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I. ACKNOWLEDGEMENTS

II. ABSTRACT

With its wide application in areas such as electronics, the car-, machine- and tool-making industries, energy technology, the optics industry, and textile, environmental, and medical technology, plasma technology is improving the quality and performance of many products and processes. Similarly, this thesis work researches into the laboratory-scale feasibility of the use of plasma technology to remove scale.

Scale has been a long-standing challenge to the effective production of oil and gas from various petroleum fields across the world. Though there are various solutions utilised in the industry, they have been questioned of their environmental-friendliness, cost-effectiveness, and operational-efficiency. In view of these major industrial concerns, plasma technology presents industry professionals with an approach which is more environmentally-friendly, cost-effective, and operationally-efficient.

This thesis work thus takes a look at the opportunities, challenges and remedies of the use of plasma technology in the removal of scale. From an experimental point of view, the thesis work attempts to establish the viability of using plasma-based technology to remove scale during the production life of a well.

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VI. ABBREVIATIONS

A	Area	MW	Megawatt
BHA	Bottom Hole Assembly	GPa	Gigapascal
BOP	Blowout preventer		
D	Diameter		
HTHP	High pressure high temperature		
HV	High voltage		
ID	Inner Diameter		
K_{sp}	Solubility product		
kV	Kilovolt		
LIP	Lower Intervention Package		
LWI	Light well intervention		
NCS	Norwegian continental shelf		
NORM	Naturally radioactive material		
OD	Outer diameter		
PCH	Pressure control head		
PWRI	Produced Water Re-Injection		
RLWI	Riserless light well intervention		
ROP	Rat of penetration		
SIWHP	Shut in wellhead pressure		
SPM	Side pocket mandrel		
SR	Saturation ratio		
TSM	Turbo Scale Mill		
ULP	Upper Lubricator Package		
V	Volume		
WL	Wire line		
WOB	Weight on bit		
$\varepsilon_{concrete}$	Permittivity constant for concrect		
ε_{water}	Permittivity constant for water		
μs	Micro Second		

1 Introduction

As oil and gas exploration gets more complicated and into more dangerous environments, it becomes necessary for oil and gas companies to explore more efficient ways of production. A very big challenge to the oil and gas industry is scale and its control costs the industries several billions of dollars annually. This research work is based on an alternative technology to the effective remove of scale, namely plasma based removal technology.

1.1 Background

The author of the thesis saw the potential of using plasma drilling technology for removal of scale when he had a internship at NASA Ames Research Center, California. The aim of the three months long internship was to find a solution on the cutting transport challenges faced on the planet Mars. The plasma drilling technology was and is under development to drill on Mars. However, this thesis is to investigate if there can be possibilities to use the technology in the oil and gas industry.

Scale formation is the deposition of inorganic salts on surfaces which result from the precipitation of the salts from aqueous solution (Kelland M. A., 2011). Apart from the oil and gas production, water transportation and hydro power generation are few industries faced with scale formation. Scales, among all other water-related oilfield production problems (corrosion, gas hydrate), can cause a fall in production from its peak to zero within 24 hours. This was evident in a North Sea Well in the Miller field. Most oilfields in North Sea and Canada are prone to scale and it is considered as a top production problem. The costs to remove and handle the scale precipitation usually results in hundreds of millions of dollars per year to production companies (Mike Crabtree, 1999).

Scales are either formed from direct precipitation from naturally occurring reservoir water or from produced water saturated with scale components due to incompatible waters downhole which resulted from water injection as an Enhance oil recovery technique. Hence wells producing water have a high tendency of scale deposition. Scales can either be deposited in near wellbore reservoir pores and fractures where they reduce porosity and permeability or may be deposited in perforations, casing, flow conduits, completion equipment, and pumps and even on surface facilities and result in fluid flow restrictions. The nature of scales is such that once they are formed, if not treated will continue to grow thicker (Mike Crabtree, 1999).

The focus of this thesis is to describe scale and the processes of scale formation, the types of scales usually encountered in the oilfield industry and the problems they pose to production engineers. A detailed description of scale detection and its potential of forming will be looked at including scale handling, control and prevention techniques.

Coiled tubing and wireline equipment for mechanical removal of scale and mechanical wireline milling will be described in details. However, this thesis will have a special focus on the application of plasma technology for scale removal.

Despite the availability of an avalanche of remedies to the formation of scales, these traditional methods of scale removal lead to wear, corrosion, sometimes total removal of tubing, high installation cost, and low ROP. This thesis will thus suggest an alternative solution to a better, more efficient and cost-effective method to scale removal.

1.2 Problem formulation

There have been several studies into the approach to removing scale in an environmentally friendly, cost-efficient and operationally-safe manner. Despite some success chalked, these approaches continue to show signs of inefficiency in their use. This thesis will thus investigate the following;

1. By what means can plasma technology be transported into the oil and gas field to aid in the efficient removal of scale?
2. Will the use of plasma technology be environmentally-friendly, cost-effective, and operationally-safe to workers?
3. How can this technology be scaled from the laboratory to industry?
4. The research and laboratory work to be conducted will help unearth solutions to these critical industrial concerns.

1.3 Objective

The objective of this thesis is limited to experimental design and testing. The activities are:

a) Literature study on scaling and scale removal.
b) Review of plasma technology.
c) Design concepts for a WL descaling tool.
d) Design of experimental setup and experiments performed according to the concept design.
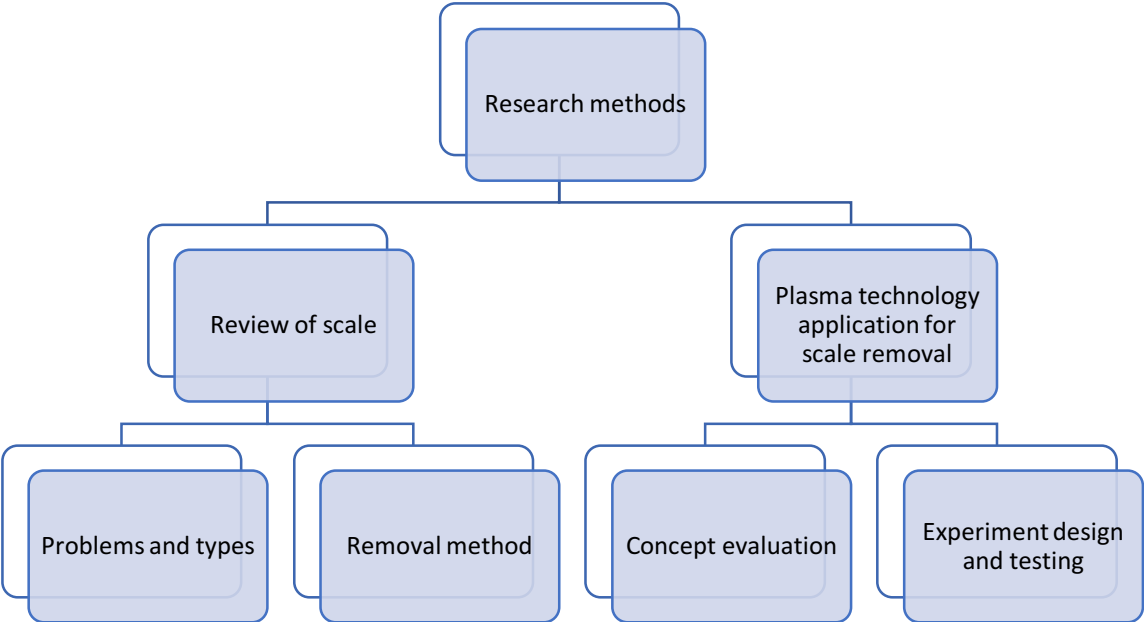
Figure 1: Shows the summary of research methods used in this thesis

2 Literature study

This thesis begins with some background literature that presents the fundamental study of scale precipitation, types of scale, problems caused by scale and current scale removal technique. This background study of current technology and approach to scale removal is necessary for understanding the concept behind the use of plasma technology.

2.1 Description of the scale Problem

2.1.1 Formation of Scales

2.1.1.1 Solubility

The solubility of a particular substance (salt) in a particular solvent (water) is the maximum amount of the substance that can dissolve in a given amount of the solvent at a specific temperature and pressure. At this point, the solution is said to be saturated. A solution is saturated when equilibrium is established between the solute and the solvent at a particular temperature. An increase in the temperature and pressure of a saturated solution will allow for the dissolution of more solute until it can no longer dissolve anymore salt. The resulting solution is said to be supersaturated. The degree of supersaturation, which is referred to as scaling index, is the driving force for the precipitation reaction. Other factors that affect scale precipitation, deposition and crystal growth can be summarized as: temperature, pressure ionic strength, evaporation, contact time and pH. Hence there is a high certainty of scale formation provided supersaturated conditions are high. (Abu, 2007) This means that a decrease in the temperature or pressure of the solution will result in precipitation of salt, a general rule-of-thumb.
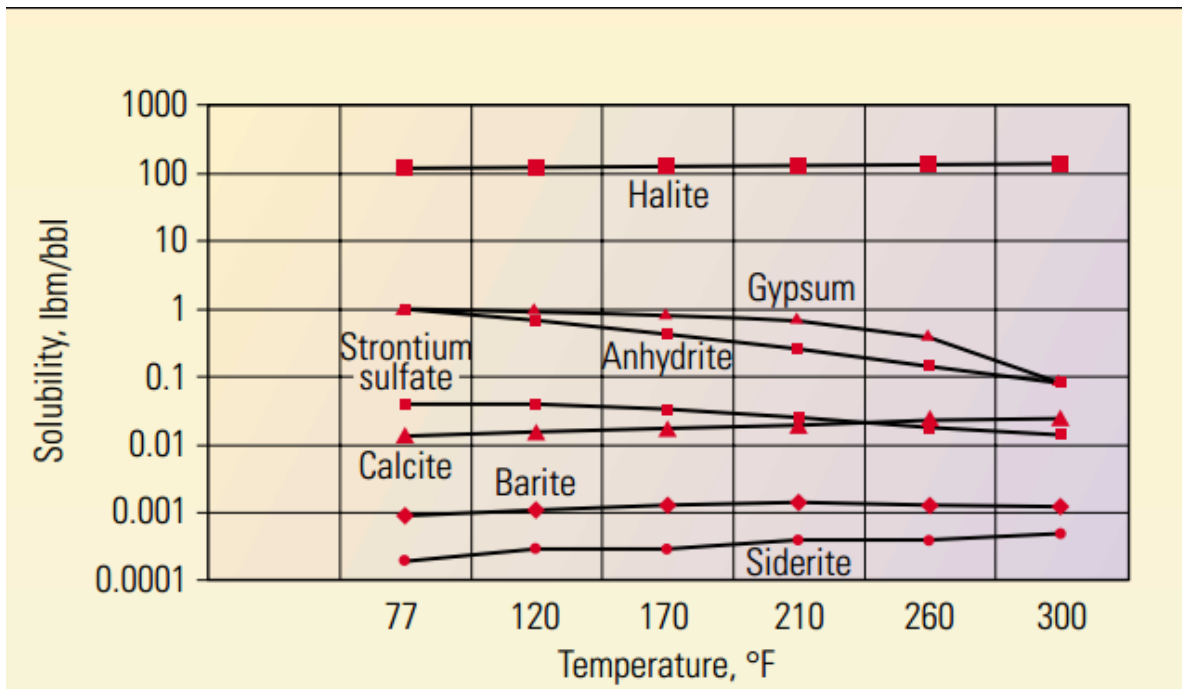
Figure 2: *Mineral Solubilities versus Temperature (Mike Crabtree, 1999)*

However, not all scales operate on this principle. Typical example is calcium carbonate which becomes more insoluble with increasing temperature and a solution at equilibrium. $CaCO_3$ will precipitate as the temperature increases. Lead and zinc sulfide solubility is much lower even than iron sulfide, which is the common sulfide in oilfield environment. Solubility of both lead and zinc sulfide increases with increasing solution pH (Yassin, 2007).

2.1.2 Solubility Product (Ksp)

Solubility product is a tool for determining scale precipitation potential. Solutes usually separate into their ionic constituent when in solution and various levels of interactions between these ions and solvent occur when in solution (ionic activity).

The product of any salt's ionic activities gives it solubility product, K_{sp}. The solubility product is a measure of how many moles of ions per unit volume of solvent that should be present in a system before a salt precipitates out. K_{sp} vary with solvent. A low K_{sp} value means that little salt will be dissolved in the solvent hence the name sparingly soluble salt (Grimholt, 2010).

For a hypothetical equation;

$$AB \rightarrow A^{2+} + B^{2+} \tag{1}$$

$$K_{sp} = [A][B] \tag{2}$$

The solubility product can also be expressed as:

$$K_{sp} = m_{Ae}m_{Ae} \cdot \gamma^A \gamma^B = a_{Ai}{}^n a_{Bi}{}^m \text{ (at equilibrium)} \tag{3}$$

Where; $m_{Ae, }m_{Ae}$ = molarities of ions A^{2+} and B^{2+} at equilibrium

γ^A , γ^B = activity coefficients of A^{2+} and B^{2+}

Saturation ratio (SR) calculated as

$$SR = a_{Ai}{}^n a_{Bi}{}^m / K_{sp} \tag{4}$$

Is used to predict precipitation of scales. When SR > 1 precipitation will occur. SR values are both temperature and type of scale dependent. That is SR depends on the temperature at which scale is formed and the type of scale. For $CaCO_3$ precipitations at 80°C, SR values as large as 5 is required and for 120°C the SR value is 2.7.

2.1.3 Formation water, Produced water and Sea Water

An important parameter to consider when considering scale formation is water, since all naturally occurring water contains dissolved substances acquired through contact with mineral phases.

Formation water and Seawater are the sources of scale materials. Formation water which when produced becomes produced water is a complex mixture of dissolved and particulate organic and inorganic chemicals. The physical and chemical properties of produced water vary widely depending on the geologic age, depth, and geochemistry of the hydrocarbon-bearing formation, as well as the chemical composition of the oil and gas phases in the reservoir, and process chemicals added during production. Produced waters from the formation tends to have higher densities than seawater since produced waters have greater salinities than seawater.

No two produced waters are alike, hence region specific studies are done to address the environmental risks they pose upon discharge into the environment. Formation water contains a variety of naturally occurring compounds that were dissolved or dispersed from the geologic formations and migration pathways in which the produced water resided for millions of years. The constituents of this water are inorganic salts, metals, radioisotopes, and a wide variety of organic chemicals, primarily hydrocarbons. Formation water have same salt constituent as seawater even though many of them have their concentration ratios to be different in seawater and formation/produced water, possibly contributing to the aquatic toxicity of produced water. The most abundant inorganic ions in high-salinity produced water are, in order of relative abundance sodium, chloride, calcium, magnesium, potassium, sulfate, bromide, bicarbonate, and iodide. Sulfate and sulfide concentrations usually are low, contributing to high concentrations of barium and other elements that form insoluble sulfates and sulfides (Jerry Neff, 2011).

Due to high temperature and pressure at deeper depth in the subsurface, subsurface water tends to contain more dissolved substances than surface water. Hence all reservoir fluids and aquifer rocks are initially at equilibrium and contain large quantities of scaling materials some of which are at their saturation limit. Once production and Injection of fluids commences, the equilibrium state of the reservoir fluids and aquifer is perturbed since there are changes in pressure and temperature and stability. The degree of pressure and temperature reduction coupled with the degree of agitation will result in the precipitates (scale) which are deposited on surfaces (Mike Crabtree, 1999). Apart from factors such as pressure and temperature other factors like pH, and CO_2/ H_2S partial pressure could also contribute to scale formation (Yassin, 2007).

2.1.4 Forming Scale

The driving force for scale formation are temperature or pressure change, out-gassing, a pH shift, or contact with incompatible water. These factors can still be available with scale prone produced water being oversaturated but scales may not form. In order for a scale to form it must grow from solution.

Homogeneous nucleation is the first stage of scale formations where unstable clusters of atoms develop within a saturated fluid. The clusters form a solid structure with imperfect surface where further growth is going on which is triggered by local fluctuations in equilibrium ion concentration in supersaturated solutions. Subsequently, there is a growth of the crystals by ions adsorbing onto imperfections on the crystal surfaces causing crystal size increments. The energy for seed crystal growth is driven by a reduction in the surface free energy of the crystal, which decreases rapidly with increasing radius after a critical radius is exceeded. Hence large crystals favor continuing crystal growth, and also implies that small seed crystals may re-dissolve. Thus, given a large enough degree of supersaturation, the formation of any seed crystal will encourage an increase in the growth of scale deposits. Scale formation is both initiated and catalyze by seed crystal formation.

Heterogeneous nucleation is another mechanism of scale formation which involves a process where crystal growth tends to initiate on a pre-existing fluid-boundary surface. Locations where this mechanism can occur are

- Surface defects such as pipe surface roughness or perforations in production liners

- Joints and seams in tubing and pipelines.

Turbulence as earlier stated catalyze this mechanism of scale deposition. Thus, the accumulation of scale can occur at the position of the bubble point pressure in the flowing system. This is an explanation for rapid scale deposition downhole completion equipment. Scale Inhibitors were developed base on the understanding of nucleation phenomena and this inhibitors work in such a way to poison the nucleation and growth of scale which results in a reduction of the rate of scale formation to the bare minimal (Mike Crabtree, 1999), (Shutemov, 2013).
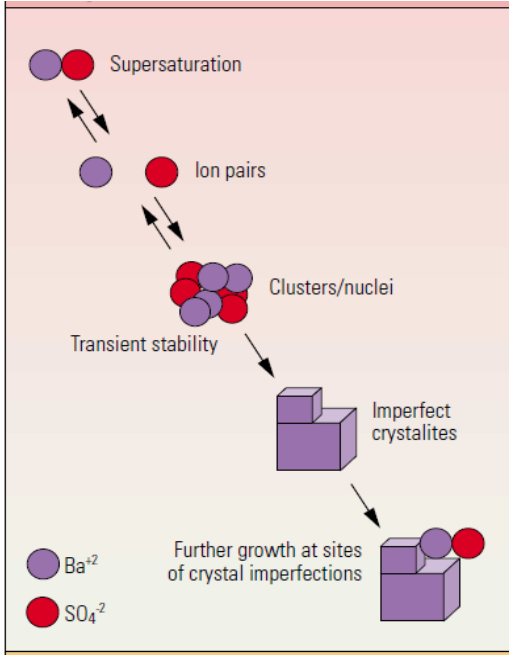
Figure 3: *Homogenous Nucleation (Mike Crabtree, 1999)*
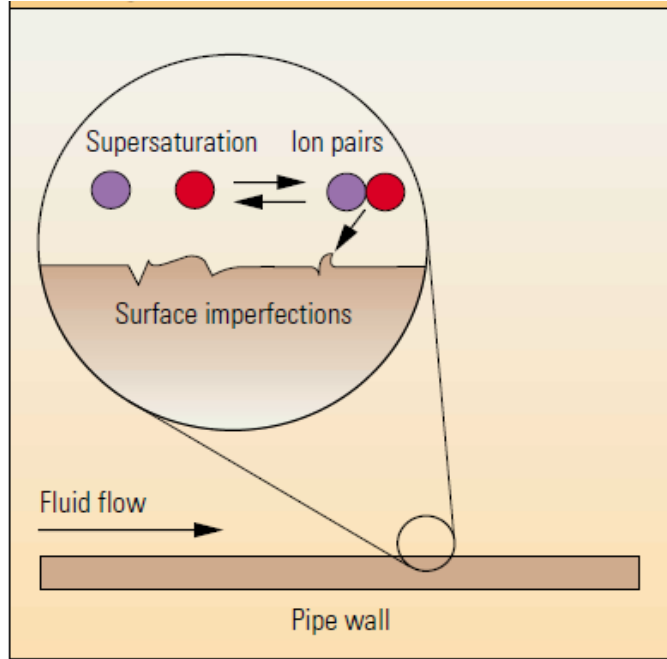
Figure 4: *Heterogeneous Nucleation (Mike Crabtree, 1999)*
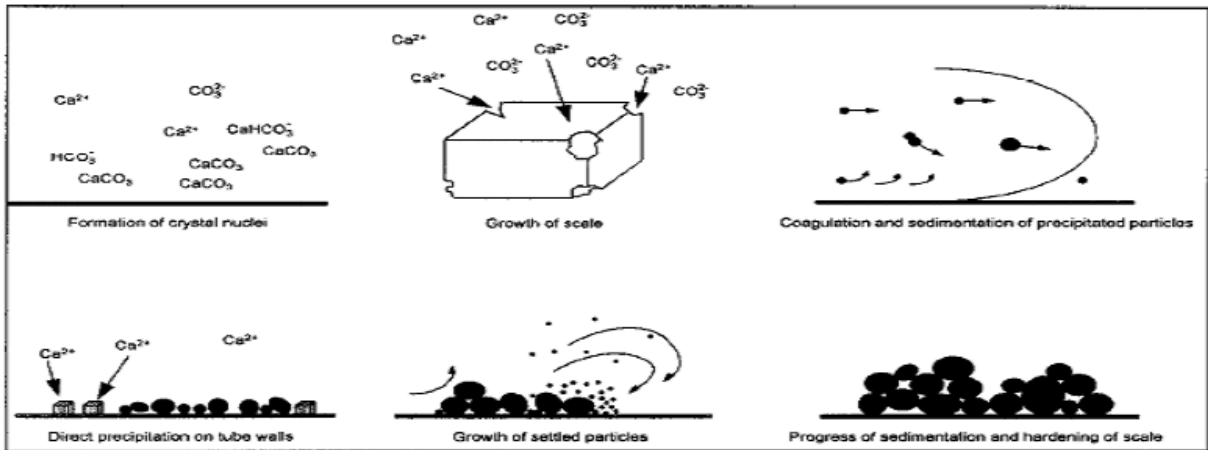
Figure 5: *Model of Scale Forming (Siegmeier) (Saaid, 2013)*

2.2 Types of Scale

The common examples scales encountered in the oil industry are calcium carbonate (calcite and aragonite) and sulfate salts of calcium (gypsum), strontium (celestite), and barium (Barite). Traces of radioactive radium ions are also found in the lattices especially that of barium sulfate which provides a radioactive principle for detecting this particular group of scales (Kelland M. A., 2011) . Other reported scales are iron oxides, iron sulfides and iron carbonate. Lead and zinc sulfide scale are of recent concern in North Sea oil and gas fields (Yassin, 2007).

