than rated for and for reduce the number of failures. Tension on cable must be monitored to avoid exceeding the cable limitations when pulling the cable upward, to prevent getting stuck and to reduce the risk for fish in the well. The current measurements can give an indication on progress made from the scale milling.

Removing the milled scale is an important part of the milling operation because the scale cuttings can cause severe problems or lack of milling progress if it is not removed. A disadvantage with wireline milling is that it is not possible to circulate fluid through the bit which makes the cleanout of scale cuttings more difficult [32]. The scale cuttings can only be removed if there is enough injectivity, to inject a fluid to pump the cuttings down in the well, or if there is enough productivity, to flow the well to produce the cuttings to surface. The removal of scale cuttings is also dependent on having injectivity or productivity from open zones below the scale restriction. If the scale has fully plugged the tubing i.e. it is not possible to flow or inject through the scale restrictions, the alternative is to use a bailer between every milling run to remove the scale cuttings. It is also possible to use a type of integrated bailer in the tool string which bails and collects the scale cuttings while you are milling, however, the capacity is limited.

If the operational planning is not good enough and rapid decisions are taken, the risk for something going wrong during the milling operation is higher. In RLWI operations this is also more crucial because tripping the tool string in and out of the hole is more time consuming than in conventional wireline operations. The time it takes is dependent of how deep the tool string is going in the well, but it may take approximately 16 hours tripping in and out of the hole with an average wireline speed around 20-30 m/min, including time spent rigging down the tool string and prepare the next tool string.

Taking regular PUW is normal during the milling process. This is done to verify that the tool string is not stuck and to check that the tension on the cable doesn't exceed the maximum cable strength. When taking PUW the tool string is lifted upward to measure the required tension to pull the tool string out of hole. This tension is compared against the maximum available cable tension to see if it is possible to pull the tool string out of hole without exceeding the cable limitation. This is particular important in highly deviated and horizontal wells where the friction may be high. High PUW can be a consequence of high friction in the well but it may also occur if the mill bit is stuck in the scale or if there is clogging of scale behind the mill bit.

Different factors like hardness of the scale or the conditions in the well affect the milling progress. Hard scale like barium sulfate takes longer time to mill than calcium carbonate which is a softer scale type. The longer time it takes to mill the scale the more likely the equipment will fail over time because of wear and increasing internal temperature in the equipment. The risk for equipment failure increases with higher temperatures in the well. High internal temperature in the equipment may lead to short circuit and equipment failure. Also the type of fluid you have in the well affects the operation. There is higher friction in wells containing gas than wells containing oil. This will have an effect on the tension on the cable. In addition, a liquid at the milling depth will help to dissipate generated heat.

The effect of acid on the scale is difficult to predict. If the scale doesn't dissolve properly there is a chance that the partly dissolved scale could clog the milling bit [4]. Therefore the use of acid should only be used if the effect of the acid on the particular scale in the well is known. The use of chemicals is also limited by the thickness of the scale. The chemical needs to be in contact with the scale to get any effect. Therefore mechanical scale removal is often preferable over chemical dissolution when you have thick scale restrictions, especially if the scale precipitation is located in the tubing [43].

Short summary of the case histories

A. When milling in "Well A" there were a lot of problems with short circuit of equipment and stalling of the bit. The milling was finally aborted because of lack of progress and problems. The caliper showed that some of the scale was removed.

B. In "Well B" the milling operation was considered as successful. A 19 m long scale bridge was removed in 7.5 hours, another one at 119 m was removed during 16 hours and finally a 24 m long scale bridge was removed in 14 hours. The milling job was considered as successful.

C. Scale in "Well C" was not expected in the well and therefore it was not planned for milling of scale when an intervention was performed on the well in May 2010. As the restriction in the well was discovered milling equipment was mobilized, but the milling was not successful and fish was lost in well. When the fishing job was finished, it was decided to stop further milling and rather go into the well at a later stage. A new and planned scale milling job was performed on the well later in 2010. Acetic acid was injected while milling. A caliper log showed that there was still scale left in the well after the milling.

D. Scale milling in "Well D" was considered as a successful operation as 5 m of scale was removed in 7,5 hours and the caliper log after the milling showed no scale left in the well.

In the four case histories from the Smørbukk field there were dissimilarities between the wells that made the milling approach different for each operation. The amount of scale in the wells varied in both thickness and length, and so did the choice of mill bit and bit size for each operation.

The available information about the amount of scale in the well varied in the four operations. The operation in "Well B" was the only one where a caliper was run in well before the milling started. This gave a good picture of the scale restrictions in the well and probably made the choice of milling approach easier. In "Well A" and "Well D" there were no caliper run in well before the milling started, instead the milling approach was based on a caliper log from previous operations in the wells that showed the scale restrictions. In "Well C" no caliper was run before milling in neither the first operation, when the scale restriction was found, or in the second operation.

The scale milling operations show the importance of having control on weight on bit. Stalling out and getting stuck with the mill bit while milling were present in well A, B and C and was one of the main reasons for problems with the milling operation. As a consequence of this, the tool string had to be pulled out of hole several times. As mentioned earlier, tripping in and out of hole is time consuming and leads to loss of both time and money.

