Universitetet i Stavanger

The Science Faculty

MASTER THESIS

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Author: Kenneth Øksnevad Høydal	…………………………………………. (author signature)
Professor Supervisor: Tore Markeset **Company Supervisor:** Monika Bakke	
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Abstract

Stimulation operations of unconventional formations, such as tight oil- and shale gas formations are often necessary to achieve profitable hydrocarbon production. Several stimulation techniques and equipment are used for different applications, including hydraulic fracturing and acid stimulation. The oil and gas industry continuously develop new and more efficient techniques and equipment to save time and costs related to production of hydrocarbons. According to the U.S. Energy Information Administration, 47 percent of the world's gas reserves and 11 percent of the world oil reserves can be found in unconventional shale formations (U.S. EIA, 2013). Therefore, the potential of entering the market with innovative and efficient technology for stimulation operations is promising.

The content of this thesis is based on a zonal isolation tool used for stimulation of unconventional oil- and gas wells. The zonal isolation tool is a re-design of a previously developed prototype of an all-electric annular fracture tool developed by Target Intervention. The background theory of well stimulation operations as well as reviews of existing technologies including the current zonal isolation tool is presented in the thesis.

The main advantage of the zonal isolation tool developed by Target Intervention is that it is electrically operated with coiled tubing. Well stimulation tools used in the industry today are usually mechanically operated, thus limiting the control of the operation process. Thus, the goal is to reduce the operation time by being able to locate perforated zones in the reservoir formation more effectively by the use of integrated real-time electrical monitoring systems.

Operation and maintenance of the Zonal Isolation Tool are two of the most critical aspects related to asset management. After the tool has been manufactured, tested and approved ready for operation, efficiency, reliability and maintenance management are important topics the company needs to consider in relation to operation and maintenance. The main objective with this master thesis is related to development of procedures for operation and maintenance of the Zonal Isolation Tool. Critical aspects of development and design of procedures are discussed, as well as background theory of maintenance and maintenance management.

Contents

Preface

The master thesis that is the background for this report is conducted as part of a development project in collaboration with Target Intervention AS where I am currently employed as a mechanical design engineer. The company is developing a zonal isolation tool for stimulation operations of unconventional oil- and gas formations. In addition to working as part of the mechanical design team, I have been given tasks related to operation and maintenance of the zonal isolation tool. This has been the basis for the final master thesis, and the report will be the completion of my master program, Offshore Technology – Asset Management at The University of Stavanger (UiS).

This master thesis has challenged me to work towards future management of the zonal isolation tool the company is developing, thus enabling me to use the knowledge I have acquired from my studies at UiS. Combined with a bachelor degree of mechanical engineering and my current job related to mechanical design, I will have the required knowledge about the operating functions of the tool. This will be a great advantage during the development of the operation- and maintenance procedures.

I would thank my supervisor at The University of Stavanger, Tore Markeset, Professor of Mechanical Engineering (Operation and Maintenance) at the Dept. of Mechanical & Structural Eng. and Material Sc., Faculty of Science and Technology. Professor Markeset has offered great help with structuring the contents and reviewing the report.

Further, I would like to thank my supervisor at Target Intervention AS, Monika Bakke Malmin, Managing Director of Target Intervention AS. Monika has offered great assistance in the development process.

Ålgård, 16.06.2013
Kenneth Øksnevad Høydal

Structure of Thesis

The initial part of the report presents the general background theory and application of well stimulation tools and techniques of unconventional oil and gas wells. This is the context for developing the Zonal Isolation Tool and forms the basis for the following elements of the report.

The main contents of the report are structured into four sections:

I) **Zonal Isolation Tool:** Presentation of the Zonal Isolation Tool developed by Target Intervention AS. Existing technology and zonal isolation case study are discussed.

II) **Operation Procedure:** introduction to the background theories and elements that forms the foundation for the operation of the Target Intervention Zonal Isolation Tool. Discussion of the development of operating procedures for down-hole tools is included. The objective is to highlight the important aspects of operation for the Target Intervention Zonal isolation tool.

III) **Maintenance:** theory and discussion of different techniques, tools, and management related to maintenance is included.

IV) **Maintenance Procedure:** discussion of the development of maintenance procedures for down-hole tools. The objective is to highlight the important aspects of maintenance for the Target Intervention Zonal isolation tool.

Summary and Conclusions: Summary of the project and the contents of the report. Conclusions on whether the objectives of the project are answered are included.

Appendix: Drafts of the procedures for operation (*Procedure Tool Operation)* and for maintenance (*Procedure Tool Maintenance)* of the Zonal Isolation Tool developed by Target Intervention AS are attached in the appendix.

1 Introduction and Background

Target Intervention is currently developing a zonal isolation tool for the oil and gas industry. The main application area for the tool is going to be well stimulation operations including hydraulic fracturing and acid stimulation of wells in onshore production areas in Canada and USA.

Stimulation operations of oil and gas wells are used to maintain or to increase the production volume of wells. Generally, stimulation operations are used in reservoir formations with low porosity and permeability such as in tight-oil and shale gas reservoirs. Different stimulation techniques will be presented later in this chapter.

The principle of the zonal isolation tool is that several pre-perforated zones in reservoir formations can be isolated and stimulated in one single operation. Down-hole operations will be done with coiled tubing (CT), which allows implementation of electrical conductors (i.e. electrical wire-line inside the cubing). The operation of the tool will be fully electric with brushless DC motors activating the isolation modules. Mechanical slips will anchor the tool inside the wellbore, thus avoiding tool movement during stimulation. By expanding the packing elements, one at each side of a stimulation ports section the perforated zones will be isolated and sealed off. Sensors including pressure sensors, temperature sensors and electrical CCPL (casing collar and perforation locator) will be used to monitor the operation process. The operation process and condition monitoring is done through a computer system with a graphical user interface (GUI).

1.1 Problem formulation

In order to ensure effective and efficient utility of the zonal isolation tool it is required that clear and complete operation and maintenance procedures are developed. After the tool has been sent to the customer, maintenance is essential to ensure reliability and expected tool performance. In relation to operational activities, the operation procedure is essential to instruct the tool operators.

The operation procedure must contain a complete description of the all the tool functions and how to initiate them. Safety and security are important aspects to consider in the operation procedure. The maintenance procedure must contain a detailed and systematic description of the required maintenance of all the components and modules of the tool. It must include information about the different maintenance techniques (e.g. corrective, preventive, and predictive maintenance), and also in which facilities and under which conditions the maintenance must be done. Additional procedures related to maintenance activities such as assembly procedure, disassembly procedure, and inspection reports must be included.