- Table 1 summarizes the common types of scales usually encountered in the petroleum industry and the factors that influence their formation.
- Table 2 is a summary of oilfield scales, their solubilities and factors influencing their formation.
- Table 3 give a summary of other types of scales. The most predominant scale encountered in oilfield operations is calcium carbonate scale deposited from reservoir water as a result of pressure drops and changes in temperature during production of reservoir fluids. Calcium Sulfate, Barium Sulfate and calcium Sulfate are scales that occur as a result of mixing incompatible waters. Incompatible waters refer to waters that interact chemically and precipitate minerals upon mixing.
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A common example is sea water with high concentration of SO_4^{2-} and low concentrations of Ca^{2+}, Ba^{2+} /Sr^{2+}, and formation waters with extremely low concentrations of SO_4^{2-} but high concentrations of Ca^{2+}, Ba^{2+} and Sr^{2+} (Yassin, 2007).

Table 1 Common Types of Scales encountered in the petroleum industry and the factors that influence their formation.

Name	Chemical Formula	Primary Variables
Calcium Carbonate	$CaCO_3$	Partial pressure of CO_2, Temperature, total dissolved salts, pH
Calcium Sulfate: Gypsum Hemihydrate Anhydrite	$CaSO_4.2H_2O$ $CaSO_4.1/2H_2O$ $CaSO_4$	Temperature, total dissolved salts, pressure
Barium Sulfate	$BaSO_4$	Temperature, pressure
Strontium Sulfate	$SrSO_4$	Temperature, pressure, total dissolved salts
Iron Compounds: Ferrous Carbonate Ferrous Sulfide Ferrous Hydroxide Ferrous Hydroxide	$FeCO_3$ FeS $Fe(OH)_2$ $Fe(OH)_3$	Corrosion, dissolved gases, pH

Acid Soluble and Acid insoluble Scales

Scales are also group in terms of them being acid soluble or acid insoluble. This classification is important since it helps in knowing effective chemical methods for fighting different types of scales.

Acid Insoluble

Acid Insoluble Scales refers to the sulfate compounds of Barium, Strontium, or Calcium. A major ionic component of seawater is sulfate ion (SO_4^{2-}) which reacts with the following ions (Ba^{2+}, Sr^{2+} and Ca^{2+}) which are naturally found in formation water depending on the field's geological history. The above mention scales are sparingly soluble in water and as a result can precipitate out and form deposits.

Acid soluble scale
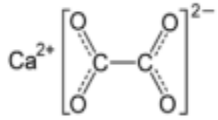
Salts of carbonates are usually acid soluble. Calcium carbonate, Iron carbonate, iron sulphide, zinc sulphide and lead sulphide are few to mention. The above mentioned Scales are by products of corrosion except for calcium carbonate. Other examples of acid soluble scales silica scales associated with injection water and halite scale associated with injection of CH_3OH into formation water. (Sulaiman, 2014)

Table 2 Oilfield Scales, Their Solubilities and Factors Influencing Their Formation

Mineral Type	Composition	Relative Solubility(mg/l)	Causes of Solubility Change
Calcite	$CaCO_3$	196	Partial Pressure of CO_2, Total Pressure, Total dissolved Solids, Temperature
Siderite	$FeCO_3$	100	Partial Pressure of CO_2, Total Pressure, Total dissolved Solids, Temperature
Barite	$BaSO_4$	44	Pressure, Temperature, Total dissolved Solids
Celesitite	$SrSO_4$	520	Pressure, Temperature
Anhydrite	$CaSO_4$	3270	Pressure, Temperature
Gypsum	$CaSO_4.2H_2O$	6300	Pressure, Temperature
Pyrite	FeS	105	Pressure, Temperature, Total dissolved Solids
Galena	PbS	0.006	Pressure, Temperature, Total dissolved Solids
Sphalerite	ZnS	0.09	Pressure, Temperature, Total dissolved Solids

Name	Chemical Formula	Mineral
Calcium Oxalate		Beerstone
Magnesium hydroxide Magnesium Oxide	$Mg(OH)_2$ MgO	Brucite Periclase
Silicates	$Me(Si_nO_x).yH_2O$	Serpentine, acmite, gyrolite, gehlenite, amorphous silica, quartz, cristobalite, pectolite
Aluminium Oxides Hydroxides	$AlO(OH)$	Boehmite, gibbsite, diaspore, corundum
Aluminosilicates Copper	$Al_xSi_yO_z$ Cu	Analcite, canacrinite noselite Metallic copper,cuprite(Cu_2O),tenorite(CuO)
Phosphates	$Ca_{10}(PO_4)_6(OH)_2$	Hydroxyapatite
Magnetite Or nickel Ferrite	$NiFe_2O_4$	Trevorite

2.3 Mechanisms of Scale formation

The formation of scales are generally classified based on three mechanisms.

The first being as a result of a decrease in pressure and /or increase in temperature of brine. If such changes result in fluid composition going beyond the solubility limit for a mineral, it will precipitate as scale. This phenomenon is called Autoscaling or Self-scaling which results in carbonate scales deposition usually in wellbore and production facilities. Sodium chloride scale also forms by this process. Also reduction in pressure during production of fluids containing acid gases outgasses the fluid, which raises pH and creates a favorable condition for scale deposition. The equation below summarizes the process of carbonate scale formation.

$$Ca^{2+}_{(aq)} + 2HCO_3^{2-}{}_{(aq)} \leftrightarrow CaCO_{3(s)} + CO_{2\,(aq)} + H_2O_{(l)}$$
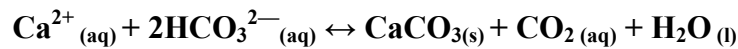
Carbonate Scales can also be formed through the process of Carbon dioxide flooding. Carbon dioxide is partially soluble in water which form weak carbonic acid upon injection as a secondary recovery technique. The acidic solution formed dissolve calcite formations. Subsequent pressure drops in the formation surrounding a producing well can cause CO_2 to break out of solution and cause carbonate scale to precipitate in the perforations and in formation. The chemical reactions are as follows

Dissolution of carbon dioxide to form weak carbonic acid

$$CO_{2\,(aq)} + H_2O_{(aq)} \leftrightarrow H_2CO_{3\,(aq)}$$
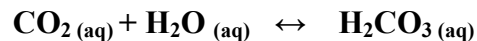
Dissociation of weak carbonic acid to form Bicarbonate and Carbonate ions

$$H_2CO_{3\,(aq)} \leftrightarrow H^+{}_{(aq)} + HCO_3^-{}_{(aq)}$$

$$HCO_3^-{}_{(aq)} \leftrightarrow H^+{}_{(aq)} + CO_3^{2-}{}_{(aq)}$$
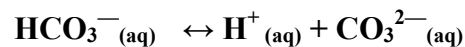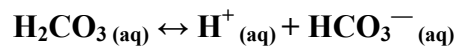
Reaction between Calcium ions and carbonate and bicarbonate ion

$$CaCO_{3\,(s)} + H_2CO_{3\,(aq)} \leftrightarrow Ca^{2+}{}_{(aq)} + 2HCO_3^-{}_{(aq)}$$

Overall Equations

$$Ca^{2+}{}_{(aq)} + 2HCO_3^-{}_{(aq)} \leftrightarrow Ca\,(HCO_3)_{2\,(aq)}$$

$$Ca^{2+}{}_{(aq)} + 2HCO_3^{2-}{}_{(aq)} \leftrightarrow CaCO_{3(s)} + CO_{2\,(aq)} + H_2O_{(l)}$$
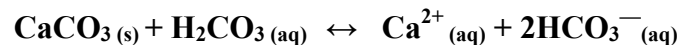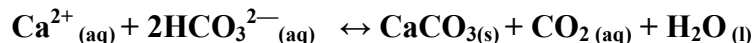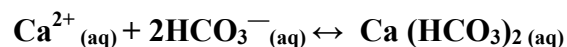
Mixing of two incompatible waters usually due to water flooding processes, most commonly formation water rich in cations such as barium, calcium and/or strontium, mixing with sulfate rich seawater, goes to the precipitation of sulfate scale which are deposited in the wellbore, production facilities and near wellbore. This mechanism is referred to as incompatible mixing. Near wellbore incompatible mixing subsequently results in a mixture of fluids with combined ion concentrations that are above the solubility limits for sulfate minerals. Calcium sulfate scale forms in limestone formations, and barium strontium sulfate scales form in sandstone formations. Below is the chemical equation for the process.

$$Ba^{2+}_{(aq)} (Sr^{2+} \text{ or } Ca^{2+}) + SO_4^{2-}_{(aq)} \leftrightarrow BaSO_{4(S)} (SrSO_4 \text{ or } CaSO_4)$$
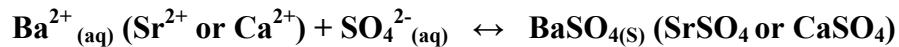
Other fluid incompatibilities include sulfide scale where hydrogen sulfide gas mixes with iron, zinc or lead rich formation waters.

$$Zn^{2+} + H_2S \leftrightarrow ZnS + 2H^{2+}$$

The last being concentration of salts due to dehydration or brine evaporation, resulting in salt concentration increasing above the solubility limit and goes to salt precipitation. Evaporation-induced scale is the term for this mechanism. It occurs in High-Pressure, High-Temperature (HPHT) gas wells where a dry gas stream may mix with a low rate brine stream resulting in dehydration and most commonly the precipitation of sodium chloride. Simultaneous production of hydrocarbon gas and formation brine (wet gas) can also results in scale formation. A decrease in hydrostatic pressure in production tubulars results in expansion or an increment in the volume of the hydrocarbon gas while the hot brine phase associated with the flowing stream evaporates. This results in dissolved ions being concentrated in excess of mineral solubilities in the remaining water. In high-pressure, high temperature (HTHP) wells, this is a common mechanisms for halite scale formation. However other scales may also form by this mechanism (Yassin, 2007) (Mackay, 2008) (Mike Crabtree, 1999) (Precipitation and Solution of Calcium Carbonate, n.d.) (M. Jordan, Nalco Champion; E. Mackay, Heriot Watt University, 2015).

Production systems that use steam flooding and Alkaline Surfactant flooding as Enhance Oil Recovery Techniques can experience Silica scale formation. Silica scale also occur from geothermal brine. Silica scale formation is based on mechanisms similar to the above mechanisms of scale formation. Briefly, due to the environmental conditions of exposure, saturated brines can become supersaturated. The deposits are commonly amorphous silica or colloidal silica. At pH (>9) or pH (<5) together with elevated temperature and low salinity, silica compounds are more soluble. The silicate deposits can be rich in iron, calcium, magnesium, sodium, or aluminum (M. Jordan, Nalco Champion; E. Mackay, Heriot Watt University, 2015).

The above mechanisms of scale formation are occurring simultaneously as well as both the homogeneous nucleation and heterogeneous nucleation. Hence it should be noted that no scale deposit is of single composition but a composition of other scales and organic impurities or organic contents of the reservoir fluids. However the composition can be one species dominant (Saaid, 2013).

2.4 Detailed Description of the Formation of Calcium Carbonate Scale and Sulfate Scale

This section presents a detailed description of the processes and the influencing parameters in the formation of Carbonate scale and sulfate scale. This scales are the most encountered scales and their formation represent two different mechanisms of scale formation. Also in terms of treatment Carbonate scales are of soft to medium hardness while sulfate scales are hard scales.

2.4.1 Carbonate Scale Formation

Though carbonate scales are the most common scales encountered in upstream oil and gas industry. Calcite, Vaterite and Aragonite are the various forms of carbonate scales of which calcite scales are the most common because calcite have a stable crystalline form. Calcium carbonate in its pure state have relatively large crystal. However due to co-precipitation with other scales and impurities the resulting scale deposits are characterized by finely divided crystals making the scales have homogeneous appearance.

Effect of Total Pressure

In a two-phase system calcium carbonate solubility increases with increased pressure. The increase in solubility is because an increased pressure increases the partial pressure of CO_2 and this in turn increases the solubility of $CaCO_3$ in water.(Fig) Increased pressure also increases the solubility due to thermodynamic considerations. Hence a reduction in pressure is most likely to result in precipitation. During production of fluids there are pressure drops along the flow paths of the fluids. If the pressure drops results in the fluid pressure being less than the bubble point pressure of the fluids, then carbon dioxide will evolve out of the solution into the gas phase and this will result in precipitation of $CaCO_3$. Phase separation usually occurs in flow conduits. Hence carbonate scale deposit are usually found in production tubings.
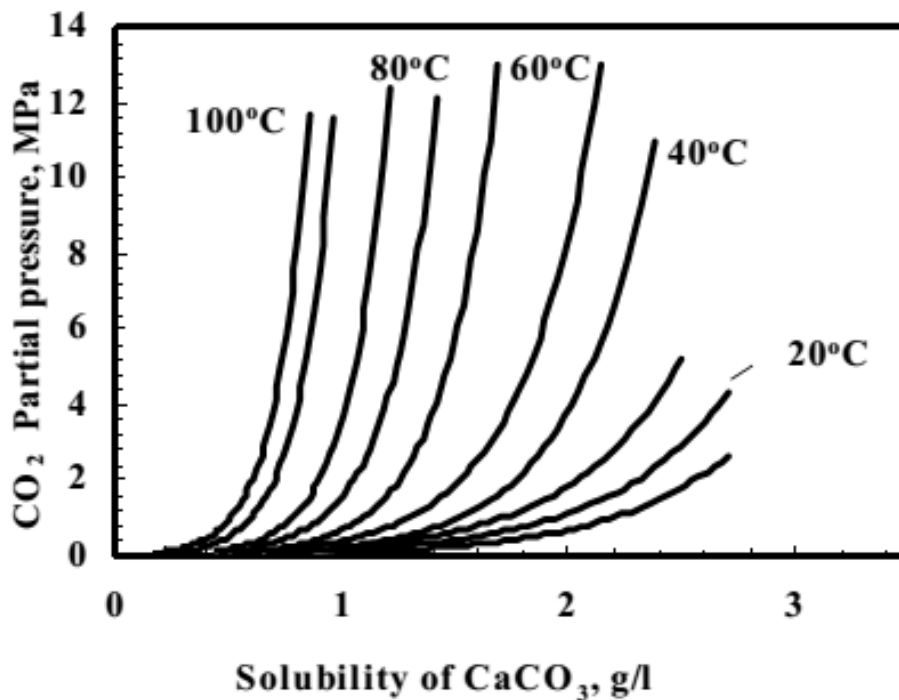
Figure 6: Effect of CO2 Partial Pressure on CaCO3 Solubility (J. Moghadasi, 2007)

Effect of pH

The presence of CO_2 in formation water affects solubility of calcium carbonate and the pH of the water since CO_2 dissolves in the water to form weak carbonic acid which lowest the pH of the formation water. However as fluid pressure drops CO_2 evolve out of solution causing pH increments. With a low pH, there is a less tendency of $CaCO_3$ precipitation. Conversely, higher pH, higher tendency of precipitation occurrence. Hence the cause of acidity or alkalinity is not of much concern.
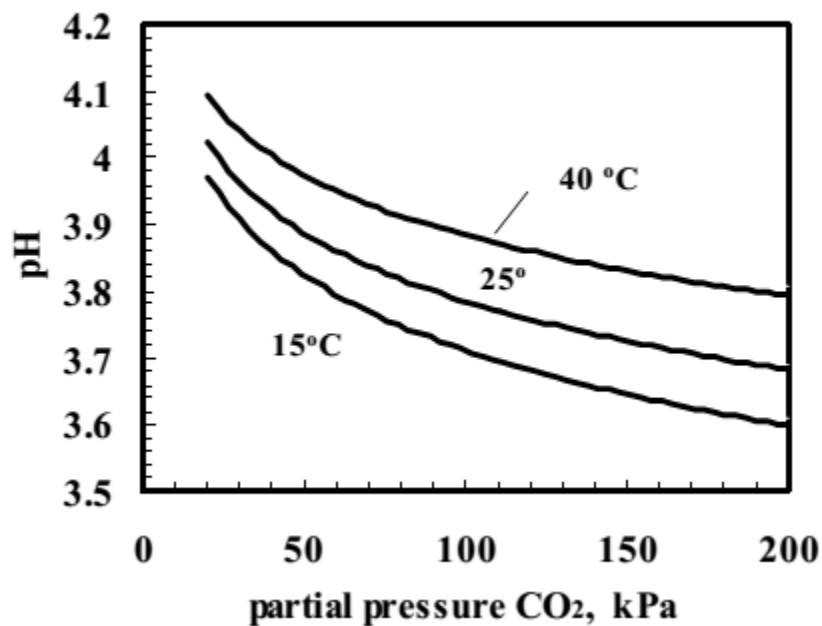
Figure 7: Effect of CO2 partial pressure on the pH of water (J. Moghadasi, 2007)

Effect of temperature

Unlike other solutes that obey the general rule of thumb of solubility, calcium carbonates behave otherwise. As temperature increase calcium carbonate becomes less soluble. This implies that increments in temperature are mostly likely to result in precipitation. As a result of the above explanation, non-scaling water at surface may become scaling in an injection well provided downhole temperatures are sufficiently high.

Effect of dissolved salts

Calcium carbonate solubility increases as the dissolved salt content of the water increases. Actually, the higher the total dissolved solids (not counting calcium or carbonate ions), the greater is the solubility of $CaCO_3$ in the water and the lower the scaling tendency, up to a maximum of about 200 g/l total dissolved solids. (J. Moghadasi, 2007)

2.4.2 Sulfate Scale Formation

Sulfate scales are formed when there is incompatible mixing of formation water and sulphate containing injected water (seawater) as described under the topic mechanisms of scale formation. Barium sulfate, strontium sulfate and calcium sulfate are examples of sulphate scales. Sulfate scale may form through the whole production system depending on the location of incompatible mixing.

Calcium Sulfate Scale

Calcium sulfate is a crystalline deposit that is very adherent to many surfaces. Its composition is of calcium and sulfate ions as the name suggests. However, other traces of ions can be found in association with this scale type since scales are not of pure composition as a result of co-precipitation. Calcium sulfate often co-precipitates with strontium sulfate.

Also, upon precipitation from production fluids, wax, rust and silt becomes components of this type of scale.

Types of Calcium Sulfate

Calcium sulfate crystallizes from aqueous solution in three forms: gypsum ($CaSO_4 \cdot 2H_2O$), hemihydrate ($CaSO_4 \cdot \frac{1}{2}H2O$), and anhydrate ($CaSO_4$). The stability of the three forms that is whether the deposition results in gypsum or hemihydrate or anhydrate scale depends strictly on temperature and ionic strength.

Solubility and Temperature and pressure Effect on Sulfate scale

According to Landolt-Bornstein, solubility of all calcium sulfate forms increases with temperature up to about 40 ºC, and then decreases with temperature. Anhydrite are less soluble in water than gypsum for temperatures above 40°C. Hence anhydrites are expected to be the dominant form of calcium sulfate scale in deeper hotter wells. The temperature at which the scale changes form from gypsum to anhydrite or hemihydrate is a function of many factors including pressure dissolved salt content, flow conditions, and the rate at which different forms of calcium sulfate can precipitate out from water solution. However there is difficulty in predicting which forms of calcium sulfate will precipitate under any given conditions.

Due to the low solubility of anhydrite, precipitates of anhydrites are expected above 40°C as compared to gypsum. However, gypsum may be found at temperatures up to 100ºC. Anhydrite precipitation from solution is mostly difficult, but with the passage of time, gypsum undergoes dehydration to form anhydrite. For flowing systems at temperatures above 100°C, precipitation of anhydrites is usually direct. But for quiescent systems, hemihydrate solubility becomes limiting. Conversion of hemihydrate to anhydrite is expected to occur with time.
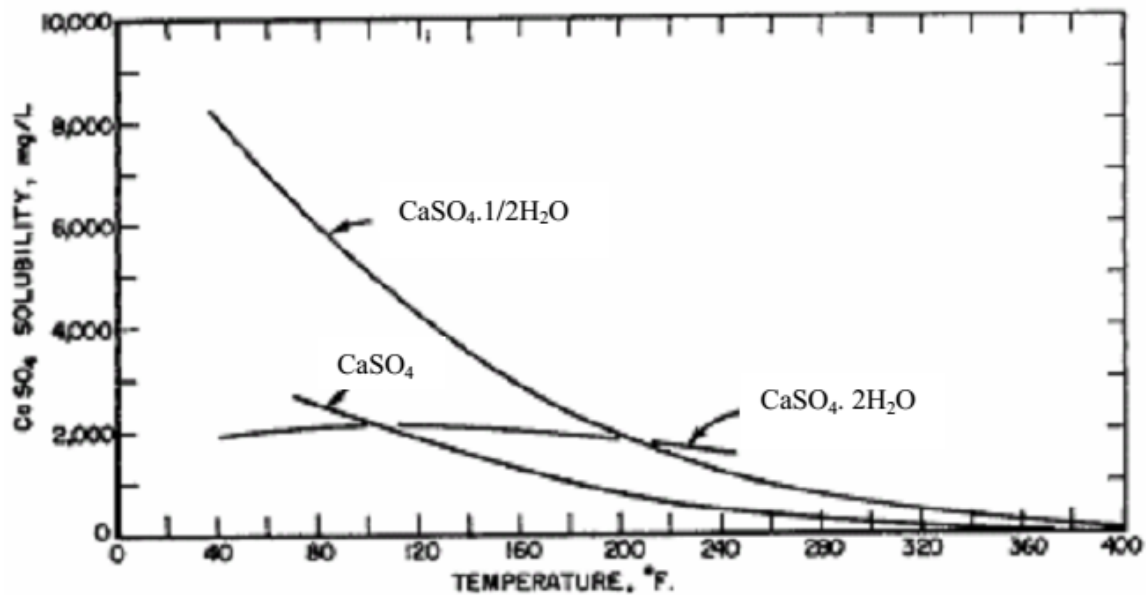
Figure 8: *Calcium sulfate solubility in water (Merdhah, 2007)*

Dickson et al. showed the effect of pressure and temperature on anhydrite solubility. The solubility of calcium sulfate in water increases with pressure. This increase in solubility is due to the fact that when the scale is dissolved in water, there is a decrease in the total volume of the system.

$$CaSO_4 + H_2O \leftrightarrow Ca^{2+} + SO_4^{2-} + H_2O$$

Pressure drop can be a major cause of calcium sulfate scale in producing wells and near the wellbore can create scale back in the formation as well as in the piping. Under downhole conditions, anhydrite or gypsum deposition is caused mainly by pressure drop, which has a stronger effect than temperature. Under downhole conditions, anhydrite or gypsum deposition is caused mainly by pressure drop, which has a stronger effect than temperature.