The different milling equipment and the tractor used in the operations stopped working several times due to short circuit. The Smørbukk field has high temperatures up to 165°C and this can be one of the reasons for the short circuits and equipment failure. Different equipment is only rated for a certain temperature and can just work in higher temperatures than rated for in short periods before they fail. Another reason for the equipment failure may be the load that the equipment experience when milling for a long time which can lead to an increased internal temperature in the equipment and cause the equipment to fail.

The amount of scale removed, and how fast it was removed, varied in the operations. In “well B” 19 m of scale was milled in 7.5 hours, while in well D 5 m of scale was milled in 7.5 hours. The variation in the time it takes to remove the scale may be dependent on the thickness of the scale restrictions, the hardness of the scale and also the type of bit used.

Acid in combination with milling for removal of scale was only used in “Well B” in the second operation. In the first run 4m^3 acetic acid was injected while milling, but the mill bit got stuck and no milling progress was made. Thereafter, 10m^3 acid was injected while stuck. In the second run 8 meters of scale were milled. When the tool string was retrieved to deck it was seen some scale on it. The PLT tool string run in well after the scale milling run was coated with scale when it was retrieved to deck. As a consequence the well was flowed to remove the dissolved scale and a new PLT tool string was then run in well. It is difficult to conclude if the coating is a consequence of the acid treatment, however, the tools run after the flowing was not coated. This may indicate that some scale has been dissolved and produced out of the well.

In “Well C” the milling equipment for the first operation was rapidly mobilized when a scale restriction was discovered in the well. The milling was not seen as successful due to several tool failures such as gas influx in the tractor and loss of tool string in the well. The problems may come from quick decisions and planning, but there may also be other factors effecting the operation.

When the head tension measurement was lost in “Well A” the WOB got more difficult to control. This occurrence is seen in figure 5-7 in chapter 5.2.1. The stable milling periods got shorter and the bit stalled out more often than in the previous milling run (see e.g. figure 5-6), where head tension measurements were available. This occurrence shows the importance of taking measurements during a milling operation to have the best control over the milling.

8 Conclusion

This thesis has given a general introduction to scale formation and has looked into both preventive methods and removal approaches for controlling scale in wells. The thesis has had a special focus on removing scale with wireline milling and therefore important aspects of milling operations have been presented. The objective has been to look at different aspects of a wireline scale milling operation to see if there are parts of the operation that can be improved. This includes looking at the planning part of the operation to best practice during the scale milling. Four scale milling operations from the Smørbukk field in the Norwegian Sea have therefore been studied.

The following conclusions can be made:

When carrying out a scale milling operation; as much as possible information about the scale, and other well conditions, should be obtained before the scale milling start. This can be information about the scale type, where it is located, and the length and thickness of the scale restrictions. Other important information is temperature, pressure and fluid in the well. This can make the choice of equipment easier and reduce the risk for something going wrong during the operation. A caliper should be considered to be run in hole before the scale milling starts, instead of only looking at logs from previous operations, or run in hole without any information about the scale restrictions. Lack of information around the scale in the well can lead to increased trips in and out of hole. In a RLWI operation, a trip in and out of hole is time consuming and has large impact on the cost of the operation.

The weight on bit should be controlled carefully throughout the milling operation. The correct weight on bit is crucial to avoiding stalling out with the bit. The tool string must therefore contain a head tension device which gives correct WOB measurements during the scale milling.

Real time measurement taken during the scale milling is important for having optimal control over the operation. An example of this was seen from the plots with different measurements in chapter 5.2.1. The mill bit stalled out several times and the stable milling periods got shorter when the head tension measurement was not detected compared to earlier run where head tension measurements were available. The operator must therefore monitor these measurements carefully and know how to react to changes.

For operations in wells with high temperatures the equipment should be pre-tested in the present well conditions. This should be done to see how long the equipment can work before it fails. The testing can be a good measure to prevent equipment failures and short circuits during the milling operation. It can also decrease the need for tripping in and out of hole more than planned for. An alternative pre-testing is to develop new and better equipment that can cope with the high temperatures or install a type of cooling system in the tool string, which cools down the tool during the operation.

The removal of scale cuttings is very important during a milling operation. If the cuttings are not sufficiently removed there will be an accumulation of cuttings around the mill bit and no progress in the milling. New mill bits which better removes scale cuttings away from the bit should therefore be developed.

The effect that acid has on scale is difficult to conclude based on these case histories, and should be further investigated.

From the case histories it has been difficult to extract the reason for the technical decisions taken during the operation. It can be advantageous to have more detailed reporting related to the choice of equipment for solving the milling problems. Better information can be used to make a road map for these purposes.

The overall experience from the scale milling operations emphasizes the need for detailed planning of milling operations. Experience, equipment limitations and the different aspects of a milling operation should be thoroughly addressed before one start to mill the scale. This may help to reduce the number of problems during the milling operation.

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