One of the main challenges related to development of procedures for operation and maintenance is to make the documents clear and easy to use for operators and maintenance personnel. At the same time, all the required information and contents of the instructions must be included. Thus, practical experience along with theoretical knowledge is essential to include in the development process.

1.2 Objectives of the Project

The main objective of this thesis is to identify important aspects related to development of procedures for the operation and maintenance of the Zonal Isolation Tool developed Target Intervention AS. The report is intended to be used as a guide during development of the final procedures for the tool. The report includes important theory and information that should be considered when the final procedures are going to be developed in the future. When the production of the Zonal Isolation Tool is completed and it is ready to enter the market, both procedures should be of a quality that satisfies the requirements in relation to function, reliability and operability.

Sub-objectives

1. Identify the critical aspects of general design and development of operation procedures. Define the related tools/techniques used for creating operation procedures.

2. Create a drafted operation procedure for the Zonal Isolation Tool developed by Target Intervention AS.

3. Identify techniques, tools and strategies used for maintenance processes and maintenance management.

4. Identify the critical aspects of general design and development of maintenance procedures. Define the related tools/techniques used for creating maintenance procedures.

5. Create a drafted maintenance procedure for the Zonal Isolation Tool developed by Target Intervention AS.

1.3 Limitations

The development of the Zonal Isolation Tool is still on the prototype stage. Therefore, operation and maintenance procedures have been drafted without being tested as actual processes. Field testing of the tool prototype is scheduled in June 2014. This means that the use of the operation and maintenance procedures in practice will not be tested and verified during an authentic operation before the due date of this master thesis.

1.4 Research Approach and Resources

Information has been collected from available literature on well stimulation of oil and gas wells and on operation and maintenance of down-hole equipment. Internal documents from Target Intervention AS, as well as former master and bachelor reports have been studied. Moreover, material from lectures in courses taken during the Master program of Offshore Technology – Asset Management has been used. Knowledge, experience and recommendations from colleagues have also been considered during the project.

2 Context for Developing the Zonal Isolation Tool

The background for utilizing well stimulation tools are based on unconventional tight oil- and gas formations such as shale and dolomite. The natural permeability in these formations is extremely low, and production of hydrocarbons cannot be efficient unless formation stimulation is performed. Moreover, reservoir formation damage caused by drilling operations, cementing, and completion, etc. will reduce the formation permeability in the area surrounding the wellbore. Thus, stimulation operations may be needed for production of hydrocarbons in more conventional oil- and gas reservoirs as well.

This chapter covers the context for developing stimulation tools, such as the Zonal Isolation Tool developed by Target Intervention AS. Firstly, a brief introduction to an onshore well drilling and completion process is presented. This is the initial part of oil and gas production, and the first operation to be performed before stimulation activities can start. Further, important aspects related to operation of the tool such as reservoir formation properties, including pressure gradients of pore pressure and fracture pressure are introduced. This is important measures to consider when determining the required stimulation pressures during operation of stimulation tools. Finally, important aspects of formation damage and well intervention techniques are discussed.

2.1 Drilling and Completion of Onshore Wells

Well drilling and completion have the main purpose of extracting natural resources such as hydrocarbons from reservoir formations in deep layers of the earth. The overall drilling and completion process covers several stages of operation including various functions and processes. The different processes are often separated between individual companies that specialize in one particular function. A common breakdown of general processes would be (Petroleum Online, n.d.):

1. Well Planning
2. Well Design
3. Well Drilling
4. Reservoir formation Evaluation and Testing
5. Well Completion

It is essential that as much information as possible regarding the actual reservoir and the working conditions are known prior to drilling a well. Analysis of data gathered by geologists performing seismic surveys makes it possible to get a useful indication on where the reservoir formation is located. Further, in the well planning phase the specifications of the well design must be defined. All requirements and limitations such as completion intervals, final wellbore size and drilling depth have to be clarified.

Oil rig system

The most common method of onshore well drilling today is the rotary method. The major systems of a land oil rig are illustrated in figure 1. The main source of power in an oil rig system is provided by large diesel engines. A drill bit connected to the end of a series of joints of steel pipes, called a drill string, breaks the rock into cuttings during the drilling operation. The turntable drives the rotation of the drill bit using power from electric motors. The derrick is the structure that supports the drilling tool. It is essential that the derrick is tall enough to allow new sections, usually 10 meters long, to be added as the well gets drilled deeper. The casing is placed inside the wellbore to allow for circulation of drilling fluid and to prevent the borehole from collapsing. A blowout preventer is placed over of the well and under the rig with the purpose of sealing and bleeding off pressure when necessary to prevent a blowout of the well (Freudenrich and Strickland, 2010).

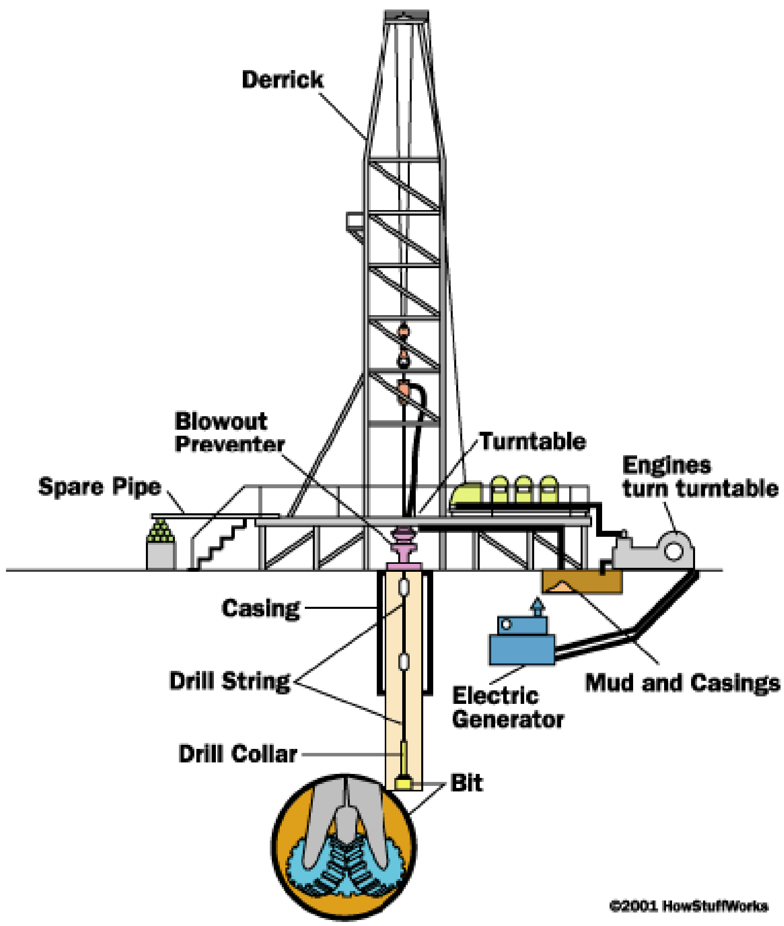

Figure 1 – Anatomy of a land oil rig (1)