Effects of agitation and vaporization:

Agitation and vaporization can increase scale production. The evaporation of water reduces the solvent and results in making the solution supersaturated. Agitation causes the formation of crystal nuclei unto which precipitates attached themselves too and increase crystal growth.

Effect of ionic strength

Ionic strength is defined as:

$$I = \frac{1}{2}\sum C_i Z_i^2 \tag{5}$$

The solubility of calcium sulfate is strongly affected by the presence and concentration of other ions in the system.
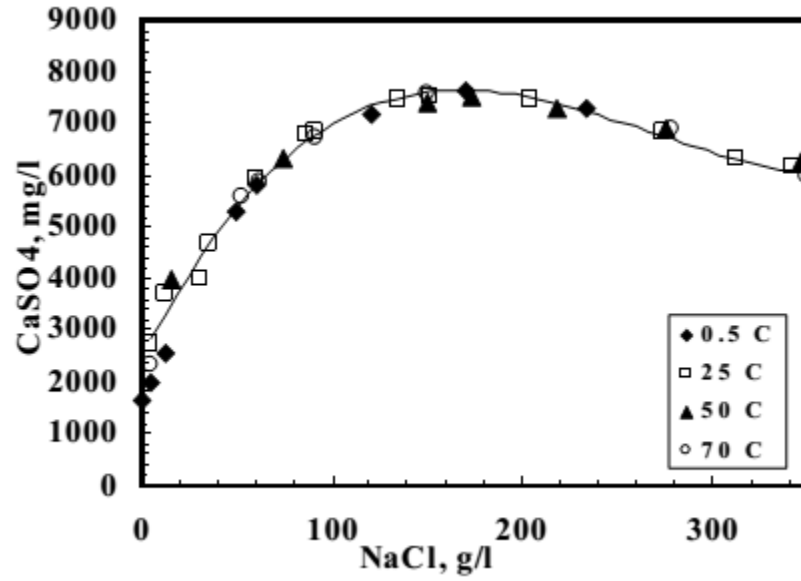
Figure 9: Solubility of Gypsum in NaCl Brines at Temperatures from 0°C to 70°C
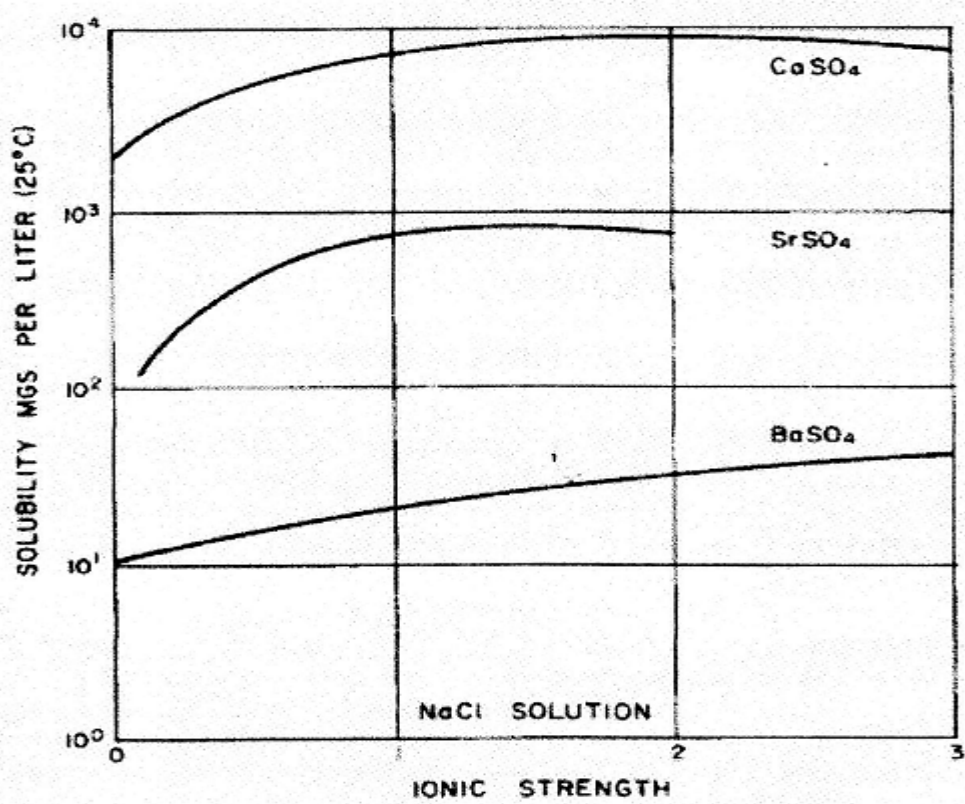
Figure 10: Relative Solubilities of Three Sulfates in Brine (Yassin, 2007)

Effect of pH on crystal growth

Schierholtz investigated the unseeded crystallization of calcium sulfate dihydrate and followed the change in calcium concentration during the initial induction periods and subsequent growth at pH values ranging from 4.5 to 6.6. Within this range, the pseudo first order rate constant decreased by a factor of three. It was concluded that nucleation of calcium sulfate dihydrate is affected by pH. Austin et al. studied the spontaneous precipitation of calcium sulfate phase from simulated seawater in the temperature range of 125 to 150ºC at pH 2.3 to 8. Under these conditions, the hemihydrate phase precipitated first and there was a relatively slow transformation to the anhydrite phase, the rate of which was increasing with temperature (J. Moghadasi, 2007).

2.5 Potential Scale Generation Operations

Some major activities or operations carried out on oilfield have a high tendency of scale formation. Most scale deposition are as a result of reservoir fluids production and Enhance Oil Recovery techniques such as water flooding and chemical flooding.

One operation during production with a high tendency of scale formation is commingled production, where wellstreams from various formations, reservoirs or individual wells are mixed together. Scale deposition is likely if fluids from the different reservoirs are incompatible. Other production operations or scenarios in which scales are formed are described in details under the section possible locations of scale formation.

Drilling and well completion operations are other operations; if the drilling mud or completion fluid is incompatible with the formation water scale deposition is likely (Statoil, 2007).

Disposal of oilfield waste such as produced water and drilling fluids by the method of reinjection into disposal wells or abandoned wells can result in scale formation due to fluids incompatibility (Bader, 2006).

Even scale control techniques can result in scale formation. Some scale inhibitors (e.g. phosphonates and polymers) used in treating scales can react with Ca^{2+} and/or Mg^{2+} present in the oil field brine to form a pseudo-scale which does not only look like a real scale, but causes the same problem like the real scale. There have been many instances of this occurrences. An example was a production well located in the Williston Basin of North Dakota (Saaid, 2013).

2.6 Possible Locations of scale formation

Scale deposition usually occurs at 6 important regions. These regions are as follows

- Near the injection well bottom hole

- In the reservoir between the injector and the producer

- At the skin of the producer well

- In the injector wellbore

- In the producer well.

- At the surface facilities

Apart from the listed general locations, some fields have experienced scale depositions at other locations (Saaid, 2013).

Bader gave a detailed possible locations of scale deposits throughout the flow path of water. The figure (Figure 8) below depicts the possible locations.
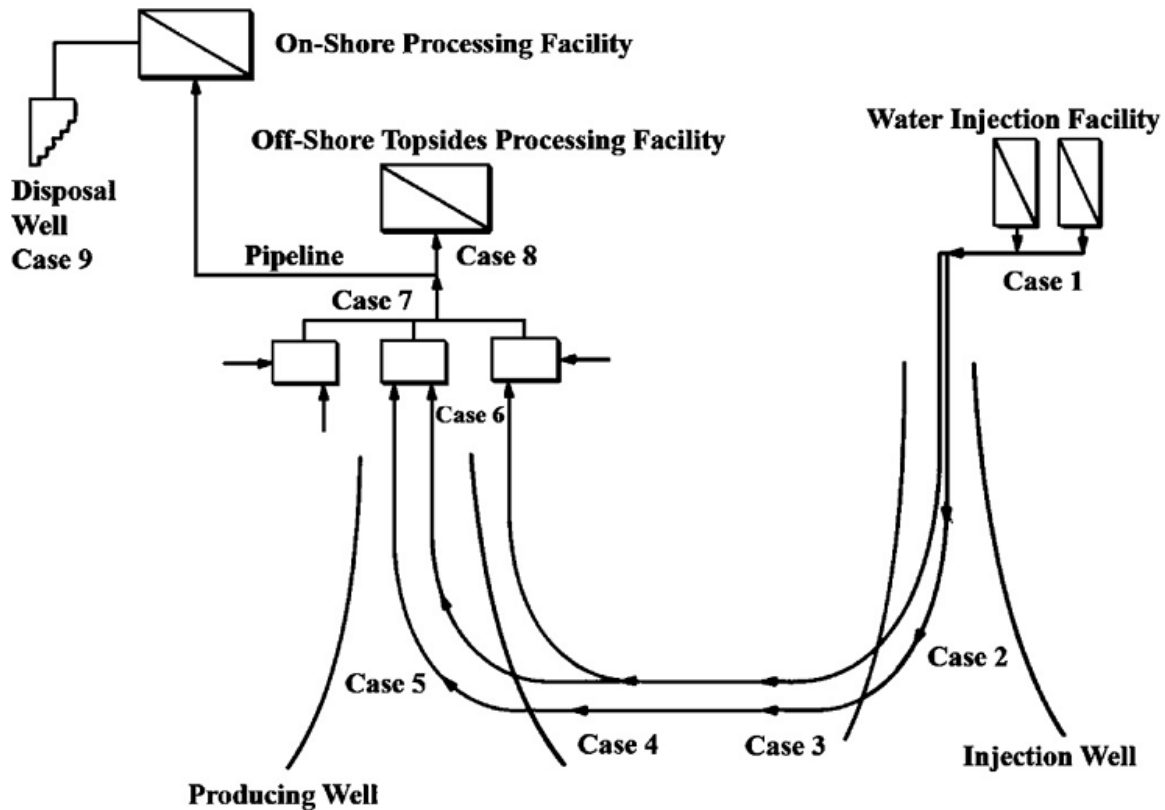
Figure 11: Possible Locations for Scale Deposition (J. Moghadasi, 2007)

- Case 1: At the surface water injection facility where incompatible sources of water 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.

- Case 5: Downhole in the reservoir where the mixed (injected and formation) 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.

- Case 8: At topside facility where produced fluids are mixed from different production zones to separate oil and gas from produced waters, or in pipelines that transport produced fluids to on-shore processing facilities.

- Case 9: At disposal wells where produced water is injected for final disposal (Bader, 2006).

According to Jordan et al (Moghadasi, 2010) the possible scale formation environments for sea water, aquifer, natural depletion and produced water re-injection is shown in the Figure below
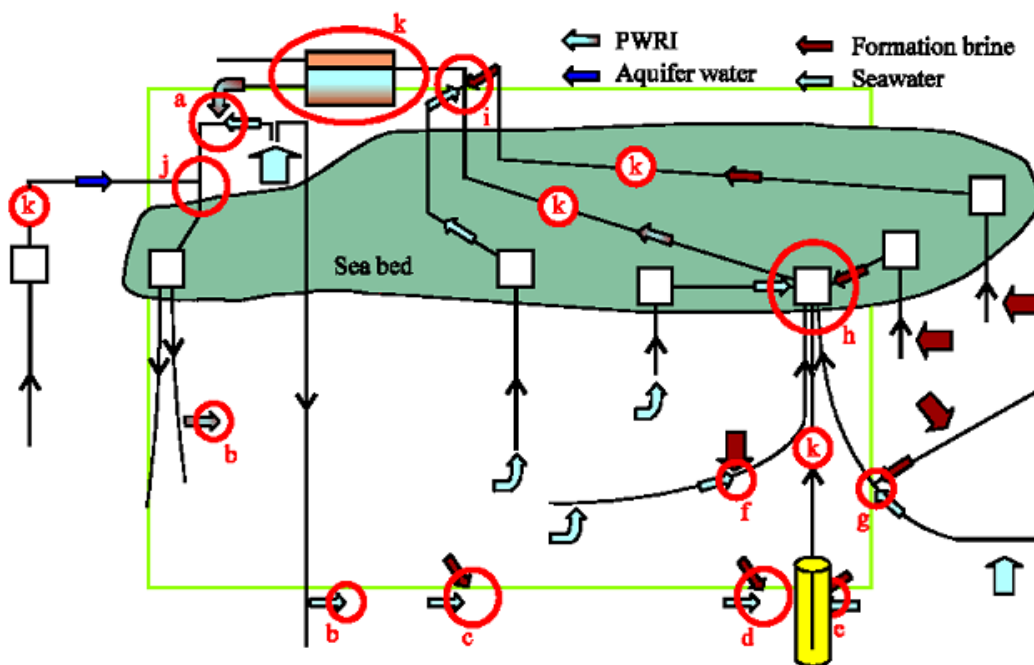
Figure 12: Possible Scale Forming Environments (Saaid, 2013)

a. Prior to injection, if seawater injection is supplemented by Produced Water Re-Injection (PWRI)

b. Around the injection well, as injection brine enters the reservoir, contacting formation brine

c. Deep in formation, due to displacement of formation brine by injected brine, or due to meeting flow paths.

d. As injection brine and formation brine converge towards the production well, but beyond the radius of squeeze treatment.

e. As injection brine and formation brine converge towards the production well and within the radius of squeeze treatment.

f. In a completed interval of a production well, as one brine enters the completion, while other brine is following up the tubing from a lower section, or as fluid pressure decreases.

g. At the junction of a multilateral well, where one branch is producing single brine and the other branch is producing incompatible brine.

h. At a subsea manifold, where one well is producing single brine and another well is producing different brine.

i. At the surface facilities, where one production stream is flowing one brine and another production stream is flowing another brine.

j. During aquifer water production and processing for re-injection, scale formation is likely by either self-scaling brine or mixing with incompatible formation brine.

k. During pressure reduction and/ or an increase in temperature within any downhole tube or surface processing equipment, leading to the evolution of CO_2 and to the generation of carbonate and sulfide scale if the suitable ions are present. Temperature reductions could lead to formation of halite scales if the brine was close to saturation under reservoir conditions (Moghadasi, 2010).

Figure 12 gives further details of possible scale deposition site and and mechanism of formation:

Production facilities

Injection facilities

Production well

Production well

Injection well

G   Casing leak

Producing zone

High   permeability
layer

F   E   D   C

Reservoir

Location	Change which could produce scale formation
A to B	Mixing of brines for injection
B to C	Pressure and temperature increase
C to D	Pressure decline and continued temperature increase
C to F	Solution composition may be adjusted by cation exchange, mineral dissolution or other reactions with the rock
D to F	Mixing of brines in the reservoir
E to J	Pressure and temperature decline. Release of carbon dioxide and evaporation of water due to the pressure decline if a gas phase is present or forms between these locations.
F	Mixing of formation water and injection water which has "broken through" at the base of the production well
G	Mixing of brines produced from different zones.
H	Mixing of produced brine with brine from casing leak

Figure 13: Possible scale deposition site and mechanism of formation

2.7 Problems caused by scale

One major problem caused by scales is corrosion to both downhole and surface equipment. One important condition for corrosion is that material's surface must be dampened by an electrolyte, which is a water solution that can conduct an electric current. Naturally occurring reservoir water contains dissolve salt which makes it a good electrolyte. Some salts do dissolve with a decrease in temperature and pressure rather than the general principle of precipitations with increasing temperature and pressure hence creating a good electrolyte. Other factors contributing to corrosion are pH, salt concentration, and oxygen concentration, along with the velocity of the flowing medium. Also as a result of turbulence flow of fluid during production, scale deposits or fragments that are carried in the flowing medium tend to scratch and erode the surfaces of tubulars and equipment, causing a reduction in the corrosion resistance ability of materials (Catherine Houska,CSI, TMR Consulting) (Mona El-Said, 2008).

Scales also cause equipment damage including coating and damaging downhole completions equipment, restriction to flow in flow conduits by reducing the internal radius of tubulars due to the growth or the increase of scale thickness. Once scales are formed, if not treated will continue to grow thicker. Calcium carbonate scale in production tubing can grow and obstruct over 40% of the flowing area of the tubular whiles restricting access to lower sections for workovers.

Formation damage around wellbores of both injection and producing wells is caused by scale formation. Scales develop around wellbore and cause a reduction in near wellbore porosity and permeability and even block perforations (Mike Crabtree, 1999). Injection water at the wellhead is usually of lower temperature as compared to reservoir temperature and when this water travels along the injection pathway and well string the water cools the surrounding formations whiles gaining heat (temperature) and pressure increment. If the water is saturated at surface conditions with salts whose solubility decreases with increasing temperatures (e.g. anhydrite), scale may form along the well-string. Also scale precipitation from the injection water may happen behind the mixing zone resulting from pressure and temperature changes. This is particularly true of waters containing salts whose solubility decreases with increasing temperature and decreasing pressure (Yassin, 2007).

Figure 13 shows the image of the problems caused by scales.

Figure 14: Scale Problems; Examples of heavy scale precipitation

In summary the consequences of scales can be adverse including equipment failure which can result in safety dangers, emergency shutdown, water injectivity decline with time, increased maintenance cost (workovers), and overall decrease in production efficiency (Yassin, 2007).

2.8 Scale Identification and Detection

A good understanding of scale formation helps in the early detection of scale formation so as to prevent adverse operating conditions. Successful early detection and identification of the location and composition of scale deposits is the most powerful tool to minimizing the effects of scale and also designing a cost effective remediation program.

A common detection technique is the monitoring of abnormal decline in oil production and/or pressure drop across the production system. This however is not an effective technique since other factors contribute to increases in pressure loss and decline in production. The use of Nodal Analysis as complementary and evaluation tool can indicate tubing scale provided the well indicates restrictions or limits present in the production system that were not present during earlier stages of producing the well.

Another detection technique is a comparison between a post-production (through tubing) and open hole gamma ray log for the detection of Barium Sulphate scale since naturally radioactive material(NORM) such as Radium (Ra^{226}) precipitates with this type of scale. This technique is not use for surface conduits since gamma ray logging is only done downhole. Caliper log can also be run down your flow conduit to measure a decrement in internal radius of flow conduits in order to determine the presence of scale deposits.

Presence of scales can be detected by X-ray evidence from core analysis. Inspections and Visual confirmation of scales when control valves and chokes are removed upon a decline in production is one method that is also used (Gerard Segeral, 2003) (Mike Crabtree, 1999).

The use of X- Ray diffraction in combination with energy dispersive spectroscopy (XRD/EDS) provide a reliable analytical tool for scale composition determination. Combination of the mentioned tools can yield the percent mineral composition of any scale sample (Saaid, 2013).

2.9 Scale prevention and control methods

Chemical and Mechanical approaches are employed solving scale problems, each comes with its own challenges depending on the location, type and physical properties of the scale. Unlike Calcium Carbonate scales that can be dissolved with acids others like hard Barium sulfate are resistance to dissolution. Some properties of crude such as is waxy or tar-like nature protect scales from dissolvers by forming coatings around the scale and hence limiting contact between the scale and the dissolvers. The growth of scales cause impermeable scale to line production tubing, sometimes completely blocking it, which requires the use of mechanical techniques or chemical treatments to cut through the scale blockages. Nevertheless, hard barium sulfate is extremely resistant to both chemical and mechanical removal. The worse approach use for solving hard scale problems involving production tubings is to force a shutdown of production, move in workover to pull out the damaged tubing and either treat the tubing on surface or completely replace the tubing (Mike Crabtree, 1999).

Reduce scale potential

The maximum amount of scale which can precipitate out from any system in equilibrium can be predicted from the following equations.

Considering a general case of formation of a mineral say AB;

$$M^{2+} + A^{2-} \leftrightarrow MA \tag{6}$$

If the solution is supersaturated with respect the mineral AB:

$$[M][A] > Ksp \tag{7}$$

Upon reaching equilibrium MA will precipitate out until the solution reaches its saturation point. Since a mole each of M^{2+} and A^{2-} is required for the generation of a mole of MA, both ions will experience a decrease of one mole each of their corresponding concentration for every mole of scale which precipitates out of solution.

If P is the number of moles of MA which precipitates as a result of the solution reaching its saturations, then:

$$Ksp = [M\text{-}p][A\text{-}p] \tag{8}$$

Rearranging;

$$p^2 - (M + A)p + MA - Ksp = 0 \tag{9}$$

Taking the negative root of the resulting quadratic equation:

$$p = \frac{(M+A) - [\,(M-A)^2 - 4Ksp]^{0.5}}{2} \tag{10}$$

Let

$$G = M + A \quad \text{and} \quad X = M - A \tag{11}$$

Then

$$p(molesL^{-1}) = \frac{G - (X^2 + 4Ksp)^{0.5}}{2} \tag{12}$$

Gives the following relationship

$$p(mgL^{-1}) = 500(MW)[G - (X^2 + 4Ksp)^{0.5}] \tag{13}$$

This equation is used to estimate the maximum amount of any scale likely to precipitate out of solution (Moghadasi, 2010).

2.10 Description of scale removal technologies and intervention approaches

Scale removal techniques come in various ways. The key, however, is that, whatever the approach may be, it should be able to keep the integrity of the wellbore, tubing, and formation environment intact. Any damage to the wellbore, tubing, or formation environment is highly unacceptable.

In this section, the various mechanisms by which scales are removed in an efficient manner without causing damage to the wellbore, tubing, and formation environment are considered.

2.10.1 Chemical

On the basis of their solubility, scales can either be non-acid-soluble or acid-soluble. As their names imply, non-acid-soluble scales are scales which are not soluble in acid. On the other hand, acid soluble scales are soluble in acids. This type of acid-soluble scales can thus be removed using acids.

For example, scales which are calcium carbonate and iron carbonate in nature are acid-soluble. Their solubility in acid makes them easy to dissolve in both organic and inorganic acids such as citric or formic acid or hydrochloric acid respectively.

Among the aforementioned acids which are good solvents for scales, hydrochloric acids are cheaper and more readily available. However, the downside of the use of hydrochloric acid is that, it is found to be a very corrosive acid. As such, for one to be able to use hydrochloric acid without causing damage to the wellbore, tubing and formation environment, it will be prudent to employ the use of corrosion inhibitors. These corrosion inhibitors reduce the extent to which the acid could cause corrosion to any of the well systems (Margrethe, 2013).