Throughout the entire drilling process a special drilling fluid called drilling mud is continuously pumped down the well and circulated through the drill string. The drilling mud is a mixture of water, clay, chemicals and weighting material (Freudenrich and Strickland, 2010). Circulation of the drilling mud through the wellbore annulus ensures that:

- Cuttings are removed from the bottom of the well and transported to surface.
- The drill bit are cooled and lubricated during drilling
- Corrosion of drilling equipment are avoided/reduced
- The drilling mud acts like a pressure barrier against sub-surface pressure

In the circulation process the mud is returned through a shale shaker at the surface which removes the cuttings from the mud. The cuttings are then examined by reservoir geologists to identify the properties of the reservoir formation.

Pore pressure

Pore pressure is the hydrostatic pressure exerted by fluids within the pore space of rock in a reservoir. The pressure is generated by the weight of the rocks and fluids above the pore zone. The pore pressure can be predicted by a formula (Biot, 1941, Terzaghei et al., 1996):

$$p = (\sigma_V - \sigma_e)/\alpha \qquad (1)$$

where

- σ_c = overburden stress
- σ_e = vertical effective stress
- α = Biot stress coefficient

Prediction of pore pressure is essential for avoiding or mitigating risks during drilling. Drilling and completion in unconventional formations, such as shale gas formations, may present significant challenges in relation to pore pressure. In these formations, the pore pressure can increase to unusually high pressure over a short depth interval (Zhang and Wieseneck, 2011). The prediction in shale gas formations is critical because of formation anisotropy (i.e. directionally dependent properties such as permeability and stress) that may affect log responses.

A wellbore runs through several layers of the earth each with different material compositions and properties. During the drilling process the drill bit may encounter various formation zones with different pore pressures before reaching the targeted reservoir formation. In a zone of porous hydrocarbon bearing rock, the pore pressure in the formation will force the hydrocarbons out of the rock and into the wellbore (i.e. influx). Drilling mud is used to avoid such situations by counter balancing the pore pressure. As the well is being drilled, the weight/density of the mud column inside the wellbore is adjusted to generate a balanced pressure equal to the pore pressure within the reservoir rock. Depending on the depth of the well, the density of the drilling mud is increased as the pore pressure in the layers increases with depth. This type of wells, where the weight/density of the circulating drilling mud is always kept over the formation pore pressure, is in an “overbalanced mode” (Bennion and Thomas, 1994). Most conventional formations are drilled using this technique.

If the pressure above a porous formation (i.e. hydrostatic pressure exerted by a mud column) in a well is less than the pore pressure the well is underbalanced. In such low-pressure reservoirs drilling fluids can easily escape to the surroundings causing invasive formation damage. A highly fractured sandstone or carbonate formation where the main permeability is contained in the fracture system is an example of and underbalanced well (Bennion and Thomas, 1994). In such low-pressure reservoirs, underbalanced drilling is a commonly utilized technique.

Because of the low pore pressure in underbalanced wells, a casing (i.e. cylindrical steel pipe) is set into the wellbore. The casing both prevents the wellbore from collapsing and inhibits drilling fluids from penetrating the wellbore surroundings. Lighter drilling mud or foam is used to reduce the weight of the mud column, thus reducing the pressure on the fragile formations and preventing the rock to fracture.

Fracture pressure

Fracture pressure is the pressure that will cause the rock formation to break/fracture (Schlumberger, 2013). It is determined by the mechanical properties of the rock structure and material composition. If the pressure of the mud column created during drilling exceeds the pore pressure in the rock formation by more than its fracture pressure, drilling mud will flow out of the wellbore and into the formation instead of returning to the surface. This causes what is known as lost returns/lost circulation. Moreover, as drilling fluids are lost to the surrounding formations, mud can damage the formation by pore throat plugging. In unconventional formations, prediction of the fracture pressure encounters the same challenges as prediction of pore pressure due to the formation properties (Li, Purdy, Wu, 2012).

Pressure gradients

Pressure gradients are the change in pressure per unit of depth, typically measured in units of psi/ft or kPa/m (Schlumberger, 2013). During conventional drilling, the pressure in the well must be kept between the pore pressure gradient and the fracture gradient. Figure 2 illustrates the pressure gradients graphically showing the graph of the mud weight is always between the two gradients. It is essential to consider the pressure gradients as they change with depth when selecting the properties of the drilling mud. The lithostatic pressure gradient is the pressure of the weight of the overlying rock (i.e. the overburden) (Schlumberger, 2013).

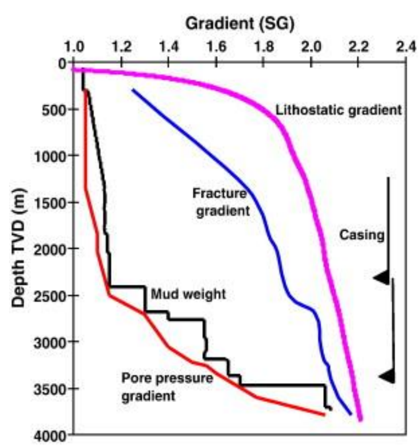

Figure 2 – Pressure Gradients in a well (2)

Formation damage

Reservoir formation damage is recognized by a reduction in the well production rate due to low formation permeability in the area surrounding the wellbore. Shallow damage around the wellbore is the most common damage and makes a large impact on the well production (King, 2009). Generally, the most fragile zones in a formation are the zones with the highest permeability. Thus, the damage will tend to occur along the easiest path in the formation and the damage will be uneven, Figure 3 and 4.