Below is an equation which governs the use of acid in scale removal;

$$2HCl(aq) + CaCO_3(s) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$
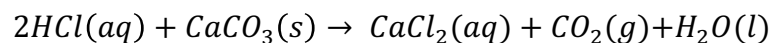
As mentioned earlier, other types of scales are insoluble in acid. As such, using acid as a way to remove them will be unproductive. For these types of scales such as Barium sulfate and calcium sulfate, other types of scale-removal chemicals are used for their removal operations. An example of such chemical is EDTA (Ethylene-diamine-tetra-acetic acid). Another type of scale-remover for such non-acid-soluble scales is diethylene-triamine-penta-acetic acid (DTPA).

These chemicals used to remove non-acid-soluble scales are known to be chelating agents which are complex molecules.

The disadvantage of the use of these chelating agents is that, they are time-consuming and require the use of high temperatures (Kelland M. , 2009), (Al Salami & Moneim A. Kader, 2010).

2.10.1.1 Bullheading/pumping

Bullheading is a chemical scale removal technique which involves the pumping down of chemicals to areas affected by the scales in the well. When the chemical to be used for the scale removal process is pumped down the well to the affected area, another chemical is pumped to displace the first chemical. This displacement process helps to rightly position the scale-removal chemical in a way to efficiently remove the scale.

The displacement chemical must often be lighter than the scale-removal chemical. A widely-used displacement agent for such operation is diesel. When the displacement chemical is pumped into the well, the well is shut in for the chemicals to stay in the well for a period of time. The longevity of this process is dependent on the corrosive nature of the chemical. A highly corrosive chemical will be made to stay for a relatively shorter period of time than a less corrosive chemical.

2.10.2 Mechanical

The mechanical approach to the removal of scales employs the use of mechanical tools and processes.

2.10.2.1 Brush/Scratcher

For important components such as gas lift mandrels, downhole safety valves and other forms of sensitive valves whose operations are key in the normal running of a well, a brush or scratcher could be used to remove the scale deposited on them. This is normally carried out downhole. For the scale-removal to be achieved, the brush or scratcher is pulled to and fro multiple times over the area which has scales. This brush can also be operate using tractor technology. In certain jurisdictions, brush is used with other forms of chemical dissolvers of scale (Ramstad, 2013).
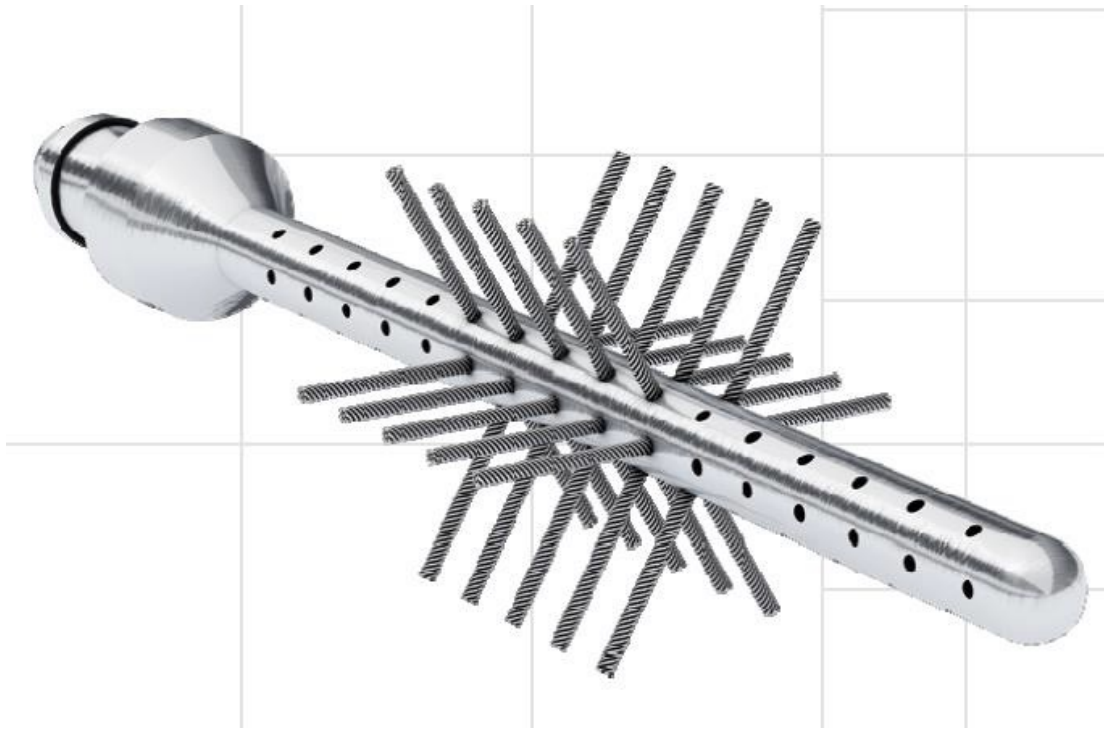
Figure 15: PowerTrac Brush from Aker Well Services (Altusintervention, u.d.)

2.10.2.2 Broach

Broaches are another type of mechanical tools employed in the removal of scales from the upper sections of the production tubing. This is normally done to increase the inner diameter of the tubing thus allowing for wireline access into the deeper parts of the well. Broach is a downhole tool hat is run on a wireline to achieve efficient removal of scales. While on the wireline, the broaches are moved up and down repeatedly to remove the scale. As the scales are removed, bigger diameter broaches are used to help in the total removal of scales of the tubing wall.

Figure 16: Broach (Harestad, 2009)

2.10.2.3 Explosives

The use of explosives are another means by which scales are removed. When run on electric line, the explosives are detonated in the area of the tubing where the scales are located. For efficient scale removal, these explosives are run repeatedly (Ramstad, 2013), (Engineering, G.E.K., 2009).

Figure 17: *A detonating cord taped to a bar and a string shot (Statoil I. t.)*

2.10.2.4 Milling

Another way to removing scales mechanically is milling. This is a tool string with a bit at the end of it to help in the milling process. The bit is usually referred to as a milling bit. Milling operation can be carried using coiled tubing, wireline or snubbing. This will further be explored in a later chapter.

2.10.3 Coiled tubing for mechanical removal of scale

The use of coiled tubing can be employed in the efficient removal of scales in tubing. This method of scale removal has been known to have resulted in the most consistent success rate (Schlumberger, 2014). A typical coiled tubing bottomhole assembly has a Turbo Scale Mill operated below a Workover Motor. The face of the Turbo Scale Mill has a cutting matrix and layout specially designed to operate as such. Typically, the Turbo Scale Mill (TSM) is designed with a small contact area during milling operations. This helps to minimise the amount of torque required. Due to the minimum torque that is required, the rate of penetration increases as a result.

To offset the situation where a worn-out mill has to be pulled out of hole and replaced, a second lower layer is attached to ensure quick replacement. This clearly reduces the amount of time required to make a trip to the surface in a bid to replace the mill.

Figure 18: Baker's METAL MUNCHER® Turbo Scale Mill. (Hughes, 2016)

Advantages of the use of coiled tubing for scale removal:

1. It achieves increased reliability in zones with high stresses.

2. Even in temperatures above 400°F, operations are successful.

3. Relatively less flow rate is needed to obtain optimum horsepower.

4. It has reduced milling times.

5. Run times are extended.

2.10.4.1 Wireline rig-up equipment for mechanical scale removal

To be able to carry out wireline operations, a positive wellhead pressure is required (Dulger, 2012). To achieve effective pressure control from the wellbore, various pressure control equipment are installed at the top of Christmas tree. Obviously, the pressure rating of the pressure control equipment should be greater than the pressure expected from the wellbore. There are normal ratings for such equipment. Some of these are 5000, 10000, and 15000 psi (Coiled Tubing Services, 2016).

According to (Dulger, 2012), the pressure control equipment needs to handle the following functions;

a. Under both static and dynamic conditions, the pressure control equipment seals around the area which in turn surrounds the wire.

b. It also ensures that the sealed area is protected against the maximum wellhead pressure.

c. Before the well is opened, the lubricator must be leak tested to be sure it can withstand the maximum pressures from the well. The pressure control equipment allows for the lubricator to be leak tested.
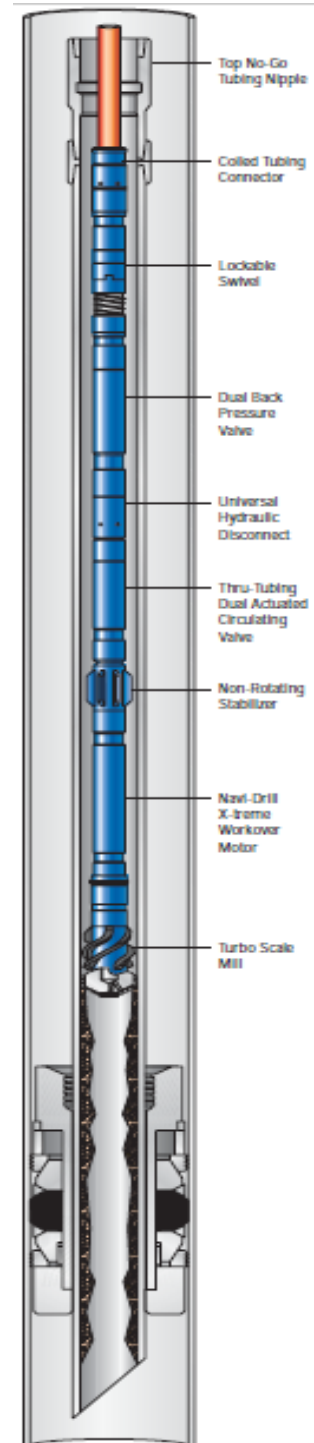
Figure 19: A typical bottomhole assembly of a Turbo Scale Mill run on coiled tubing (Schlumberger, 2014)

2.10.4.2 Wireline rig-up – Platform
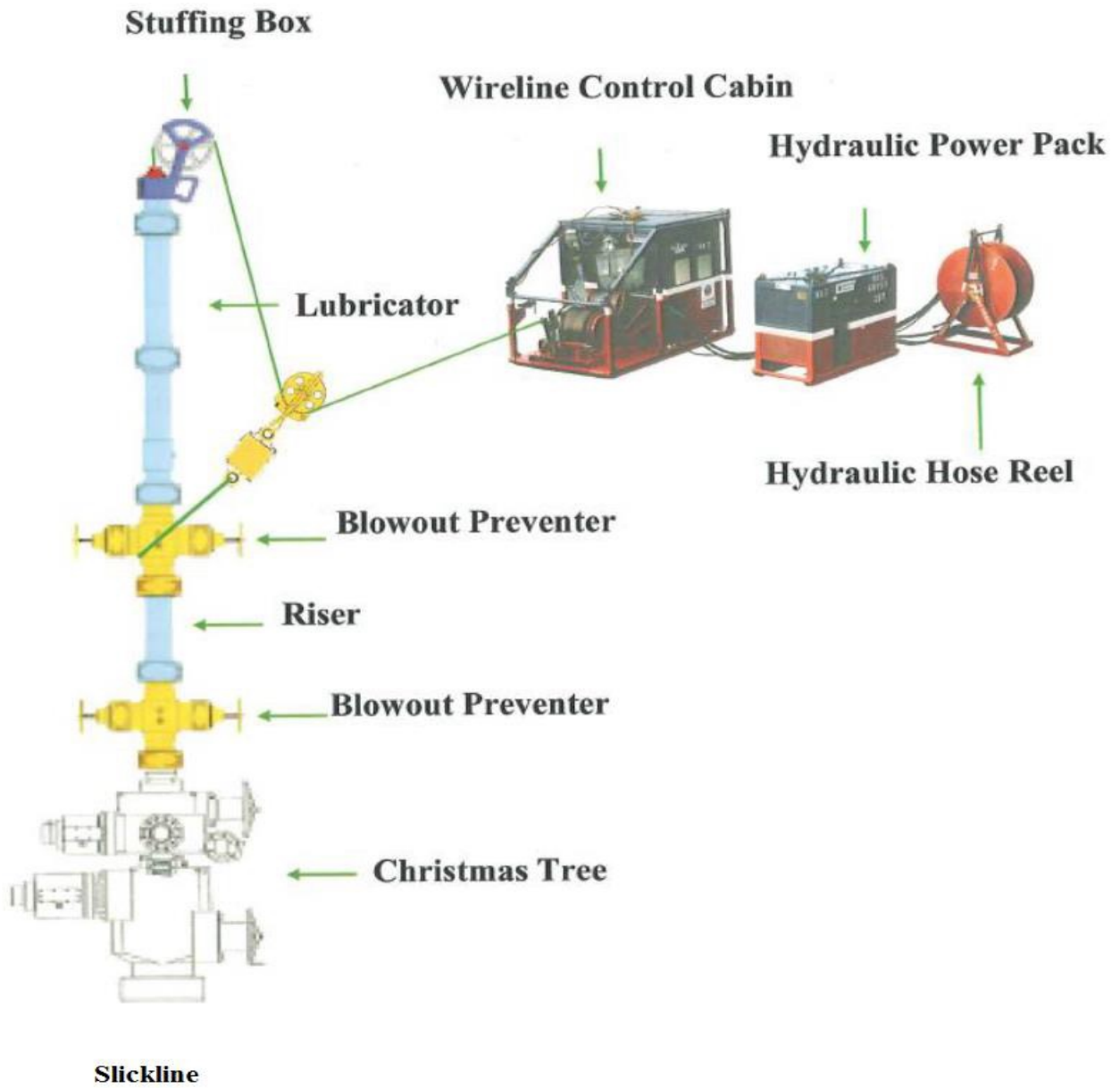
Figure 20: *Surface rig-up equipment installed on Christmas tree on the deck of a platform for slick line (Dulger, 2012).*

Grease Injection Head

Safety Check Union

Chemical Injection Sub

Hydraulic Tool Catcher

Upper Lubricator

Lower Lubricator

Hydraulic Tool Trap

Manual Dual BOP

Well Head Flange Adapter
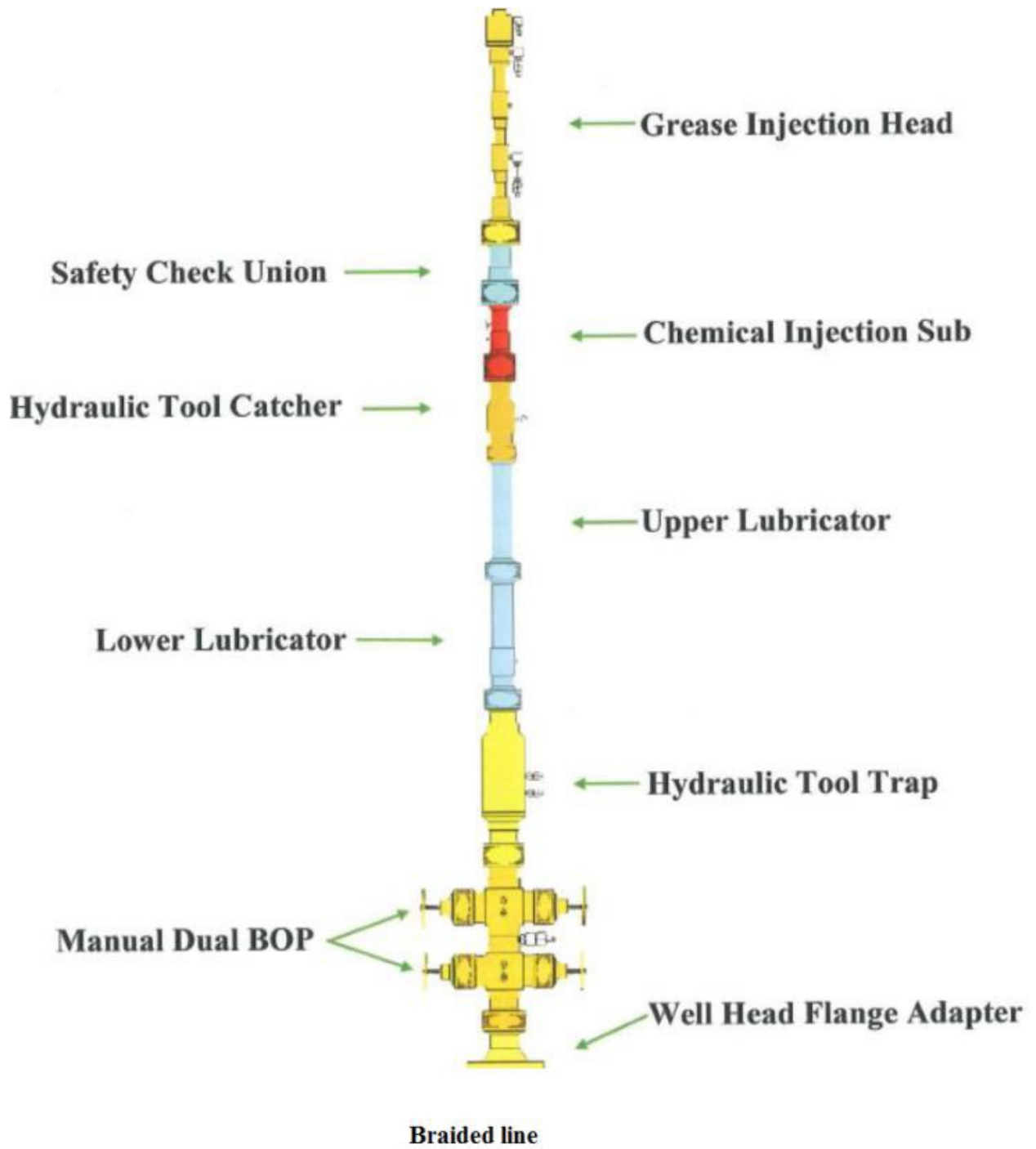
Braided line

Figure 21: Surface rig-up equipment installed on Christmas tree on the deck of a platform for braided line (Dulger, 2012).

41

Functions of the various parts of a surface rig-up equipment

Grease injection head

The grease injection box serves as the primary barrier element during any well operation. The purpose of the grease injection head is to be able to hold the prevailing pressure when the well is being run into using a braided/electric cable. In the internal setup of the grease injection head are flowtubes which could differ in number based on the prevailing well pressure (Dulger, 2012). To be able to achieve a good seal a good liquid seal against well pressure, the grease is pumped repeatedly to fill the annular space between the external surface of the wireline and the internal walls of the flowtubes. The injection pressure of the grease is typically about 70 bars more than the well pressure (Khurana, 2003).

Stuffing box

For a slick line operation, the primary barrier element that serves as a seal around the wire is the stuffing box. This contains rubber packers which aid in sealing the surrounding area of the slick line. This is done to contain wellbore fluids in the pressure equipment located at the surface (Khurana, 2003).

Blowout preventer (BOP)

In a typical wireline operation where braided line/electric line is employed, the secondary barrier element is the blowout preventer. The BOP is normally installed right atop of the Christmas tree to provide a sealing mechanism around the cable in the event of a leakage in any of the components (Dulger, 2012). The cable in use determines the number of rams found in the BOP. In the case of a slick line, only one ram is needed in the BOP for safe operation. With the use of braided/electric line, two rams are required. This is due to the need for grease injection between the rams to achieve a good sealing effect around the wire. The combo BOP is the commonest type of BOP used for typical wireline operations (Khurana, 2003).

Tool catcher

The tool catcher helps in catching the tool string before it impacts the top of the lubricator. Its function is important because it aids in the prevention of the snapping of the wireline and halts the tool string from getting down of the hole if the wireline reaches its weak point where it can break (Khurana, 2003).

Chemical injection sub

This component is located just below the grease injection head or stuffing box. This operates in a way to permit the injection either an inhibitor or a de-icing agent to help control H_2S/CO_2 corrosion prevent gas hydrates respectively (Dulger, 2012).

Check valve union

This is designed to provide a sealing effect and thus ward off well pressure if it so happens that the wireline separates from the tool string (Dulger, 2012).

2.10.5 Wireline rig up – Riser Less Wireline Intervention (RLWI) Vessel

Riserless Light Well Intervention (RLWI) – is the method of carrying out maintenance operations on subsea wells without the use of a riser system.

To be able to maintain a subsea well using riserless light well intervention, downhole tools are inserted into the well under pressure with the use of wireline. This approach of subsea well maintenance reduces the total cost per operation by almost 40 to 60% as compared to the use of traditional drilling rigs and other accompanying equipment (FMC-Technologies, 2016).

It can thus be deduced that cost reduction and operation efficiency is the rationale behind the development of the RLWI technology.

Typical subsea well operations that can be carried out with the use of RLWI are as follows;

- Removal of scale by milling
- Sand removal
- Well stimulation
- Plugging and zone isolation
- Installation of insert downhole safety valves
- Re-perforation of new production intervals
- Running production logging tools
- Running gauging tool

The figure 21 demonstrates the standard configuration as observed for a typical riser less wireline operation.
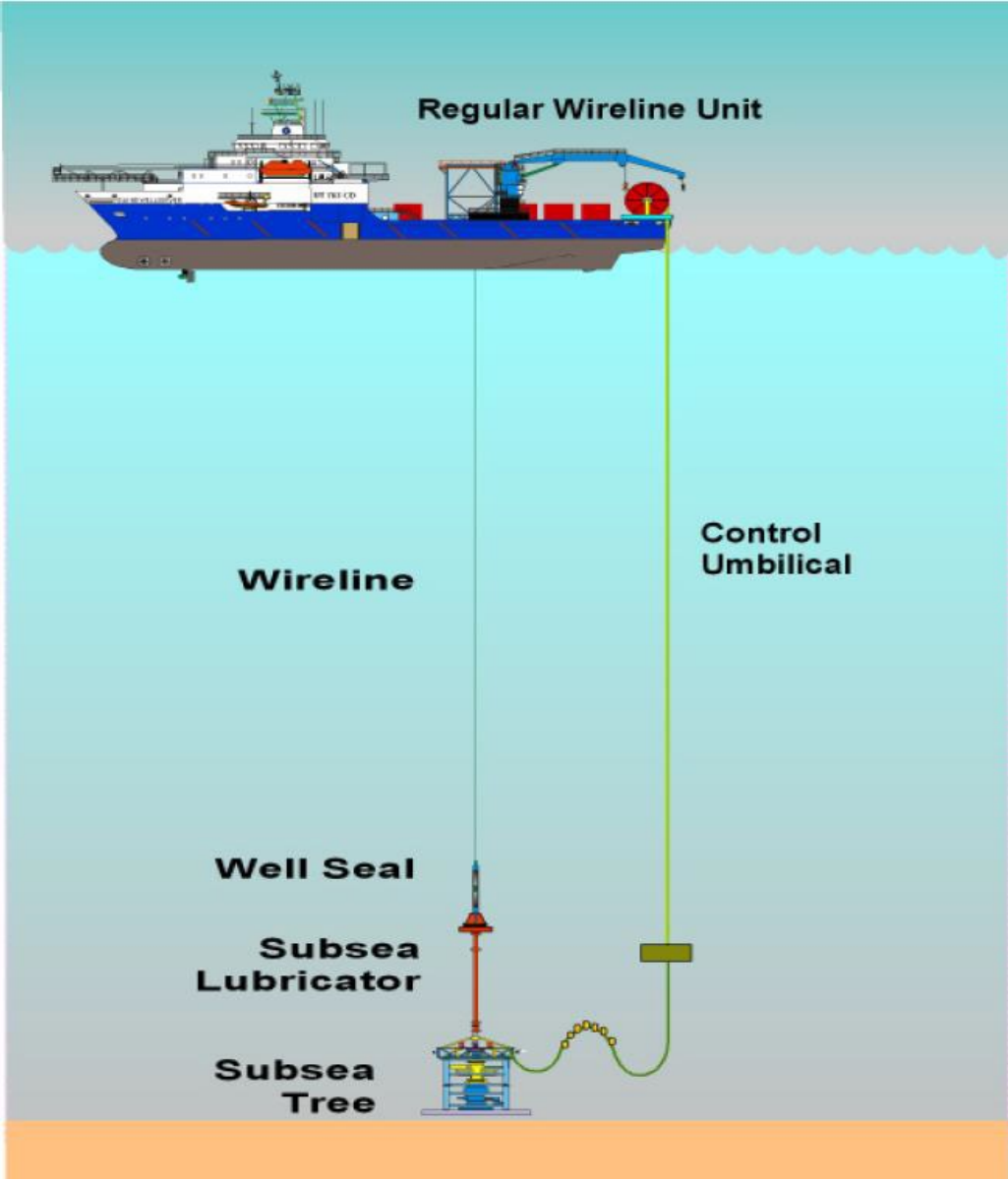
Figure 22: *Standard configuration for wireline operations (Munkerud & Inderberg, 2007).*

Figure 22 also shows how a RLWI system is configured at the top a subsea Christmas tree on a subsea well during well intervention.
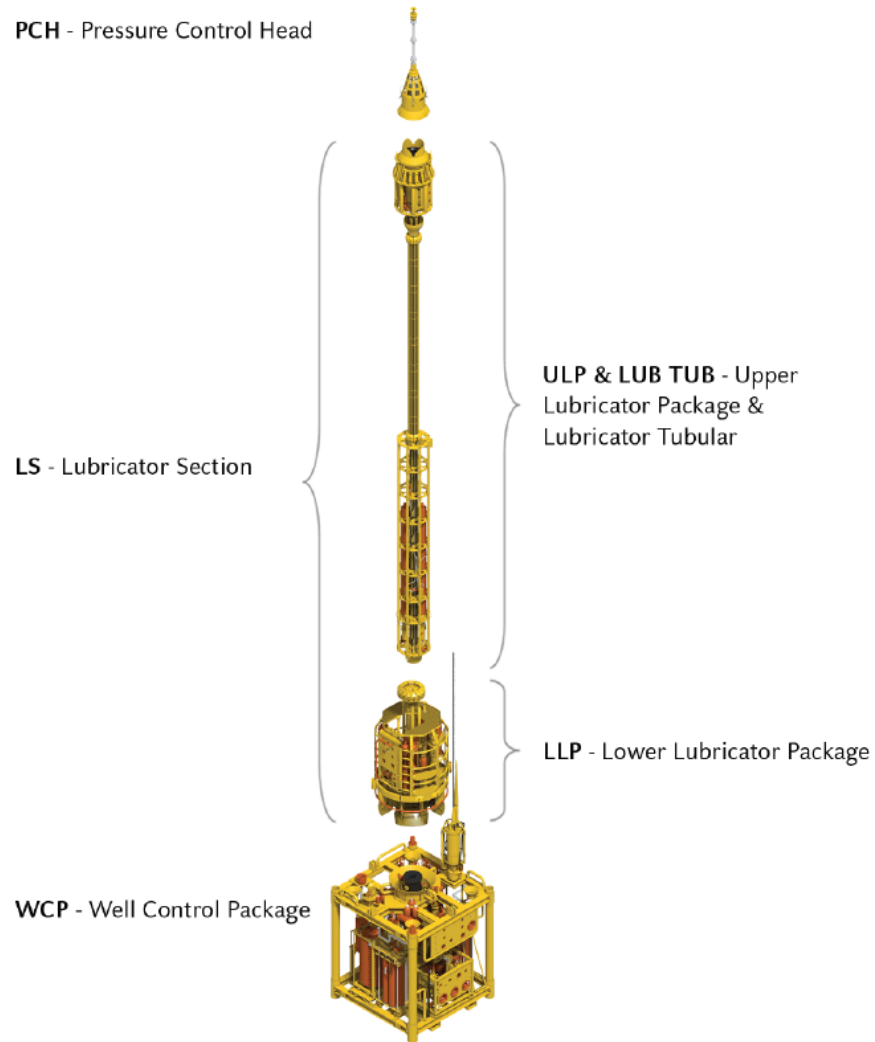
Figure 23: Riserless Light Well Intervention system (FMC, 2015).

Lubricator section

The lubricator section usually determines the length of the tool string. This consists of the lubricator tubular, the upper and lower lubricator packages. The lubricator tubular is often located on top of the lower lubricator package. It is made to carry injection pumps with a high pressures and grease reservoirs. Also, the upper lubricator package is placed atop the lower tubular (Delot, 2012).

Pressure control head

Typically, the pressure control head is linked with the top of the upper lubricator package. During wireline operations, the pressure control head serves as a primary barrier element (Delot, 2012)

Well control package

This component is fixed above the Christmas tree. This serves as a secondary barrier element when operating a wireline assembly.

WELL BARRIER SCHEMATIC
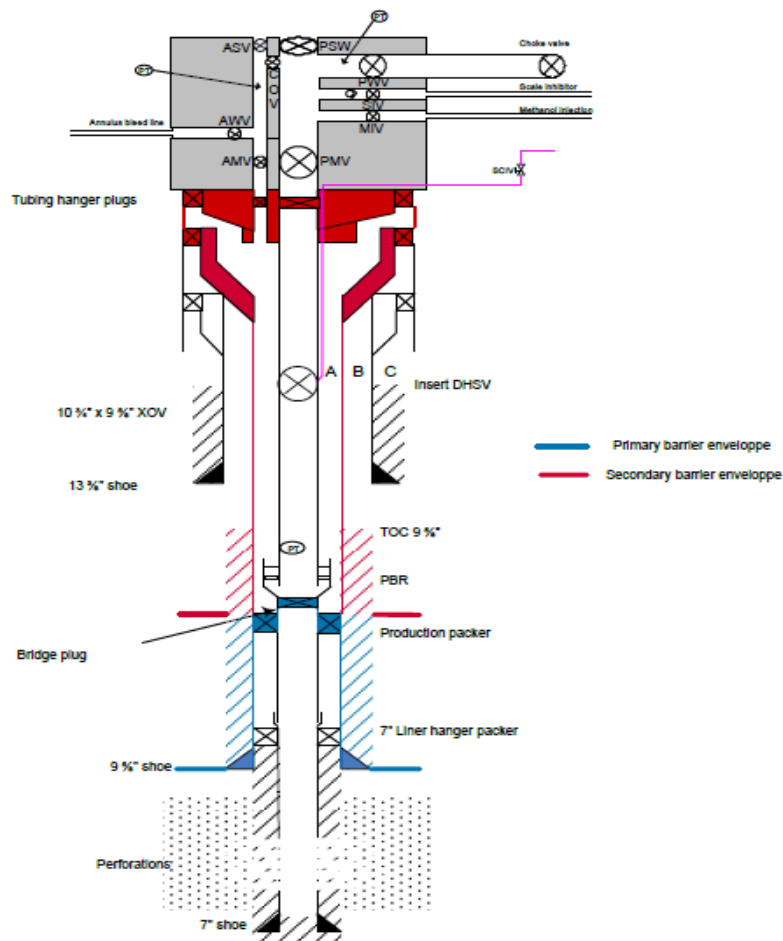
Figure 24: A well barrier schematic showing the primary barrier elements (in blue colour) and secondary barrier elements (in red colour) of a a repair operation of a vertical subsea tree using RLWI (Morrison, 2016).

2.10.6 Mechanical wireline milling with tractor

2.10.6.1 Wireline milling

A tractor, rotation assembly and a milling bit are the main equipment used to carry out the operation of wireline milling. Weight on Bit (WOB) and torque are two prime properties of importance proper operation of a wireline milling tool string. The WOB is the quantifiable downward force that is exerted on the bit. On the other hand, torque is the rotational force that influences the rotation of the bit.

To avoid stalling out in a normal milling operation, the WOB component force is held constant and must be controllable. In the event of stalling of the tool, the bit would get stuck and not rotate. Stalling would usually occur in the event that the applied WOB is greater than the torque. When this happens, the bit is unable to rotate.

The rotation of the mill bit causes a reactive opposite force to cause the tool string and the cable to rotate. This rotational phenomenon of the tool string and cable are highly undesirable. It is to prevent this rotation that electrical wireline tractors are employed. The merit with the use of such electrical wireline tractors is that, the tractor can propel the tool string through highly deviated and horizontal wells where the gravity magnitude is minimal.

Upon activation of the tractor, a hydraulic pump which is driven by an electric motor releases the wheels against the wellbore. This also helps to drive the tool string down the well. What the tractor does thereafter is to provide a consistent force against whatever is being milled (Krüger & Sælensminde, 2005).

Figure 25: Well tractor whose wheels are released against the wellbore ((Nergaard & Grimholt, 2010))

The milling bit is what helps in achieving the milling effect. It comes in various sizes depending on the expected target material to be milled and the restriction posed by the wellbore. The figure below shows different types of milling bits.

Figure 26: Milling bits (Courtesy Welltec) (Welltec, 2016)
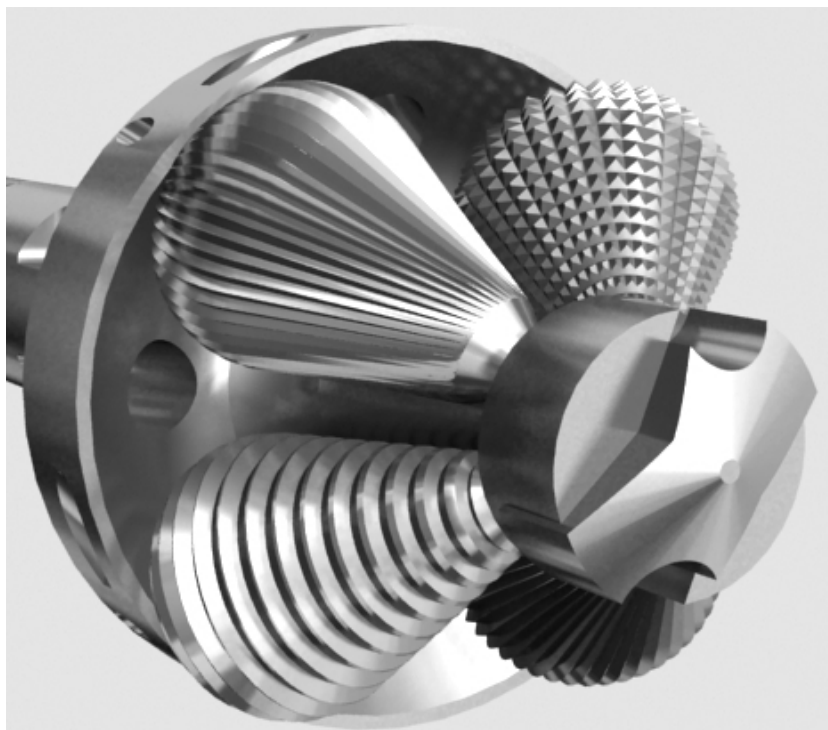
Figure 27: The Cone-Crusher type of mill bit (McInally & Osaland, 2007)

2.10.7 Surface readout parameters during a milling operation

Different parameters are essential to achieve optimum milling operation. The electrical wireline cable serves as the medium through which data is transmitted from subsurface to surface.

In this section, we take a look at some of these parameters.

2.10.7.1 Wireline tension

To be able to monitor how much tension is applied on the cable, the wireline tension ought to be measured. Since the cable has tolerance for a certain amount of tension before it breaks, monitoring it is worthwhile so as to prevent any breakage.

2.10.7.2 Depth

A counter is installed as part of the total assembly to record the total depth being run into. This gives an idea of how much of the tool string has been strung into the wellbore. In the event where the tool string gets stuck in the well but the cable continuously spools, it could record a false depth measurement which could be misleading. To be certain that the tool string hasn't gotten stuck to record false depth readings, an increase or decrease in the value of tension is observed as a check.

2.10.7.3 Current

A flat and even current reading observed on the readers indicates that the milling bit is milling. Contrarily, an abnormally high current reading indicates stalling out of the bit. This abnormally high current reading is normally observed because in the event of stalling, more current is needed in an attempt to rotate it.

2.10.7.4 Temperature

The temperature reading observed on the sensor indicates the internal temperature in the tool string. This parameter becomes a matter of concern in high-temperature wells. This is because most tools used for such milling operations are designed to operate in a limited range of temperatures.

2.10.7.5 Head tension

The head tension demonstrates the tension/WOB applied on the bit.

3 Plasma technology concept & Experimental study

This chapter focuses on principles of plasma technology, evaluation of design concept and experiments performed according to the design concept.

3.1 Plasma Technology

As the oil and gas industry gets more complicated, technology that hitherto helped in descaling are not enough. In an attempt to research on better and more efficient technology, the plasma technology seeks to provide a key to meeting these challenges of scaling to the benefit of oil and gas players in the industry. As the industry becomes more demanding for more efficient and ecologically-friendly processes of descaling, research continues to open up newer opportunities where more dependable, relatively cheaper and efficient solutions will be sought to contribute to the efficient production of oil and gas resources now and in the future.

The reason why plasma technology makes a field to look towards is because it simultaneously satisfies the industries demands and requirements for quality, productive, environmental friendliness, precision and adaptability.

Scale of various types require different methods for the inhibition and removal. The interest in developing new technology to remove scale on than more efficient and profitable way, has been the focus of many large and small companies. Until this day removing scale is still a major problem due to inefficient removal methods.

Based on advanced technology developed, we want to solve this problem in an unconventional way. This technology utilizes plasma formation to remove scale, and is already being developed for use in several other areas, including drilling on Mars and geothermal drilling (Zaptec internal, 2015). The technology will provide advantage over existing solutions by increasing efficiency, reduce costs, reduce damage to the tubing, remove WOB requirements, enable scale removal in producing well, and streamline the removal of scale with RLWI.

3.2 Zaptec plasma technology

3.2.1 Introduction to Plasma
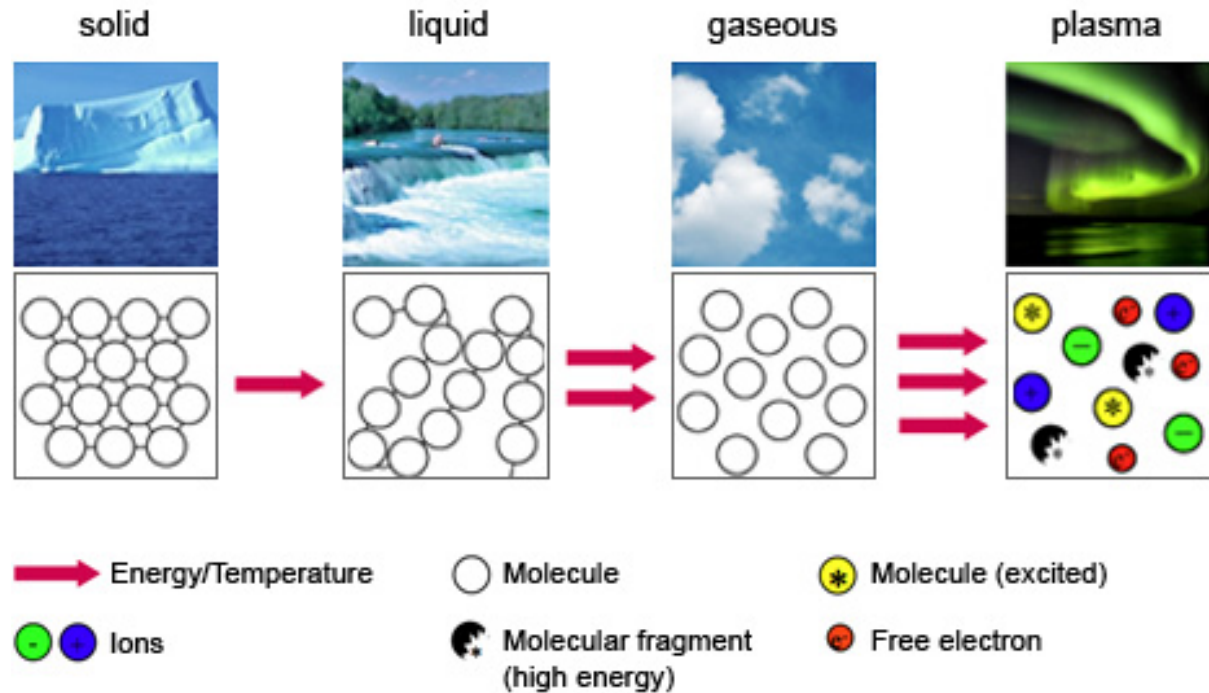
Figure 28: *The figure shows the different stats of matter with gradually increasing energy input (Plasmatreat, 2016).*

Taking a look at the atomic structure of a gas, there is an equal number of protons and electrons; the protons which are positive charges found in the nucleus are surrounded by electrons which are negatively charged particles. Due to the equal number of protons and electrons, the atom is electrically neutral as the positively charged particles neutralize the negative ones.

To produce plasma out of a gas, the application of a significant amount of heat or another form of energy would cause huge number of atoms to release some or all of their electrons. When the electrons are released due to the application of energy, the resultant atom becomes positively charged as the number of positively charged particles outnumber those of the negative ones. This also causes the unattached electrons to move about freely (Bittencourt, 1986). When this happens, the gas is said to be *"ionized".* Then, plasma is produced when a reasonable number of atoms are ionized to affect their electrical characteristics.

From the above expose therefore, it can be observed that there is a difference between ordinary neutral gases and plasma. For example, while plasmas are electrically charged particles, neutral gases have no net charges as their positive charges are balanced out by the negative charges. Also, plasmas undergo a great deal of electrical and magnetic influence while neutral gases are not (R. J. Goldston, 2000)

Plasmas are not only influences by external fields such as the Earth's magnetic field and other fields produced by interplanetary forces, they are influenced by internally-generated magnetic and electric fields created within the plasma. Both the internally- and externally-generated fields act on the charged particles contained in the plasma. These fields influence the particles in the plasma over long distances; this in turn influences the total nature and characteristics of the particles inherent in the plasma. This influence on characteristics aid in giving the particles in the plasma an admirable quality that neutral gases do not possess.

As a matter of fact, natural plasmas are uncommon. On the other hand, however, plasmas made by man are common and seen daily. For example, fluorescent light bulbs, which look quite different from the ordinary bulbs most people are used to. In a fluorescent light bulb, gas is stored in the long tube; when connected to a source of power, electricity flows through the tube where we see that the light is turned on. This electricity is thus responsible to supply the needed energy required to charge up the gas. The process of charging and exciting of the particles in the gas atoms create the plasma that glows inside the bulb (Artsimovich & Sagdeev, 1979).

Looking at the stars, we see that plasma works. These stars have inherent high temperatures which act like electricity as discussed previously to supply the required energy to charge up the atoms and create plasma in the process (Fridman, 2004).Furthermore, it is important to mention that about 99.99 per cent of matter is in the plasma state. By natural extension therefore, the Earth is said to float in plasma (Puerta & Matin, 1999)

3.2.2 Plasma Sparks vs. Plasma Welding

Even though mostly confused and thought of as being the same, there is a considerable difference between plasma sparks and plasma welding. Plasma welding is a common process employed in diverse fields and industries. This process of plasma welding, like seen in previous text, is based upon the application of high temperature to supply sufficient heat energy to a material to be removed by its melting point. Contrarily, plasma sparks employ the use of pulses created from an electrical source to create a continuous stream of plasma within or on the surface of the body of material. Each stream of plasma leads to the removal of the material. The material removal process leads to the fragmenting and fracturing of the body of the material. In a general sense and application, the amount of energy required to produce plasma sparks is only a fraction of what is required in the case of plasma welding. Zaptec's plasma technology unit is based on plasma sparks or plasma channel drilling for their drilling technology.

3.2.3 Plasma Application – Drilling/Breaking solid matter

Drilling tools are generally driven into the earth by any of the following processes such as fusion, vaporization, mechanically-induced stress, and chemical reactions. Zaptec's technology would employ a different approach, which is plasma spark. Their technology has many advantages and their goal is to use it to drill on Mars and microgravity environments. This technique (plasma spark) can also be categorized under mechanically-induced stress mechanism (Carley-Macauly, Hitchon, & Maroudas, 1966) and (Vorobiev, 1966). Zaptec's method is based on high voltage pulses with microsecond duration and two electrodes which are close or in contact with the rock (Maurer, 1968). Plasma drills induce fracture and fragmentation by using two different ways. These are;

(1) Excited sonic impulse/pressure wave which breaks the rock surface.