Figure 3 – Idealized view: evenly damaged formation (3)

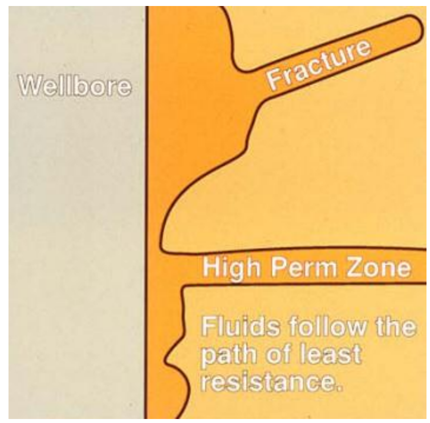

Figure 4 – Actual damage: uneven damaged formation (4)

The severity of the damaged formation is typically referred to as skin. This is the rate of the reduction in the formation's natural permeability and the size of the damaged area (Samuel and Sengul. 2003). As a result of reduced natural formation permeability the production rate of the well will decrease. Darcy's equations take into consideration the effect of formation damage on production by adding a dimensionless skin factor. A positive skin factor indicates increased pressure drop in the well causing low production, whereas a negative skin factor indicates a reduced pressure drop resulting in normal/high production because of well stimulation (Samuel and Sengul, 2003).

The skin factor can be calculated from the formula:

$$s = \left(\frac{k}{ks} - 1\right) \ln\left(\frac{rs}{rw}\right) \tag{2}$$

where

- K = formation rock permeability, mD
- K_s = rock permeability in the damaged or stimulated zone, mD
- r_s = radius of the altered zone, ft.
- r_w = radius of effective wellbore, ft.
- r_e = radius of formation, ft.

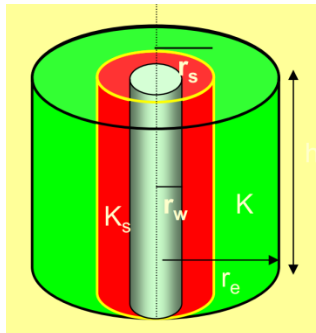

Figure 5 – Formation damage
(5)

Typically, horizontal wells are drilled to enhance hydrocarbon production. However, when comparing horizontal wells against vertical wells the trend is that they produce the same volume under the same conditions (Samuel and Sengul, 2010). As horizontal wells may have long perforation intervals and open-hole sections the chance for formation damage is larger than for vertical wells running through shorter formation intervals. For example, in horizontal wells, the reservoir surrounding the wellbore may be exposed to drilling fluids that potentially can invade and plug the formation pores for a much longer time. Generally, formation damage in horizontal wells is more difficult and costly to remove (Samuel and Sengul, 2010).

Origins and Effects of Formation Damage

Damage in reservoir formations can be caused by various factors and may occur during different stages of operation in a well. During the initial drilling process, the mechanical rotation of the drill bit penetrating the formations can change the pore structure in the near wellbore. Moreover, hydrostatic pressure can force drilling mud into pore throats in formations around the wellbore and block the flow of hydrocarbons. Also during cementing of a well, pore throats can be invaded by mud as it is pushed ahead of the cement. Both these damage mechanisms are known as pore-throat plugging (Samuel and Sengul, 2003). The effect of damage on production can be calculated by the formula (King, 2009):

$$\text{rate} = \left(\frac{\Delta P * kh}{141.2\mu o \beta o * s}\right) \tag{3}$$

where

- ΔP = differential pressure
- k = reservoir permeability, mD
- h = height of zone, ft
- μo = viscosity, cp
- βo = reservoir vol factor
- s = skin factor

It is essential to consider the potential of formation damage during well construction and intervention. Table 1 presents some of the damage mechanisms that can occur during various phases of well operation. Possible stimulation techniques that can be utilized to remove the damage are also included in the table. (Well stimulation techniques are discussed later in this chapter). The degree of damage severity is presented with numbers 0 to 4, where 4 is most sever.

Damage severity	0	1	2	3	4

Origin of damage	**Damage mechanism**	**Stimulation Techniques**	**Damage severity**
During drilling	• Particle invasion (i.e. drilling mud solids, debris)	• Matrix acidization, Hydraulic fracturing	
	• Water block/Emulsion block	• Matrix acidization, Surfactant treatment	
During cementing	• Cement particles migrate into the formation	• Matrix acidization, racturing/Perforation	
	• Precipitation of solids from the cement within the formation	• Matrix acidizaiton, Perforation	
During completion and work-over	• Plugged perforations due to improper perforating conditions	• Acid stimulation, Perforation	
	• Precipitation of scales (i.e. scales accumulates in pores)	• Acid stimulation	
During sand control	• Fines migration (i.e. fine sand entering the formation pores)	• Acid stimulation, Clay stabilization	
	• Debris from perforation plugging the formation pores	• Acid stimulation	

Table 1 – Common origins of formation damage and corrective measures (Pandey, 2010)

2.2 Well intervention

Well intervention includes any operation carried out in a well that has the aim of increasing production of hydrocarbons or extending the wells production life. Down-hole work related to well intervention may be done at any time during a wells production life. However, it is typically performed when the production volume is considerably decreasing. Essentially, the main purpose of any well intervention is to maintain or increase the production volume by changing the state of the well and stimulating the production of hydrocarbons.

The main application area for the Target Intervention Zonal Isolation Tool will be based on unconventional onshore wells in North-America. The formations in these wells are usually shale or dolomite which is relatively hard formations with very low permeability. Thus, it is necessary to perform stimulation operations in the formation zones by utilizing methods such as hydraulic fracturing or acid stimulation (more on this later in the thesis).

Recent study has indicated that 47 percent of the world's gas reserves and 11 percent of the world's oil reserves can be found in unconventional shale formations (U.S. EIA, 2013). Therefore the potential of performing well intervention operations and in particular stimulation operations is promising.

Down-hole mechanical work are typically performed with mechanical tool strings connected to coiled tubing (e.g. acid stimulation/fracturing operations), jointed pipes (e.g. drilling operations) or wire-line (e.g. perforation operations). Depending on the type of well intervention performed, the actual tools may range from simple logging tools to advanced hydraulic fracturing- or zonal isolation tools.

Examples of well intervention operations:

- <u>Coiled tubing (CT) operations</u>
    - Used for operation where circulation and fluid flow directly to the bottom-hole tool string is required.
    - The zonal isolation tool currently being developed by Target Intervention is going to be run with coiled tubing.

- <u>Slick-line/Wire-line operations</u>
    - Used for completion, work-over, fishing, setting or removing plugs, deploying or removing wire-line, etc.
    - Fast trip time, but does not support circulation.