(2) A plasma channel that vaporizes a significantly small part of the rock which expands and breaks the rock (Yutkin, 1955).
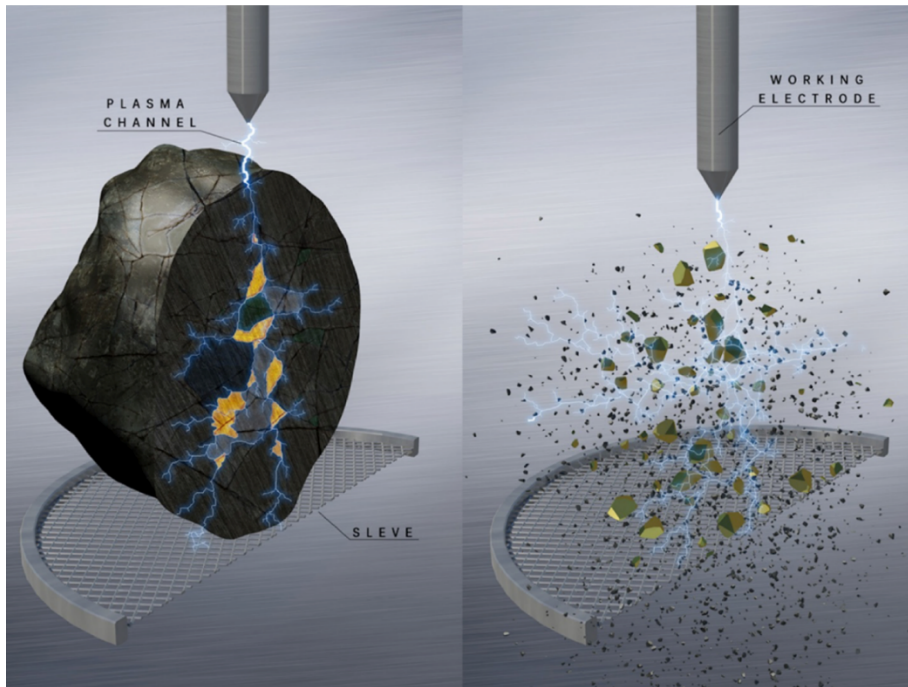
Figure 29: Plasma channel effects on rock (Zaptec Internal, 2015)

3.3.4 Plasma Channel Drilling Technology

Plasma channel drilling is a process of fragmenting a rock in an efficient manner using a source of electricity. To do this, a solid body by the formation of an electrically conductive gas-plasma-filled breaks down by making a channel in or on the solid body.

The physical properties of the solid body dictate the electrical resistance of this plasma-filled breakdown-channel. The electrical resistance of the plasma-filled breakdown-channel also depends on the nature of the discharge circuit of the pulsed generator and the electrode assembly (Yutkin, 1955). Following the breakdown of the material from electrical sources, it is possible to expand the discharge channel during the first hundreds of nanoseconds by increasing the diameter of the discharge channel from several micrometers to several hundred micrometers. This helps to accommodate the high stream of current emanating from the driving circuit.

The expansion of the discharge channel as seen previously influences the processes of fragmenting and fracturing of the described material.

The plasma channel, which is generally elongated, is formed many times per second with different radial orientations. This process helps in removing the need of heating the rock formation or body of material to reach its melting point or to focus a shockwave onto the surface of the formation or body of material or to have a rotary drill bit. The time that plasma channel takes to deplete to a sufficient level before the creation of the next plasma channel, limits the effectiveness of the pulse repetition rate in removal of material. So, high voltage pulses will be produced by pulse generator which has a current waveform close to that of the critically damped response of the circuit created when the plasma channel is produced. It is important to consider that an increase in the pulse repetition rate of the high voltage (HV) generator is not always a parameter to increase drilling rate of the plasma channel drilling device (Cole, 1948). The specific energy represents the drilling efficiency, and is a function of many variables such as: strength of the formation, drill bit design, drilling parameters, bottom hole cleaning, type of drilling and atmospheric pressure.

Table 4 Energy consumption of different drilling methods (Usov & Tsukerman, 2006)

Method	Specific Energy (J/cm^3)
Rotary Drilling	600-950
Percussion Drilling	200-650
Percussion-Rotary Drilling	400-800
Electro Thermal Drilling	5.000
Electro Hydraulic Drilling	400-500
Electric Discharge Machining	~10.000
Plasma Channel Drilling	100-200

To successfully achieve plasma channel drilling, high voltage is applied to electrodes which are situated on the surface of the rock. The said high voltage could be either of a negative or positive polarity. During the growth of the streamer, there is an exponential decay of the voltage which passes through the electrode. To achieve maximum energy required for useful fragmentation, the length of time used in this stage of the breakdown of the spark needs to be minimized.

When the streamer bridges the gap between the inter-electrodes and thereby closes the electrical circuit, the accumulated electrostatic energy stored in the capacitor bank of the pulse power supply is released into the breakdown channel. Extremely rapid expansion of the plasma column and generation of a pressure pulse will be achieved by Joule heating of the plasma formed in the breakdown channel. Plasma has a really short life time (about microseconds) that will let the very high power turn to breakdown channel. The spark discharge generates a peak power which is typically hundreds of mega watt (MW). The high powers allow the pressures of several giga Pascal (GPa) to be developed in the breakdown channel. The compressive and tensile strengths of rock which are in the range of tens to hundreds of mega Pascal (MPa) so these pressures go beyond it and therefore cause the surrounding rock to fracture and fragment (Skvortsov, Komelkov, & Kuznetsov, 1960)

3.4 Technology concept and experiment

3.4.1 Plasma descaling tool

The concept for removing scale using a more efficient approach is by the use of plasma-based technology. Theoretically, this new method for the removal of scale deposition in well tubing leads to less harm on the tubing as well as eliminates the demand of supplying a weight-on-bit when compared to current milling technology. By eliminating the requirement for a weight-on-bit, a much smaller tool dimension is achieved. This helps in achieving less weight of the tool and reach deeper length without any connection to tractors which could be expensive to operate.

Current milling technology especially for removing the harder types of scale like $BaSO_4$, either by using wireline or coiled tubing milling tool requires the use of a bit size of the tubing. That will lead to a stop in production and more likely scratch the internal parts of the tubing. This scratching phenomenon could make the tubing prone to corrosion which could lead to equipment failure in the life of the well. With the plasma tool concept, the size of the bit or the tool size will be smaller than the tubing since the lightning will stretch out from the tool head through the scale and the plasma channel will create a pressure difference inside the scale that breaks the scale into smaller sizes.

Since a smaller diameter tool is used in the plasma technology as compared to the tubing, hydrocarbons can continuously be produced when the cleaning process is ongoing. This continuous production during cleaning aids in the achievement of a better cleaning process as well as to transport the scale-cuttings up to the surface. The concept tool will also be a very good solution for removing scale from subsea-well (by running a light well intervention (LWI)) since it is only connected to a wireline cable. Indeed, a certain amount of weight is needed in the bit to lower the tool into the well. This weight requirement depends on the Shut-In Wellhead Pressure (SIWHP), cable diameter, friction in the stuffing box and buoyancy.

Another advantage of using plasma technology is that a much better cleaning process is achieved in narrowed sections like side pocket mandrel (SPM) which is difficult with mechanical milling process.

3.4.2 Electronics

The main parts to create a plasma descaling tool are based on the electronics from the Norwegian technology company, Zaptec, located in Stavanger. They have developed and patented a transformer that is super-compact and super-efficient and outperforms transformers up to 10 times its weight and volume. In other words, this means that one can, with low voltage and current, through a wireline cable, get a much higher voltage after it has passed the transformer. With the use of such a small and powerful electronic instrument, it will be possible to reduce the space and create a tool that fits into even the smallest production tubing. The transformer has a temperature capacity of up to 154 °C, which is relatively high and can be used in many wells on the Norwegian Continental Shelf (NCS), especially if the tool is used for removing scale from the upper part of a well where the temperature is lower than the reservoir temperature (Zaptec internal, 2015).
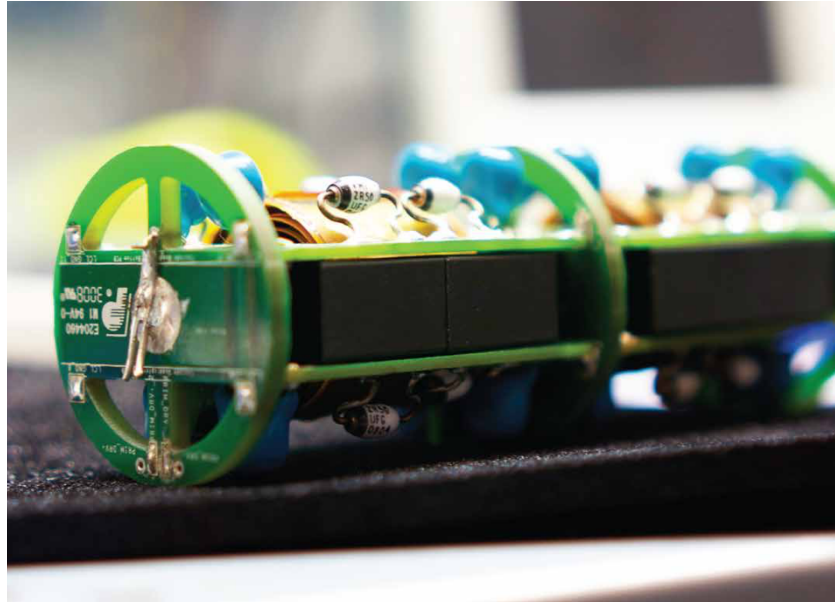
Figure 30: *The Transformer from Zaptec (Zaptec internal, 2015).*

The transformer alone will not create the electric sparks. With a range of other electronic components connected with the transformer, it will be able to create small lightning/sparks. The energy and length of sparks is determined by the number of capacitors and the liquid resistance around the spark head. These sparks will then go through the scale and theoretically cause their break up and loosen up from the production tubing. A schematic drawing of electronics is shown below:
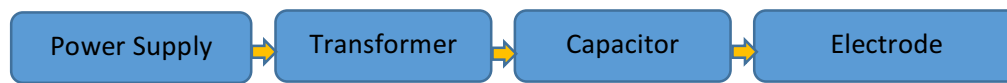
Figure 31: *A simple schematic of the simulation circuit.*

3.4.2.1 Capacitor

The capacitor is one of the main component where the electrical energy is stored. It consists of least of two parallel conductive plates, commonly a metal. The two plates are separated with an insulating material between the plates, called the "dielectric". When charging a capacitor by applying voltage, a current flow adds positive charges to one of the plates while the second plate will become negatively charged. As results, the potential difference between the plates increases. The applied voltage (V) is proportional to the stored electrical charge (Q), for a given capacitance (C) (Electronics Tutorials, 2016).

The transformer from Zaptec has the ability to increase the voltage by 10 times (Zaptec internal, 2015) and thus the capacitors charging process is accelerated. When a high voltage capacitor is discharged across the assembled electrode the dissipated energy result is a high temperature and high-pressure plasma sparks for a few microseconds (Zaptec internal, 2015).

$$Q = C \times V \tag{14}$$

The power and the rate of the sparks depends of the number capacitors. Therefore, the length of the tool is determined by the number of capacitors.
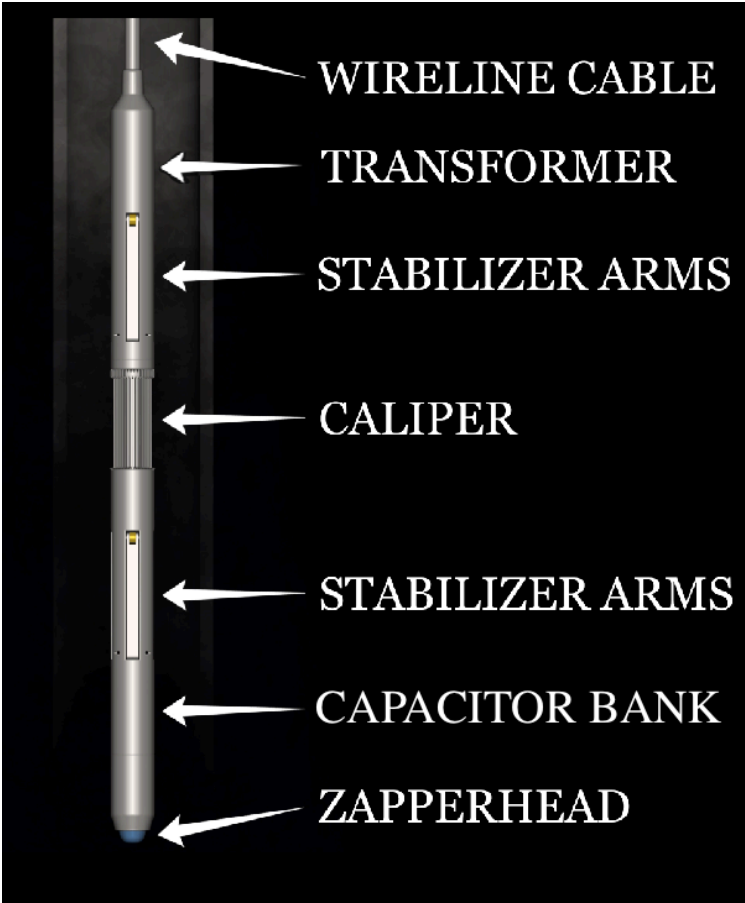
Figure 32: An example of locations for the various components

3.5 Plasma descaling tool

3.5.1 Introduction
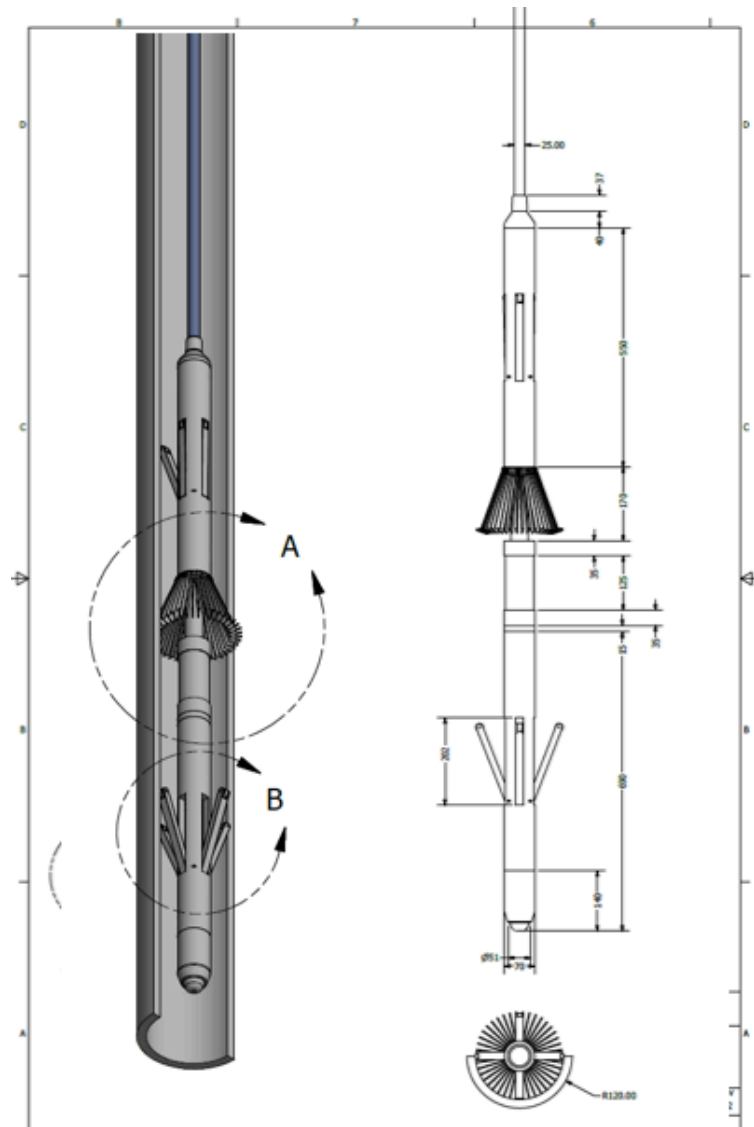
Figure 33: *The plasma descaling concept, WL-tool with stabilizer caliper (A) and arms (B). Designed by the author of this thesis.*

The idea behind the concept is to create a WL tool that can remove scale with a higher rate of penetration (ROP), in a more profitable manner without causing damage to the production tubing. The WL tool will also be able to enter a live subsea well with a riser less well intervention (RLWI) operation. As previously mentioned, without the requirement of weight-on-bit, the tool can be run without any connection to tractor motor removing scale from the upper section. Of course, further down into the well (due to friction between the cable and the tubing wall) and in addition operations in horizontal wells, the tool must have the ability to connect to a tractor motor.

Zaptec's electrical components have an advantage as they are small and compact. This helps to design a tool that can fit into any size of a production tubing, and go into a live well. By controlling the voltage, it is possible to determine the length and energy of each spark. This will provide an opportunity to clean areas like SPM and around the down hole safety valve with the same tool size. The tool must also have a metal shell so that the electrical components are protected from the high pressure and temperature environment.
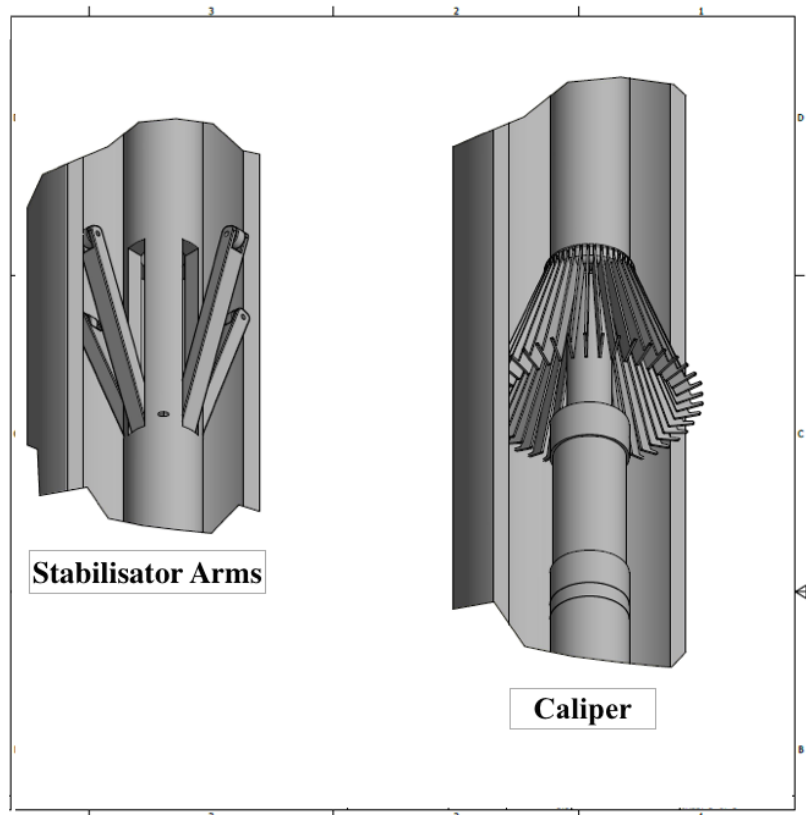
Figure 34: *Stabilisator arms and caliper. Designed by the author of this thesis.*

In addition to the electrical components, its also necessary with some mechanical components, such as stabilisator arms and caliper. The stabilisator arms will centralize the tool and also make it move smoother into the well without any scratches on the tool wall or tubing wall. This in turn will increase the surface area of the tool, therefore more force is needed to get the tool further in a live well. In this case, the stabilisator arms design and the flow rate are important when operating in a live well. The preferred design to get less flow resistance is v-shaped arms.

The caliper tool measures the diameter of a tubing. It is often used for detecting well bore damage as well as tubing damage. In this concept, this tool will help to confirm the clean-up process. The reason why the caliper device is upside down (Figure 34) is because it will be activated after the cleaning process when the tool is pulled out of the well.

3.5.2 Dimensions

The optimal weight and dimension of the tool are dependent on several parameters. First of all, the electronic components need to be tested to see how much power is needed for the removal of diverse types of scale and different thicknesses. On the other hand, the effect and the number of sparks per unit time is dependent on the number of capacitors. Incase of higher power demands due to condition of the scale, an increased number of capacitors will result in a bigger tool.

The length of the tool also has a limitation because of the lubricator section which is around 22 m to 24 m (Juel, 2009). As discussed in class normal diameter used for production tubing in NCS is $4^{1/2}$", $5^{1/2}$" and 7".

The weight for entering the well, as mentioned earlier, depends on SIWHP, cable diameter, friction in the stuffing box and buoyancy.

The pressure from the tool for entering the well is shown below (if we neglect friction in the stuffing box and buoyancy):

$$P = \frac{F}{A} \tag{15}$$

Where:

P: Pressure, this need to be greater than the SIWHP for entering the well [Pa]

F: Wight for entering the tool [N]

A: Diameter of the WL cable [m^2]

3.5.3 The Zapper head

The zapper head is the specialized name of the head of the tool where the electrodes are located. This is where the high voltage sparks leave the head of the tool and enter into the scale. The presence of a return electrode is required in order to create sparks. If there is no return electrode, there will be a short circuit inside the capacitor package. The concept here is to use the tubing as the return electrode. This will force the sparks through the layer of scale and into the tubing. Theoretically this is the easiest way to go for the sparks (a thumb rule for electricity sparks is that the sparks will always try to find the path with least resistance). Further study in a real well is needed to confirm this, due to the fact its hard to recreate real life scenario in the laboratory.

Figure 35: *Animation of the concept. Designed by the author of this thesis.*

3.5.3 Operation steps for WL tool entering a live subsea well:

The sequence of operation for a live well is located subsea. An Island Frontier vessel is used. It includes a lubricator without high-pressure riser that is tied back to the vessel.

Figure 36: *The RLWI vessel Island Frontier. (Juel,2009)*

1. The Lower Intervention Package (LIP) is the first element which includes the main barrier elements which consists of a shear seal ram and two barrier valves, and a subsea connector.

2. The lower lubricator package (LLP) is the second main element. This consists of the workover control module that controls the functions in the subsea lubricator system, and the subsea grease system.

3. The Upper Lubricator Package (ULP) is the third element and includes a cutting ball valve and the lubricator tubular.

4. The pressure control head (PCH) is the fourth element and consists of the emergency packing elements and wireline flow tubes.

5. The deployment of the PCH and wireline bottom hole assembly in open sea results in each wireline run. The PCH is locked onto the ULP and the BHA is lowered into the lubricator
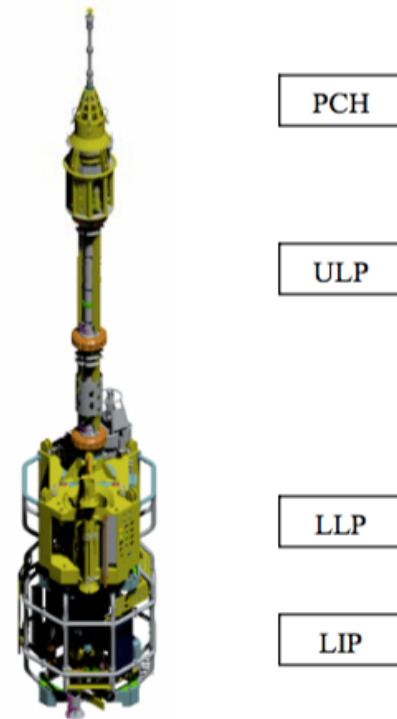
Figure 37: Subsea lubricator system. *(Juel, 2009)*

The control function of the stack and the grease system located subsea are employed through a long umbilical that is about 900 m in length. This umbilical is connected to the workover control system container located on the vessel. During the process of lubrication of the wireline BHA, there is a flushing mechanism of all hydrocarbons into the wellbore. The main umbilical and the wireline cable serve as the only connection to the vessel. The deployment of tool strings up to a length of 22 m is facilitated by the availability of a lubricator (Juel, 2009).

Operation sequences after the tool has entered the well:

1. Entering a live well: The tool is lowered to the target where the scale is precipitated (Figure 38 A).
2. The tool reaches the target: Data on the depth of the target is given by the operator (Figure 38 B).
3. Activation of the stabilisator arms: If there are uncontrolled movements of the tool, the stabilisator arms are activated further up (Figure 38 C).

Figure 38 A   *Figure 38 B*   *Figure 38 C*

4. The cleaning process begins: The scale is zapped, and the cuttings are transported up along the produced hydrocarbons (Figure 38 D).

5. The cleaning process is completed: The caliper is activated (Figure 38 E).

6. Pulling up the tool: The cleaning process is confirmed by the caliper (Figure 38 F).

Figure 38 D   *Figure 38 E*   *Figure 38 F*

3.6 Experiments carried out

The purpose of this master thesis is to evaluate the feasibility and effectiveness of the descaling tool in pipe/tubing, with respect to how the cleaning process affects steel pipe and what is the optimal spark effect.

The theory is based on Zaptec's technology. Their technology is currently being researched for drilling on Mars and microgravity environments. The concept differs from Zaptec's as this is to remove scale precipitations; thus, the environments of operation differ totally.

3.6.1 Design of the Tool

To better understand the concept technology and due to lack of existing plasma based WL tool in oil and gas industry, a new tool had to be designed from scratch. The concept design was based on Zaptec's drilling technology and current wireline technology. As a result of poor knowledge in design and animation software, design engineer *Oleiv Høyland* assisted. The software that were used: Autodesk Inventor Pro, Autodesk 3Ds max and Adobe After Effects.

The dimensions on the figures below are not representative and can not be considered as final dimension for the tool.
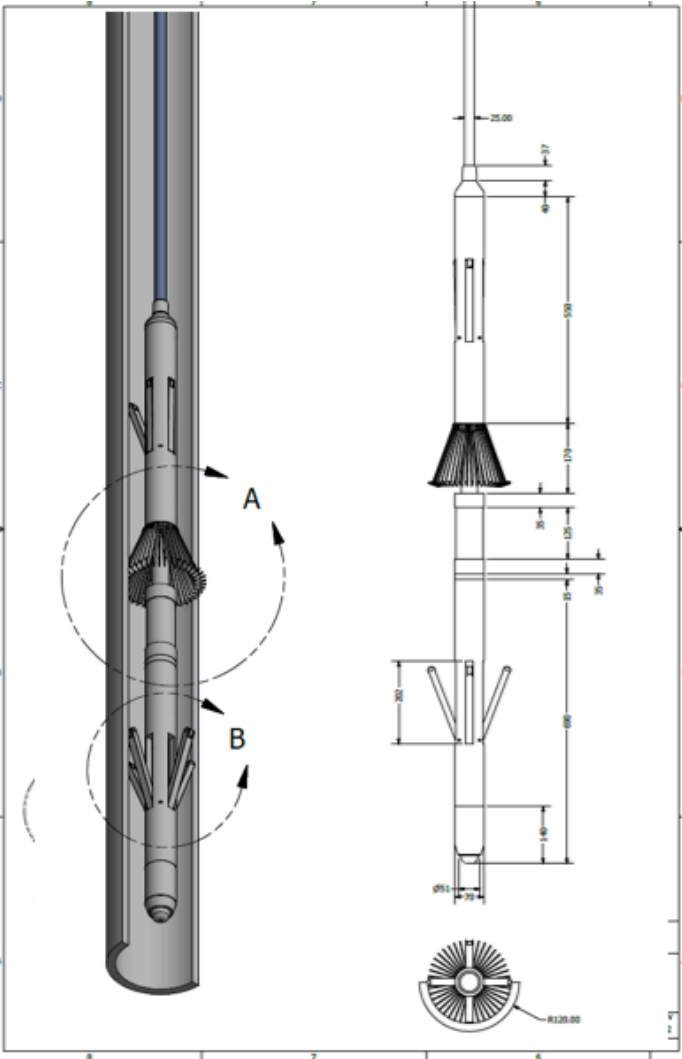
Figure 39: The design concept of plasma descaling tool with caliper (A) and stabilizer arms (B). The dimensions on the figure is not representative (Designed by the author of this thesis)

3.7 Preperation of the lab tests

The concept was tested experimentally in Zaptec's laboratory. The experiments had to be designed in such a manner that it replicates the real life conditions inside a well yet feasible with the limited resources currently available at the laboratory. The high pressure and high temperature inside a hydrocarbon producing well are the most challenging conditions to replicate.

3.7.1 Scale precipitation in tubing

It is commonly know in the industry that $BaSO_4$ is the hardest kind of scale and most difficult type of scale to remove is $BaSO_4$ (Mike Crabtree, 1999). The ideal time, pressures and temperature conditions for precipitating $BaSO_4$ in lab is also unsure. It is necessary to have the right equipment, such as a chamber that can withstand high pressure and temperature for a longer time. Furthermore, we were in touch with an engineer from ConocoPhillips to acquire a test tube, which contained $BaSO_4$, but due to the radioactive nature of content it was not safe to handle with our resources. Due to time limitations, the uncertainties around creating $BaSO_4$ in the lab, we chose to use cement as an analogous material to $BaSO_4$.

3.7.2 Tubing Size and Length

To perform the tests most realistically, we used old production tubings from the oil industry. We chose four different tubing sizes for the preparation of the first tests.

Table 5 The different tubing dimensions used in the experiment.

No.	Inner diameter [cm]	Length [cm]
1	13,6 cm	23,0 cm
2	10,2 cm	20,0 cm
3	12,5 cm	20,0 cm
4	12,5 cm	22,0 cm

Processing of the tubs

The practical length of the tubing was set to around 20,0 cm long. The cutting process was done using a metal saw, ARG 400 Plus S.A.F, accessible at the mechanical engineering department at the University of Stavanger.

.

Figure 40: The metal saw, ARG 400 PLUS S.A.F

After all the various sizes of the tubings were cut to the desired length, a hole was drilled into the tube for a screw. This was done to secure the grounding wire. In addition, the surrounding area of the tube was scratched to remove the surface coating of the tubing so the grounding wire would have better contact with the metal tube. Figure 41 and 42.

Figure 41: Create the screw threads

Figure 42: Scraped around the screw hole to get better connect between the wire and screws.

3.7.3 Cement mixing

As mentioned earlier, cement was used an analogous material as a replacement for scale. The cement was mixed by Hobart N50 5-Quart Mixer for 23 minutes (Figure 43) and dried for three days. The mixing ratio used was according to the *industry* standard 792 g of cement was combined with 349 g of water (Nelson & Guillot, 2006). At this ratio the water would fill all the pores in the cement. This combination yields a cement volume of 1,57 l.

The equation used to find the volume was:

Figure 43: Hobart N50 5-Quart Mixer (www.hobartcorp.com, 2016)

$$A \ [dm^2] = \frac{\pi}{4} * D^2 \ [dm^2] \tag{16}$$

$$V \ [dm^3] = A \ [dm^2] * L \ [dm] \tag{17}$$

Where:

V: Volume [dm^3] (1 dm^3 = 1 l)

A: Area [dm^2]

D = Diameter of the tube [dm]

L = length of the tube [dm]

Calculating the volume of cement needed for tube no. 4:

- Inner diameter of the tube: 1,22 dm

- Outer diameter of the metal tube: 0,87 dm

- Length of the tubing: 2,2 dm

Volume of cement needed:

$$A = \frac{\pi}{4} * (1,22^2 - 0,87^2) \, [dm^2]$$

$$V \, [dm^3] = 0,5745 \, [dm^2] * 2,2 \, [dm]$$

$$\underline{V = 1,26 \, [dm^3]}$$

In other words the ratio mentioned previously would yield enough cement.

We started off by determining the volume needed to fill the different tubes. Two of the tubes (no. 1 and no. 2) were completely filled with no conduit passing through. Tube number 2 was filled cement as well as barite. The barite to cement ratio used was 50/50 with small quantities of water added. This was done to strengthen the cement and get properties that reflect barium sulfate. The last two tubes (no. 3 and no. 4) were filled with cement and had a conduit through them with a cement thickness of 2,5 cm and 1,8 cm respectively. The cement thickness was made by using a closed-ended metal tube, positioned centrally. The metal tube was lubricated with grease, in order to remove it easier when the cement was dry.

Figure 44: Tube number four with a metal tube inside for creating the desired cement thickness.

Figure 45 shows the different tubes filled with cement.

Figure 45: A Tube number 1 filled completely with cement and barite mix.

Figure 45: B Tube number 2 filled completely with cement.
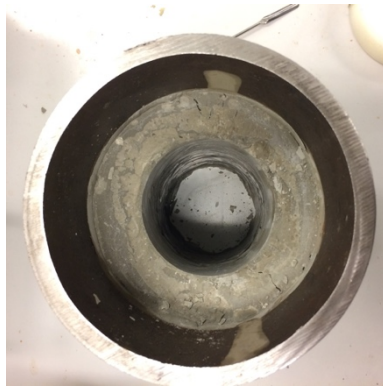
Figure 45: C Tube number 3 with 2,5 cm cement thickness.

Figure 45: D Tube number 4 with 1,8 cm cement thickness.

Table 6 Summary of the different tubing sizes and cement height for experiment phase 1.

Nr	Inner diameter [cm]	Length [cm]	Height of Cement [cm]
1	13,6 cm	23,0 cm	18,3 cm
2	10,2 cm	20,0 cm	15,5 cm
3	12,5 cm	20,0 cm	14,2 cm
4	12,5 cm	22,0 cm	15,0 cm

3.7.4 Test rig setup

A test rig was built to perform the tests. The figure below (Figure 47) shows the setup made by a combination of wood and metal holders for holding the tube in the right position. It was also taken into account incase the zapping caused movement of the tube. The whole platform then placed inside a container to hold excess water.

Figure 46: Plastic container for putting the test rig setup inside and holding the water in place.

Figure 47: The test rig setup for holding the tubing in position during the experiments.

The final rig setup is illustrated below, figure 48;
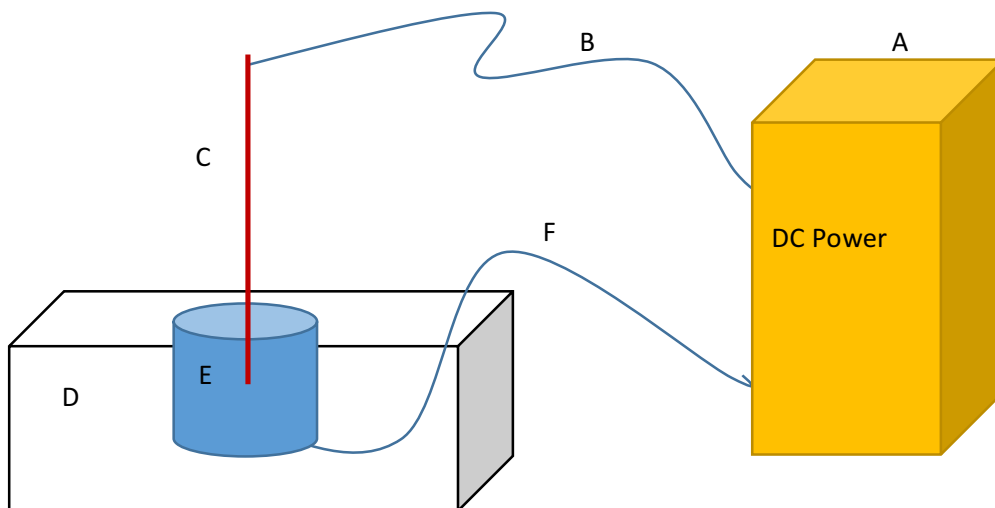
Figure 48: Final setup for the rig.

Description of Figure 48:

A: Power supply: Can deliver up to 35 000 V. This power supplier is only used for tests in the laboratory. According to Zaptec, their electronic device can deliver up to 200 000 V.

B: High voltage cable.

C: Metal rode made out of stainless steel with a grade of 316 is used (Figure 65 B). Isolated with electrical tape to the tip of the metal rode. This will prevent the sparks from returning back to the electrode itself.

D. Plastic container for holding the water during the experiments.

E. Metal tube with cement inside.

F. Return electrode connected the metal tube with bolts.

3.8 The lab tests

To obtain most accurate results we preformed six tests in the lab in the first phase. Based on the results obtained from the first phase, we made some adjustment to the experiment and carried out another four tests in the second phase of the project. The description, pictures, results and comments to all the test are described below.

3.8.1 Phase 1

In the first phase, the experimental setup was based on theoretical knowledge. An electrode with power output of 35 kV was used in all the tests.

Setup 1

Description: Test tubing no. 2 was used. It had a conduit with an inner diameter equal to 10,2 cm and the tubing was filled with cement and it had a distance of 5,5 cm from the tubing top. Fresh water was used to get the effect of shock wave created by the plasma channel. The electrode was centralized in the tubing, attached to the cement top. The plastic container was filled 1/6 with water.
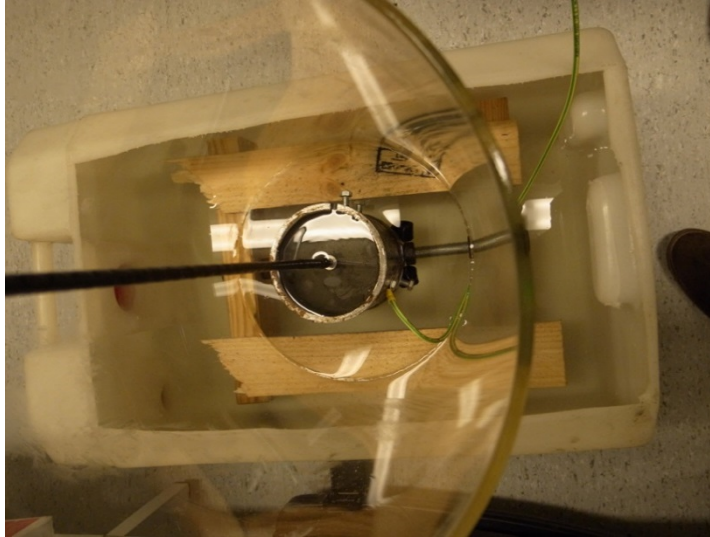
Figure 49: *Test upset 1. The electrode rode was centralized in the tubing, attached to the cement top. Fresh water was added.*

Result: One spark was fired and the plasma channel went directly to the wall of the tubing. Neither the plasma spark nor the shock wave had any affect on the cement.

Comment: Nothing happened to the cement and this can be explained by the fact that sparks tends to follow the least resistant path, and in this case it was straight to the metal cylinder wall through the water. The whole process was over in some microseconds; hence it was only possible to see a flash with the naked eye. However, we managed to film the process and replayed it in slow motion. This allowed us to observe what actually took place. We also noticed a shock wave in the water due to movement of the water. However, this didn't have any effect on the cement.
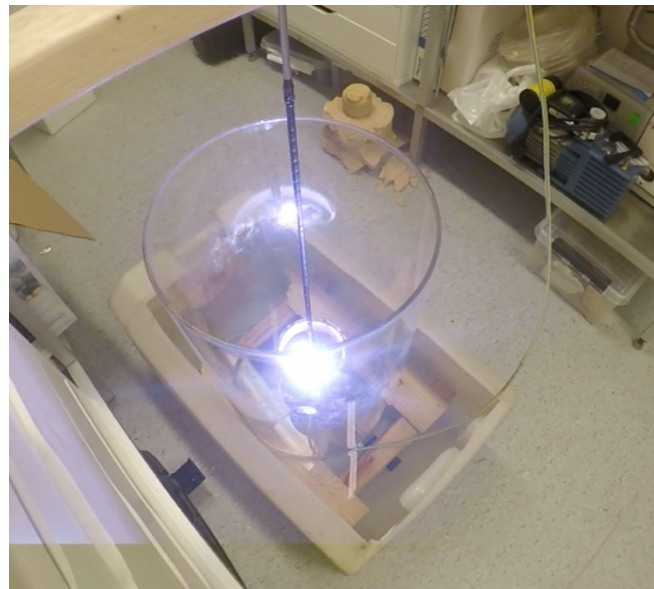
Figure 50: *Test results 1: Neither the plasma channel nor the shock wave had any effect on the cement.*

Setup 2

Description: The same tubing as in setup no. 1 was used with fresh water as dielectric liquid. Here the electrode was positioned 1 cm away from the tubing wall and attached to the cement top. We wanted to see if the sparks channel would damage the cement if the electrode was placed closer to the tubing wall. The plastic container was filled 1/6 with water.
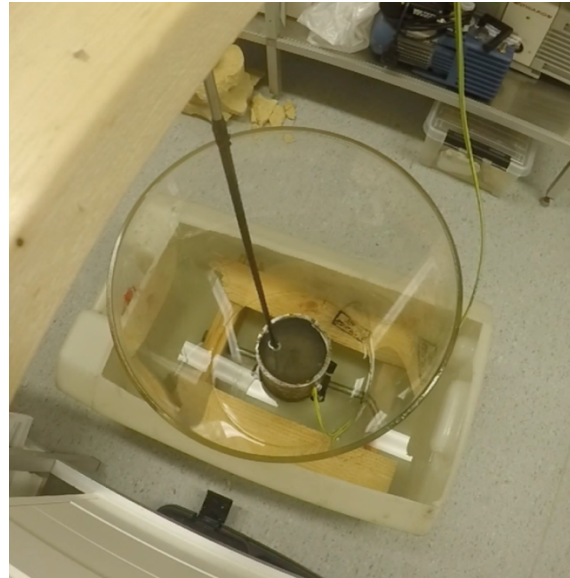
Figure 51: The electrode is positioned 1,0 cm away from the tubing wall. Fresh water is added.

Result: In total 14 sparks where fired over a period of 47 seconds. The plasma channel went directly to the wall of the tubing. Neither the plasma nor the shock wave had any significant affect on the cement.

Comment: Nothing happened to the cement. We observed that the water got slightly cloudy and contained small dust particles of cement. This is probably a thin layer from the cement surface that detached due to the shockwave.
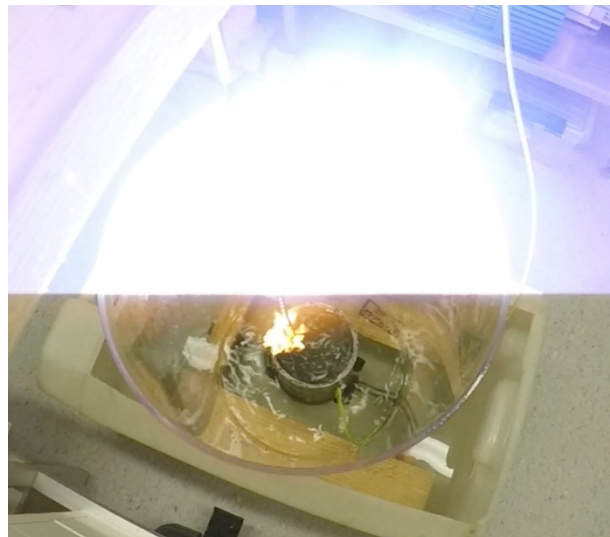
Figure 52: Test result 2: Here we see one of the sparks and electrolysis of water. The plasma channel didn't have any effect on the cement.

Setup 3

Description: The same tubing as in setup 1 was used, but here we used salt water with a ppm of 36 000 (500 ml water w/18 g NaCl) instead of fresh water. The electrode rode was centralized in the tubing and attached to the cement top. In this setup we wanted to look the effects of increasing the conductivity.
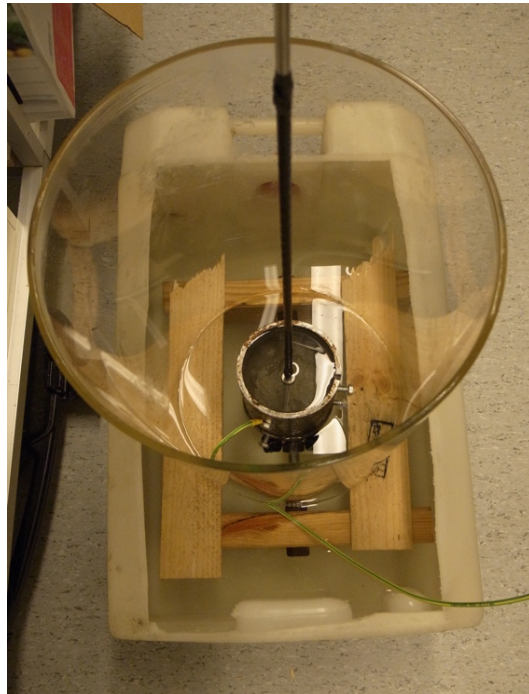
Figure 53: Test setup 3: The electrode was centralized in the tubing, attached to the cement top. Salt water was used.

Result: The plasma channel went directly to the wall of the tubing. Again we observed that neither the plasma nor the shock waves had any significant affect on the cement.

Comment: Increasing the conductivity didn't have any effect on the direction of the sparks.

Setup 4

Description: In this setup tubing no. 4 was used with inner diameter equal to 12,5 cm and the tubing was filled with cement until a distance of 5,5 cm below the tubing top. Fresh water was used to get the effect of shock wave. The electrode was positioned into the cement wall, with a depth of 4,5 cm below the cement top. This position was chosen because we wanted to create a greater distance to the metal wall at the top of the tubing, such that easiest way for the sparks will be through the cement. The plastic container was filled 4/6 with water.

Figure 54: Test upset no. 4: The electrode rode was positioned into the cement wall, with a depth of 4,5 cm from the cement top. Fresh water was used.