- <u>Stimulation operations</u>
    - Hydraulic fracturing
    - Acid stimulation (matrix acidizing)
    - Both operations can be performed by the zonal isolation tool developed by Target Intervention AS.

Coiled Tubing

CT is usually 1” to 3 1/4” diameter metal piping spooled onto a reel. It is suitable for intervention based on pumping fluids (i.e. acids/fracturing fluids) directly down to the tool string. The main advantage with CT compared to for example wire-line is that it can push the tool down by force in both vertical and horizontal wells without the help of a tractor. Moreover, the hollow tubing also allows for controlled fluid flow directly down to the tool string and supports e-lines for electrical power and signal transmitting.

One of the disadvantages with CT is that it consumes more space due to its relatively large diameter. This can certainly be a challenge at offshore installations where space on the platform decks is limited. Further, the CT is plastically deformed when spooled onto and of a reel, making replacement necessary after a certain numbers of operations. Space requirements are usually no problem in onshore installations.

An onshore coiled tubing unit is shown in figure 6. The CT is stretched from the reel and guided by a gooseneck mounted on top of the installation into an injector. Next, the CT is forced into a lubricator that works as a pressure lock and finally into the well.

Figure 6 – Coiled Tubing unit (6)

2.3 Hydraulic Fracturing

Hydraulic fracturing is one of the most common well stimulation techniques used to increase production of hydrocarbons in oil and gas wells. The process involves injection of fluids and proppants into the well at high rates building up hydraulic pressure that causes the reservoir formation to fracture. This will open up blocked flow paths and allow hydrocarbons to flow more efficiently into the wellbore.

Based on the properties of the formation rock, different types of fracturing fluids are used in hydraulic fracturing operations. The most common types are; water based fluids, oil based fluids, acid based fluids and foamed fluids (Pandey, 2010). Proppants is a sand-like mass added to the fracturing fluids that have the purpose of keeping the fractured flow channels in the reservoir rock open for oil and gas to flow through.

Before hydraulic fracturing can be performed there are different aspects regarding the well that has to be defined (Pandey, 2010):

- The state of the formation
- Formation thickness and composition
- Formation permeability
- Location of perforated zones
- Production history of the well
- Location of groundwater

In order to achieve the desired effects of hydraulic fracturing, the flow regimes of hydrocarbons into the producing well must be changed from being radial to becoming linear. This means that the flow path created by a fracture must allow hydrocarbons to enter from wider range. Figure 7 shows a radial flow regime illustrated with the wellbore in the center. Naturally, this flow is inefficient compared to the linear flow regime created by hydraulic fracturing shown in figure 8

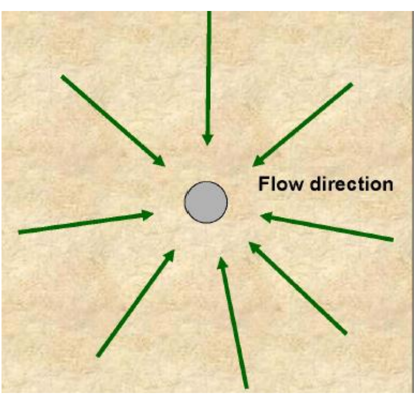

Figure 7 – Radial flow regime (7)

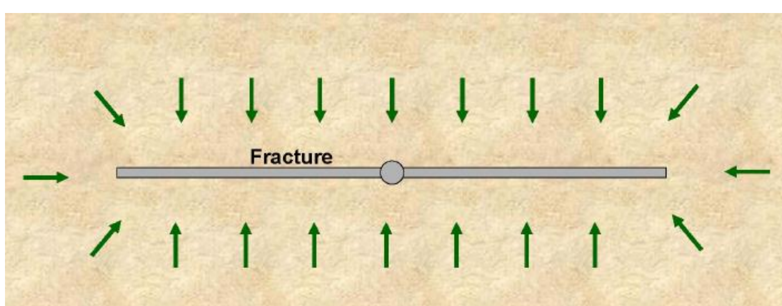

Figure 8 – Linear flow regime (8)

Challenges with Hydraulic Fracturing

In many onshore operations where hydraulic fracturing is performed, limited control and knowledge regarding the properties of the formation rock, including pore pressure and fracture pressure, can be a great challenge. The actual paths taken by the pressurized fracturing fluid will depend on the resistance in the formation rock. If the fluid finds a natural path in the rock, it may flow into other formations far-off the current reservoir. The most sever consequence of this is that fracturing fluid can enter the groundwater and inland lakes. This has the potential of eradicating fish populations and polluting drinking water.

In an attempt to avoid uncontrolled hydraulic fracturing operations, isolation of several short zones in the reservoir and less fracturing fluid volumes has become a more utilized technique. Recent development of electric fracturing tools, such as the Target Intervention Zonal Isolation Tool, has introduced seismic sensors as well as pressure sensors to monitor and control fracture operations.

2.4 Acid Stimulation Techniques

Acid stimulation is based on injection of acid from surface into the wellbore to chemically react with the material in the reservoir rock obstructing well production by dissolving it. It has the same purpose as hydraulic fracturing in that it opens up blocked flow channels in addition to create new ones, thus restoring the production volume of the stimulated well. Unlike hydraulic fracturing however, acid stimulation is done at rates and pressures designed to dissolve the blocking material without fracturing or damaging the reservoir.

Acid stimulation is performed with various blends of acids, depending on the kind of reservoir rock surrounding the wellbore. It’s essential to take into account the strong oxidising effect of acid that can eat away the metal of the pipes and equipment in the well. Additives are thus highly necessary to balance the acid strength and prevent material from etching. Commonly acidized reservoir rocks are limestone, sandstone, dolomites and carbonate reservoirs. Typically hydrofluoric acid is used for sandstone stimulation and hydrochloric acid or acetic acid is used for limestone and carbonate stimulations.

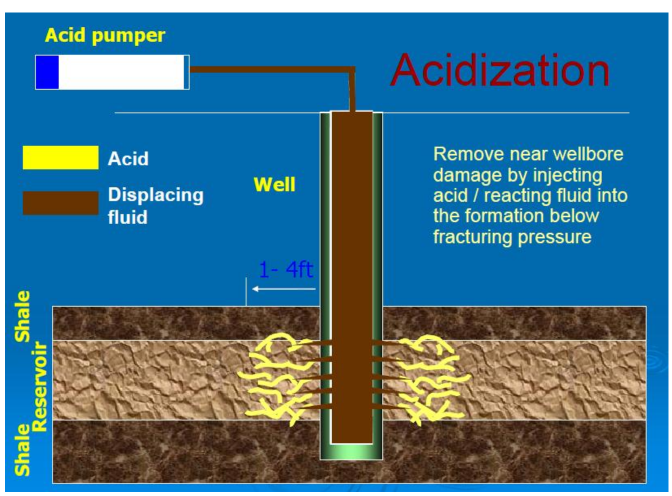

Figure 9 – Acid stimulation/acidization (9)

Matrix acidizing

Matrix acidizing is an acid stimulation technique applied mainly to remove skin damage and to improve formation permeability in the near-wellbore reservoir formation. The general objective is to increase the production of hydrocarbons. Stimulation fluids containing reactive acid are injected into the formation with the purpose of dissolving acid-soluble materials that damage well productivity. The treatment is designed to stimulate formations at high rates, but at pressures lower than the formation parting pressure (i.e. fracturing pressure). This is essential to let the acid remove or bypass the impediments in the pores and at the same time avoiding damage to the reservoir formations and leave zone barriers intact.

To determine if a well is suitable for matrix stimulation it’s essential to consider the depth of the formation damage. Generally, the stimulation radius should be no more than three meters from the wellbore. Hence, planning and execution of the formation treatment should be done with caution to minimize the amount of acid entering highly permeable sections possibly forming channels breaking into undesired gas- or water-producing zones. Another factor that decides if a well is suitable for matrix stimulation is that the reservoir formation should have a high skin factor. If there is no skin damage, matrix stimulation in dolomites and limestone has little effect. Furthermore, the natural permeability of the reservoir should be high (more than 10 md for oil wells) otherwise fracture stimulation is more suitable (*Samuel and Sendul, 2003*).

Matrix treatment with acid has different effects depending on the type of reservoir rock that is treated. In sandstone formations the acid expands the pore spaces by dissolving the soluble material in the formation matrix.
In carbonate formation, acid reacts quicker than in sandstone and matrix treatment can possibly create new highly conductive flow channels known as wormholes. The wormholes allow acid to flow through with ease, thus bypassing much of the pay zones. Ultimately the acid may dissolve the entire formation matrix (Shlumberger, 2013).

Because of the high dissolving effect of acids, especially in carbonates, and that acid in general tends to flow preferentially where the permeability is highest, it is essential to ensure that the acid is placed correctly. If not, some cases have shown an increase in water production as a result of the acid expanding high-permeability sections containing water (Samuel and Sendul, 2003). In order to control the placement of acid and ensure that the correct zones are stimulated it is common to use different diversion techniques like zonal isolation or temporary plugging (figure 10 and 11).

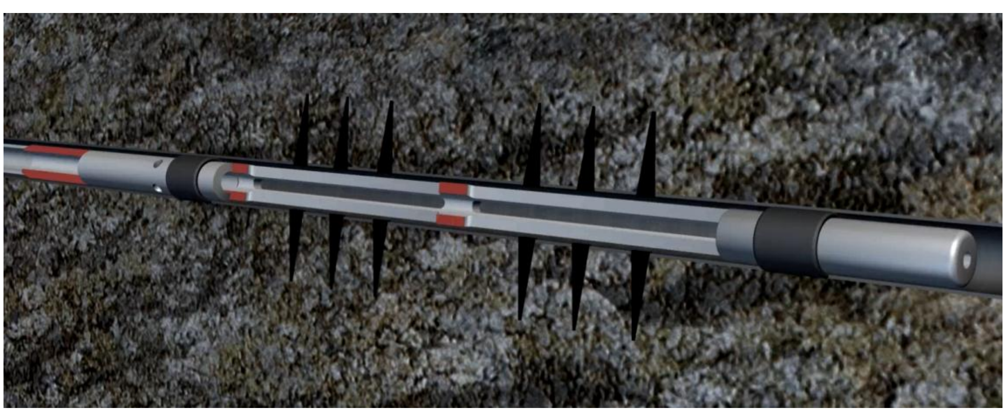

Figure 10 – Zone Isolation with coil tubing (Target Intervention animation)

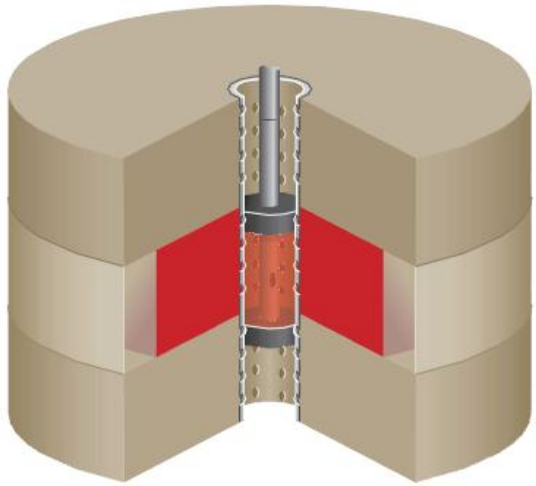

Figure 11 – Plugging with coil tubing: straddle packers ensure that treatment is isolated to a specific zone (Samuel and Sendul, 2003)

Acids have various effects on different reservoir formations. Thus, based on information about the reservoir composition there have to be distinct acid selection criteria for each different treatment operation. First the history of the well and the formation must be studied and tested to define the damage. Examinations of the formation rock, permeability and acid solubility are essential to determine the acid composition and treatment. Further, acid compositions must be compatible with the existing reservoir fluids (Samuel and Sendul, 2003).

For treatment operations in sandstone formations it is essential to gather information on what kind of damage there is in the formation, where the damage is located, the cause of the damage and what type of acid blend that is suitable for the formation rock. Usually, matrix stimulation treatment of sandstone formations is done with hydrochloric acid (HCl)

Treatment of carbonate formations is a more fragile operation due to the high-reactivity with the reservoir rock. Factors like fluid type, temperature and pumping rate are important to consider as these elements have an effect on the reservoir mineral composition. Typically, in carbonate reservoirs treated with matrix stimulation, hydrochloric acid is used. However, for reservoirs with high porosity greater than 35%, or chalk reservoirs, hydrochloric acid is not compatible (Samuel and Sendul, 2003).