Result: A total of 7 sparks were fired whereas only one of them was charged with 35 kV. The rest was ignited due to low resistance. The plasma channel together with the shock wave did some damage to the cement. Figure 55 shows the damaged zone with a crater-diameter of 2,40 cm. We observed that from the centre of the crater there is a vertical crack going all the way to the top and bottom of the cement. (Figure 56 and Figure 57).

Figure 55: Test result no. 4: Damage to cement due to the sparks and shock wave. The diameter of the damaged zone is 2,40 cm.

Figure 56: *Test result no. 4: The crack has propagated down to the bottom of the tube. The picture is taken from bottom of the tube.*

Figure 57: *Test result no. 4: The crack has propagated up to the top of the cement. The picture is taken from above of the tube.*

Comment: In this test we observed that the sparks, together with the shock wave did some damage. We believe the cause of this was the distance between the electrode and the metal tubing. This resulted in the spark penetrating the cement instead of directly entering the tubing, as that was the path of least resistance. In addition, the energy stored in the initial phase of the spark was consternated into the cement (Timoshkin, Mackersie, & MacGregor, 2004). We preformed three more tests with the same setup, but didn't get any desired result such as in setup 4. We observed that the resistance was too low due to the crater opening and the crack. The sparks disappeared before they managed to cause pressure difference to make further damage.

Setup 5

Description: After many attempts with setup 4, we chose to drain the water to increase the resistance. The same tubing was used as in setup 4 with the same position and depth of electrode.

Figure 58: Setup 5: The electrode was positioned into the cement wall, with a depth of 4,5 cm from the cement top. No water was used.

Result: One spark where fired with 35 kV. The spark went to the top of the tubing and had no impact on the cement, Figure 59.

Comment: We observed that the resistance was too low and the easiest path for the spark through the air was directly to the metal tubing.

Figure 59: Test result no. 5: The sparks went to the top of the tubing as shown in the picture.

Setup 6

Description: The same tubing as in setup 5 was used with no water added. To increase the resistance, we lowered the electrode further down, 2,0 cm away from the bottom of the tube and we also placed a rubber mat under the tube. The setup is illustrated in the Figure 60. To observe the behaviour, we fired only one spark with 35 kV.

Result: From observing of the recorded film clip, its visible that a spark was ignited, moved to the top of the cement and was reflected into smaller sparks and was again reflected by the cement wall on the opposite sides of the electrode (Figure 61 A and B). This spark was highly energized and did some damage to the top of the cement (Figure 62).
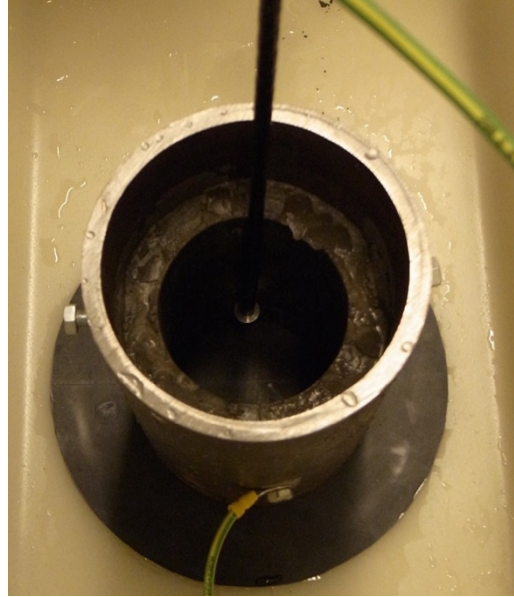
Figure 60: Setup 6: The electrode was positioned in contact with the cement wall, with a distance 2,00 cm away from the cement bottom. A plastic rubber mat was placed under the tube to increase the resistance. No water was added.

Figure 61 A: The spark was reflected from the top of the cement divided into two separate sparks.

Figure 61 B: The spark goes towards the cement top and causes some damage.

Comment: Controlling the direction of the sparks are proving to be a challenge, however when it did move in the desired direction its potential and power was evident.

Figure 62: The damaged caused by the reflected spark.

Adjustment of phase one:

As a consequence of weak result from phase one, the experiments was not performed on tubing no. 1 and 3. This was due to the similar cement composition, thicker cement wall and identical setup for the tubes no. 2. and 4.

3.8.2 Phase 2

Based on the experiments and results from phase one, we did some adjustments as we saw that the sparks always came to the top of the cement (the path of least of resistance). The top of the electrode was isolated in a better way so that the lightning does not go the cement top. The pipe size was also reduced to concentrate the sparks and reduce the distance from electrode head to cement wall. All the tests in phase two were preformed with a 35 kV power supply.

Isolation: Plastic is a good isolation material, so a plastic bottle was used with a tape around the bottle and isolation foam inside of the bottle (to fill the void) to improve the isolate further.

We made two types of isolation with two purposes. One of them was mainly made to prevent the lightning from jumping up to the surface of the tubing (Figure 63 A). The other was made in order to prevent the sparks from jumping up to surface and control the direction of the sparks (Figure 63 B). Both isolators (A and B) were designed to fit into the different tubes (no.1 and 2- phase two) with the specific cement thicknesses.

Figure 63 A: Isolater A, a funnel head from "Bilteam" was used to isolate and prevent the sparks jumping to the surface in the smaller sized tube.

Figure 63 B: Isolater B, to prevent sparks jumping upwards to the surface and controlling the directions of the sparks by an opening in the isolation wall. A bottle was used, filled with isolation foam and surrounded with tape.

Tubings: In this phase two different tubing sizes were used. The small sized tube was filled with cement with an empty inner core throughout the whole tubing to create a conduit. While the other one was close-ended with cement.

Table 7 Shows the inner diameter, the length and the cement thickness of the new tubes for experiment phase two.

No.	Inner diameter [cm]	Length [cm]	Cement thickness [cm]
1.	5,1 cm	56,0 cm	2,0 cm
2.	10,2 cm	36,0 cm	0,6 cm

Figure 64 A: *Tubing no. 1 with inner diameter of 5,1 cm and a cement thickness of 2,0 cm. Open ended.*

Figure 64 B: *Tubing no. 2 with an inner diameter of 10,2 cm and a cement thickness of 2,0 cm. Closed ended with cement.*

Electrode

A new electrode with a sharp tip was used due to the small diameter of tubing no. 1. The sparks will always be ignited in the sharpest edge. The electrode was again isolated with electrical tape similarly to the electrode used in phase one. The previous electrode was made out of stainless steel with a grade of 316. The new one was a normal metal rode with unsure metal properties.

Figure 65: A The new electrode used in experiments setup, phase two.
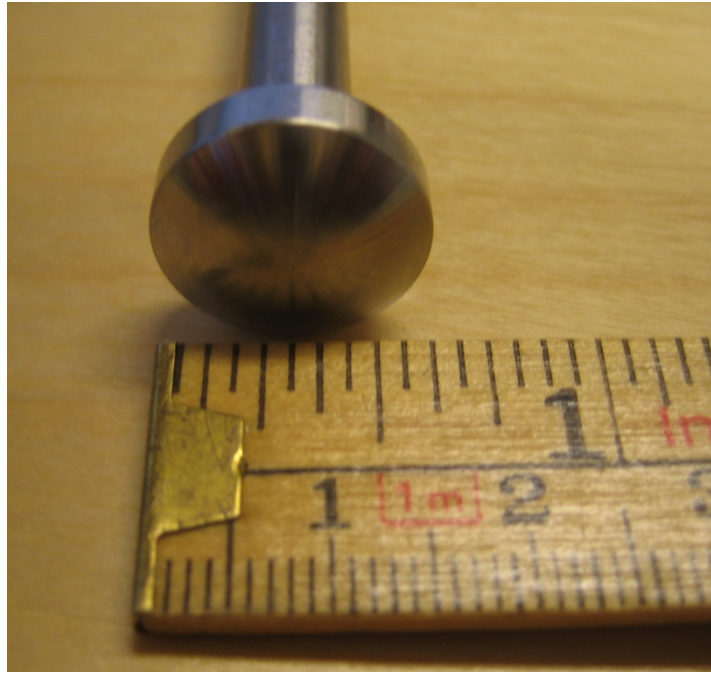
Figure 65 B: The electrode used during experiment phase one

Setup 1

Description: For this setup tubing no. 2 was used without water and with isolation B (Figure 63 B). Only one spark was ignited to observe its behaviour. The electrode was lowered 9,5 cm below the cement top.

Result: The isolation was a success and the spark created a small crater with a crack going all the way to the top of the cement. The spark was ignited at the opening area in the isolation as it was made for.

Figure 67: Setup 1, phase 2. Tubing no. 2 with isolation B.

Figure 66: Test result from setup 1. The spark created a crater and fractured the cement all the way to the top.

Comment: The damage zone was small in diameter and the bonding between the cement and tubing wall was still strong.

87

Setup 2

Description: Same setup, tubing and isolation to that of setup no. 1 in phase two were used. We added water to get the effect of the shock waves. The direction of the opening in the isolation was positioned so that the sparks would be ignited in the opposite side of test tube. Isolation A was also used to get a better isolation in the part above the isolation B (Figure 63 B).

Figure 68: Setup 2. Tubing no. 2 with isolation A and B. Water was added to the top of cement.

Result: The spark was again able to create a crater with a vertical fracture along the conduit.

Comment: The sparks and the shock wave had small impact on the cement and tubing.

Figure 69: Test result from setup 2. Minor damage to the cement and fractured to the top of cement.

Setup 3

Description: A different setup was used. The electrode and the return-electrode were both placed inside the water filled tubing no. 2. The distance between them was 8 cm. The tip of the high voltage electrode was placed 2,0 cm above the cement bottom.

Result: Four sparks were fired with five seconds intervals. The tube was leaking after the experiment. All the sparks were fired with 35 kV however only two of them were observed to have a significant impact on the cement.

Comment: The tube was closed-end with cement. After the experiment the sparks created micro channels on the bottom, which was difficult to see with the naked eye.

Figure 70: Setup 3. High voltage electrode and return electrode with a distance of 8,0 cm, placed inside the tube with fresh water.

Figure 71: Test result from setup 3. The sparks created micro channels on the bottom of the tube and led to leakage.

Setup 4

Description: The aluminium tube no. 1 was used in this experiment with isolation A. The isolation covered the electrode so that only the head was visible. As in the other experiments (except setup 3, phase 2) the return electrode was connected to the tube from outside and no water was added.

Figure 72: Setup 4. Aluminum Tube no. 1 was used with isolation A. Return electrode connected outside the tube and no water was added.

Result: One spark was fired and damaged the cement. It created a cone shape crater, however the cement did not separate from the metal tubing wall, Figure 73 (Experiment no. 1). Next we fired two more sparks, but lowered the electrode further down. Again it did damage to the cement, Figure 73 (Experiment no. 2).

Comment: All sparks from both experiment one and two did damage to the cement. The direction of the fragmentation zone was the same at both heights, suggesting that the damage was concentrated in the zone closest to the discharged electrode. Understanding the reasoning behind the choice of direction is recognised as a challenge. The cement thickness is the same for both heights.

Figure 73: *Test result from setup 4. To sparks from to different height was ignited and created two different shaped crater. Experiment no. 1 is shaped as a cone and experiment no. 2, two small elongated cone shaped.*

4 Discussion and Analysis

In chapter four the concept's technological reliability and the results gained from the experiments will be discussed. Furthermore, the different methods of performing the tests will be examined. The aim of these is to determine if the experimental setup was designed in a way that qualifies the results for drawing a conclusion on the feasibility of using the plasma technology for removal of scale precipitation on production tubing.

Due to radioactive content in $BaSO_4$, industrial cement was used as an analogue material. Scale, like $BaSO_4$ and cement, has different material properties such as its pore space volume, physical and chemical composition and structure. Because of the different chemical compounds, the material may have different conductivity, and the sparks may also change behavior. The chemical bonding, different hardness and the pore space volume of $BaSO_4$ may also have a great impact on how the material brakes, size of the fragments and how the material will yield from the tubing wall. These differences between $BaSO_4$ and cement, will mean that the conducted cement tests in this thesis may not be reliable for evaluation of the plasma based descaling method for $BaSO_4$ removal.

In phase one, we observed that the experimental setup satisfied our requirement of an external return of the high voltage pulse. The production tubing functioned as an effective return electrode. Otherwise, we would have had a short circuit inside the power supply. Even though we had a return of the sparks, we faced a difficult challenge to control the direction of the electric sparks. Most of the time the sparks went through the water, directly to the tubing wall and disappeared through the return electrode. Since the sparks went directly to the tubing it didn't have any effect on the cement. We used water as the dielectric liquid to force the sparks through cement to create permittivity differences between the water ($\varepsilon_{water} = 80$ and $\varepsilon_{concrete} = 4,44$-$7,22$) and the solid phase, which is cement in this thesis. Timoshkin I. V., et al (2004) indicated that the electrical field will then be forced out of the medium of higher permittivity (water) and concentrated in the medium of lower permittivity (cement). Water also has values of critical breakdown field greater than that of rock for electrical pulses with a rate of rising fields of more than 70 kV/cm per μs (Timoshkin, Mackersie, & MacGregor, 2004). Therefore, the rock fails electrically before the water.

This means that for high-voltage pulses with a risetime of about 0.5–0.8 μs or less the breakdown strength of water is greater than that of rocks such as sandstone, shale, or marble (Timoshkin, Mackersie, & MacGregor, 2004).

We assume that this is valid for cement as well and in our experiments, unfortunately we only had access to a maximum voltage of 35 kV. There was also no available measurement equipment to detect the risetime. Because of these errors we didn't get data about the parameters discussed above for the plasma channel.

If water is replaced by oil as the dielectric liquid, the same effect will be observed for pulses with a longer risetime, i.e., lower rates of rising fields (Timoshkin, Mackersie, & MacGregor, 2004). This means it should be easier to form a plasma channel when operating in oil producing wells.

Water was also used to get the effect of the shock wave created by the sparks. If the sparks are ignited in water they will be confined by the surrounding water. The surrounding water will confine the plasma channel, giving a narrower channel and as a result higher pressure (10^5-10^6 psi) (Maurer, 1968). As water is incompressible it will also give effective propagation of the pressure pulse in the liquid. The pressure created is dependent on the length of the sparks, risetime and also the energy emitted in the pulse (Timoshkin, Mackersie, & MacGregor, 2004) and (Page, 1977). From the experiments and observations from the video clips we saw that the shock wave was concentrated around the sparks (plasma channel), but did not appear to have any effect on the fragmentation process. There were variations in the observed pressure pulses. Sometimes strong wavy surface water movement was observed, with water occasionally splashing out of the tube after the zapping, suggesting formed pressure pulses in the water. Other times after sparking only weak movement in the surface water was observed, suggesting weak pressure pulses. This could be due to low energy in the sparks, as a result of low resistance in the tubing and uncontrolled early ignition of low energy sparks. The tubing was also open-ended and if the sparks had low risetime/energy, the shock wave would have time to dissipate. Lastly, we observed the same type of damage in experiments in water and in air, suggesting that the pressure wave in water had little impact on the observed fragmentation.

Based on observations from the experiments in phase one, another challenge with the plasma sparks was also detected. Due to the low resistance in the damage zone from the first spark, the next spark followed the same path as in spark number one. This minimized the damage zone, as the sparks following spark one mostly bypassed the solid phase.

In test setup one in phase one where the electrode was placed at the top of cement, we observed after several sparks that the water contained some cement fragments. These fragments resulted in a higher particle content of the water, making it easier for the sparks to be conducted through the water. To prevent the low resistance due to these cement fragments, the experimental setup would require a flow loop for the dielectric liquid. However, in a live production well the effect of these "scale" fragments should not be important.

Taking into account the challenges from experiment phase number one, some corrections were made. Two different types of isolator were made to prevent the sparks jumping up to the surface of the tubing by covering the area above the electrode head. In addition, isolator B (Figure 63 B) was also designed with 2 cm opening along the side of the bottle to control the direction of the sparks. Isolator B worked as desired, both controlling the direction of the sparks, and preventing the sparks from jumping up to the surface. However, small damage was made to the cement. One of the reason could be the large distance from electrode head to the cement surface. The pressure difference created by the sparks is concentrated towards the beginning of the spark, as the voltage across the electrode decays exponentially with spark length (Timoshkin, Mackersie, & MacGregor, 2004), and the sparks would have low energy once it reaches the cement wall. This problem could be solved by minimizing the duration time to the cement by positioning the electrode in contact with the cement wall. In this way the energy could be maximized for crushing the cement (Timoshkin, Mackersie, & MacGregor, 2004).

To test the implication of duration time, a second set of tests were conducted in setup four, phase two (Figure 72 setup 4 phase 2). In these experiments we used a tube with smaller diameter and an electrode in contact with the cement wall. We observed that the cement was successfully fragmented, even without water in the pipe. Here the energy of the sparks was concentrated into the cement, due to the short distance between electrode head and cement wall, with isolator A (Figure 63 A) preventing the sparks from jumping to the surface of the pipe. In this experiment the electrode was lowered further down and again we saw damage to the cement. The direction of the fragmentation zone was the same at both heights, suggesting that the damage was concentrated in the zone closest to the discharge electrode. Further examination with more sparks in the same height showed no additional fragmentation. This was, as discussed above, due to the opening in the damage zone such that the path with lowest resistance was through the already opened zone. Since the technology is based on using high voltage, there could be a risk of damaging the down hole electrical gauges. When operating nearby electrical equipment, the electrical sparks could lead to short circuits or in worst case destroy the measurement sensors. Further investigation is required to observe how far the high voltage current will propagate along the surface of the production tubing before it dissipates. Other solutions could be, (1) to disable the connection to the gauges so that there is no flow of electrical current, and (2) to have the return electrode as a part of the WL descaling tool such that the high voltage will return throughout the wireline cable instead of the production tubing.

There could also be some concern to the electrolysis effect we discovered in setup two, phase one. Normally inside a well there is no oxygen, which means no fire could occur due to the spark alone. However, in this case high voltage sparks could separate hydrogen and oxygen when water is present. This could possibly lead to an explosion, potentially fracturing the tubing. Three different thinkable outcomes are possible. (1) The pressure inside the well is large enough to prevent the electrolysis process. (2) The effect of the sparks separates few molecules and the effect of the reaction will be negligible. (3) The molecules are separated but do not react before they reach the separator at the surface. This could have dangerous consequences, and in the worst case lead to an explosion. However, from observations in experiment setup two, phase 1, the reactions between hydrogen and oxygen appear to occur as soon as the compounds are formed, suggesting that scenario (3) described above is unlikely.

5 Conclusion

This thesis has had a special focus on removing scale with plasma-based technology. Important aspects of spark operations have been presented. The objective has been to look at Zaptec's plasma-based drilling technology and their patented electronics to prove whether it is possible to create a better scale removal technique. Furthermore, to see if there are parts of the operation that can be improved. This includes looking at the existing plasma based technology and the experiments that were carried out.

Based on the experiments and knowledge gained, the following conclusions can be made:

- The production tubing functioned as an effective return electrode under the experiment and satisfied our requirements.
- Test setup with the large diameter tubing was not so successful due to the great distance between electrode and cement. It is necessary to have direct contact, higher voltage and lower rise time. In addition, more than one electrode is needed.
- Water was used as dielectric liquid and to get the effect of the shock wave created by the sparks. However, this did not appear to have any effect on the fragmentation process with this voltage and electrode.
- Due to the low resistance in the damage zone from the first spark, the next spark followed the same path as in spark number one. It could result in that the cleaning process will not be 100 % efficient. It is necessary to have more detailed experiments and developed an electrode that could remove the scale totally and in 360 degrees.
- Two different types of isolators were made to prevent the sparks jumping up to the surface of the tubing by covering the area above the electrode head. Both proved to be successful. (the spark didn't damage the cement because of the large distance)
- In one of the experimental setups, a tube with smaller diameter and an electrode in contact with the cement wall was used. It was observed that the cement was successfully fragmented even without water in the pipe. This indicates that the setup with electrode head distance and voltage available were too low for the tubing with greater diameter.
- The concept design of the tool needs to redesign to get direct contact with the scale wall. A recommendation of the new electrode head design is shown in the Figure 74.

The potential to use plasma sparks to fragmenting solid rock in laboratory is well known. This could also have a potential to remove scale from production tubing. To achieve this, more detail experiments need to be carried out with focus on the discussed parameters below.

### *Recommendation for the new electrode head design.*

Based on the knowledge gained from the experiments in phase one and two it is necessary to redesign the electrode shape, size and how the electrode should be in contact with the cement/scale.

The shape of the electrode is an important part to controlling the sparks into the desired direction. The size and shape of the electrode will provide better contact between the electrode and scale. In addition, it will improve the spreading of the sparks across the surface of the electrode head.

Two new improved design of an electrode head is shown in the Figure 74 and Figure 75. Both designs consist of 12 arms and each arm is equipped with an electrode. The design to the left, Figure 74, uses the tubing as the return electrode. While, Figure 75 illustrates a design of an electrode head where every second arm functions as a return electrode (shown as arms with red points). The arms have the ability to expand and retract in diameter in order to adjust them self to the scale thickness. I believe this new design is more reliable than the initial suggested electrode head design.
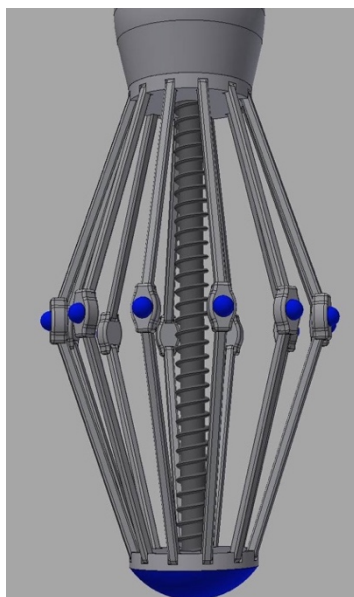
Figure 74: New electro design. Tubing used as the return electrode.
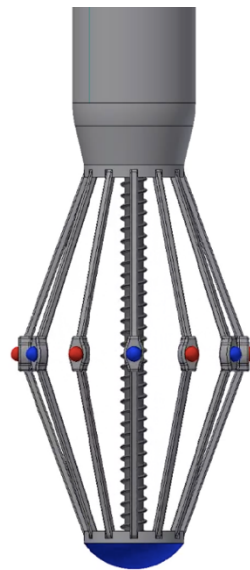
Figure 75: New electrode design. The arms with red points, functions as the return electrode.

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