Section I

Zonal Isolation Tool

This section is based on aspects related to the zonal isolation tool developed by Target Intervention AS. It has been structured into sub-sections including relevant descriptions and discussions that form the basis for the following sections, *II - Operation Procedures and III - Maintenance Procedure*:

- **3 Target Intervention – Zonal Isolation Tool**
- 3.1 Existing Technology
- 3.2 Zonal Isolation – Case Study
- 3.3 Zonal Isolation Tool – Prestenation
- 3.4 Critical aspects of tool Development – Zonal Isolation Tool
- 3.5 Procedures and Check Lists needed for tool development

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3 Target Intervention – Zonal Isolation Tool

The Target Intervention Zonal Isolation Tool is a well stimulation tool capable of performing isolated hydraulic fracturing operations and acid stimulation. The operation of the tool will be fully electric, controlled by a state of the art user interface system. Down-hole operations are done with coiled tubing (CT) which allows implementation of e-lines (i.e. electrical conductors). Sealed electronic housings contain all electronic equipment such as modems, drivers and control units that communicate with custom developed operation software. The graphical user interface (GUI) system is practically and ergonomically designed to assure efficient and easy operation as well as condition monitoring. Sensors reading pressure, temperature and loads as well as locating perforations- and casing collars (CCPL), are applied to different sections of the tool to monitor operational parameters. The convenient modular tool design facilitates transportation, manufacturing and assembly processes as well as maintenance activities.

In the following there will be a brief presentation of existing zonal stimulation techniques and a case study related to relevant aspects of zonal isolation via coiled tubing. Further, the basic design and functions of the zonal isolation tool developed by Target Intervention will be discussed.

3.1 Existing Technology

The existing stimulation technology available today comprises a range of different stimulation tools with various specifications and properties. Due to the large deposits of shale oil- and gas in the world, the frequency and popularity of stimulation operations is increasing more than ever. In addition to these unconventional tight-oil- and gas formations, it is now common to apply for example fracturing treatment techniques to more conventional reservoirs with the means of optimizing production or extending the life of production wells. Moreover, re-fracturing of old wells may be performed to restore production and make it possible to exploit the full potential of the reservoir.

Today, the current tools used in the well intervention industry, including hydraulic fracturing and acid stimulation tools, are usually operated mechanically. For these tools, rig-up time and run-in-hole operations are relatively simple procedures. However, there are several limitations to the application of mechanical tools, such as poor positioning control, limited control of setting force and no real-time monitoring of operational conditions.

CT Straddle Packer Method

This method comprises zonal isolation and stimulation of pre-perforated formation zones. Perforations of production zones are done prior to stimulation with the use of for example CT-conveyed guns or hydra-jet perforating. Isolation of a perforated zone is done by hydraulically inflate two packer elements simultaneously. During hydraulic fracturing, frac fluid is pumped through the CT at rates up to 12 bbl. /min and pumped into the surrounding formation through the perforated section between the two straddle packers. Once the stimulation operation is complete the packers are deflated by picking up on the coiled tubing. The system is then moved up to the next zone, where the process is repeated. The system can also be used for acidizing applications (TAM International, 2013).

Figure 12 – Coiled Tubing Straddle Packer Method (12)

Perf-and-Plug Method

This method is based on controlling the location of fracture stimulation by inserting bridge plugs (i.e. composite plugs) above the zones to be fractured. Perforations are then made above the plug through a cemented casing with the use of a perforation gun on wire-line or CT. Several zones can be perforated above the bridge plug, allowing stimulation of multiple zones in one operation. After perforations have been made, stimulation fluid (i.e. fracturing fluid) is pumped down the well to stimulate the perforated zones.

The main challenge with the Perf-and Plug method is that most of the proppant added to the stimulation fluid tend to enter the lower perforated zones. This usually occurs because of the higher weight of the fluid in the lower sections of the well compared the weight of the fluid in the upper sections. Moreover, the velocity rates past the upper perforated zones will be too high for the fluid to enter the zones. Preferably, the proppant should be evenly distributed into all the zones in order to achieve increased production. A solution could be to perforate fewer sections over the bridge plug, however this would increase the operation time and cost (Soliman, M. Y. et. al., 2012).

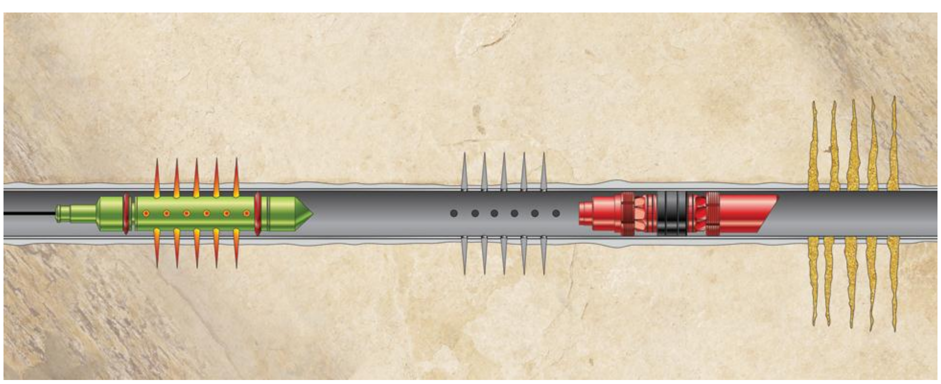

Figure 13 – Per-and Plug Method (13)

3.2 Zonal Isolation – Case Study

The following is a summary of a case study of zonal isolation operations performed by Weatherford in the Ekofisk field in the Norwegian North Sea. The study involves reviews and recommendations of operation procedures and methodology as well as equipment design and function found from several test campaigns conducted by Weatherford (Murphy and Fagley, 2012). Many of the aspects presented in the chapter are also related to the design and development of the Target Intervention Zonal Isolation Tool. Recommendations for operating procedures are also included.

Background

Production in the Ekofisk field comes from naturally fractured chalk formations with very high porosity (30-40%), but relatively low permeability. Traditionally, stimulation of these chalks reservoirs involved high-volume hydrochloric acid jobs and the use of frac balls to guide stimulation fluid flow to less-permeable sections. However, analysis of operational data indicated that only a few of the perforated zones contributed to production, and that many zones were left untreated. It was discovered that the zones had different properties with regards to porosity, permeability and pressures, thus making it difficult to predict the flow path of the stimulating acid. Hence, it was decided to conduct a test campaign where a zonal isolation tool using coiled tubing was developed in an attempt to stimulate zones individually by isolation with the use of packer elements.

The zonal isolation tool developed for the project was initially designed without slips and with packing elements activated by hydraulic pressure applied from surface against a spring loaded piston. The operational specifications specified that in order to achieve acid fracturing of a perforated zone, surface pressures of about 7,400 psi was required. This meant that a CT size of 2⅞ in. was needed due to the high flow rates. The tool was designed to be able to set and unset several times during the same run in hole.

The operation turned out successfully, and a total of six non-productive zones in the first three wells were treated. Ultimately, it resulted in a total increase of production from the three wells of 6,600 popd (barrels of oil per day). Even though this production rate only lasted for a few months after the stimulation operation, the overall long term recovery rate of the wells was increased.

Based on the initial tool design, a new and improved straddle pack isolation tool was developed known as the Surge Frac System, figure 14. This was run in a test program including a total of 96 perforation clusters. However, it was discovered in the final parts of testing that the tool failure rate was increasing after a certain number of isolation sequences. A review of the tool performance was then conducted, and a significant improvement potential in relation to design as well as operation procedure were discovered.

Figure 14 – Surge Frac System (14)

Lessons Learned

The results from monitoring tool performance and operation procedure as well as performing inspections and disassembly of the Surge Frac System, reviled several critical aspects of the system that could be acted upon. The recommendations presented in the following are based some of the most critical aspects related to design and operation procedures made by the engineers and operators that was a part of the zonal isolation test campaigns conducted by Weatherford. Emphasis has been put on the recommendations that would be relevant for the zonal isolation tool developed by Target Intervention AS.

Recommendations for Design:

- <u>Acid resistant materials</u>
    - Acid pitting of seals and surfaces caused leakage during pressure testing
    - Acid resistant Inconel material and acid-resistant sealing systems for the critical parts was recommended

- <u>Packer element design and rubber compound</u>
    - Erosion wear and chemical attack of the packer element material
    - Emphasis on development of rubber compound (elastomeric) capable of holding differential pressure and exposure to chemicals.

- <u>Anchoring system</u>
    - Anchoring of the tool to the wellbore should be a part of the tool design. This would eliminate movement of the tool during stimulation operations, centralize the packing elements and reduce rubber loss.

Recommendation for Operation Procedure:

- <u>Implementation of a real-time telemetry system</u>
    - Useful for reading down-hole pressure and temperature data during operation

- <u>Analyze waiting time before moving to new zone</u>
    - Packer elements may still be energized and set by stimulation pressure returning from the reservoir pores.
    - Bleed-off valves need time to drain the fluid pressure out of the isolated section before moving to a new zone.

- <u>CCPL – Casing Collar and Perforation Locator</u>
    - Such a system would allow real-time monitoring of the reached depth by registering casing collars and location of perforated zones.
    - This would prevent incorrect setting of packing elements, for example across perforations due to depth uncertainty

- <u>Pumping practices – Automated pump control</u>
    - During stimulation, the pump rate should be kept as smooth as possible to ensure optimum zonal isolation seal.

3.3 Zonal Isolation Tool – Presentation

The Target Intervention Zonal Isolation Tool is a re-design based on a previous developed Electric Annular Fracture Tool. In collaboration with the Canadian service company Kobold Inc. the development of a fully electric zonal isolation tool have the main goal of challenging existing mechanical tools on the oil and gas market.

The main advantage of the tool is that it is electrically operated. This allows for real-time monitoring of operational conditions such as temperature and pressures as well as identification of casing collars, perforations and accurate depth via the integrated CCPL (casing collar and perforations locator). Moreover, setting of packing elements is done with force applied from two electrical motors which makes it possible to control the setting force.

Table 2 shows a comparison between selected features of the Target Intervention Zonal Isolation Tool and existing mechanical stimulation tools.

Features	**TI Zonal Isolation Tool**	**Mechanical Fracturing Tool**
Controlling setting force	*YES* Reading power from electrical motor	*NO* Setting force is typically done by applying hydrostatic pressure
Controlling positioning	*YES* CCPL detecting casing collars and perforations	*NO* No electrical communication. Positioning done based on well log.
Reach in horizontal wells	*GOOD* CT are used to push the tool down the well without the use of a tractor	*LIMITED* Possible if tool is run on coiled tubing
Implementation of additional equipment	*YES* Modular design and electrical terminations allows for additional components	*LIMITED* No real-time electrical equipment/telemetry systems possible
Monitoring of operations	*YES* Sensors reading operational parameters	*NO* Only logs can indicate operational conditions

Table 2 – Comparing features between electrical tools and mechanical tools

Design

The tool is designed in modules as illustrated in figure 15.

- <u>CT Connector</u>
  - The coiled tubing connector is based on a slips connector design. This allows for a range of different CT sizes to be used with the tool.

- <u>Upper Collapse Function</u>
  - The upper collapse function is an emergency mechanism that is used if the tool is stuck down-hole. The design is based on shear-pins that will break at a given straight pull shear-force of 10 tons and force a collapse of the packing element and open the bleed-off valve.

- <u>Cable head</u>
  - The cable head is the module where termination of the electrical wire from the CT is located.

- <u>Packer and Valve Assembly</u>
  - The function of the packer is to seal between the tool and the wellbore. The bleed-off valve is closed during stimulation operations, but opened to bleed off any remaining pressure after operation.

- <u>Linear Actuator</u>
  - The linear actuator module contains an electrical motor, a satellite roller screw and a harmonic gear. This module has the purpose of activating the packer and valve assembly.
  - The tool consists of two identical linear actuators to activate the upper and lower modules, respectively.

- <u>Upper Electronic Chamber</u>
  - This pressurized module contains all the electrical components required for running the upper tool functions and transmitting sensor readings.
  - The components installed in the chamber are an electrical modem, controller card, motor driver, hardware for 2 strain gauges and 1 pressure/temperature sensor.

Figure 15 – Target Intervention Zonal Isolation Tool

- Stimulation Ports
    - The simulation ports are a perforated section where the stimulation fluid flows through and into the formation zones.

- Lower Electronic Chamber
    - This module is the same as the upper electronic chamber but with different electronic components installed.
    - The components installed are an analogue node (i.e. the same function as the controller card but not used for direct controlling functions), motor driver and hardware for 2 pressure/temperature sensors.

- Slips, Packer & Valve Assembly
    - The function of the packer and bleed-off valve is the same as in the upper module (i.e. seal between tool and wellbore and bleed off pressure after stimulation operations.
    - The lower tool section has a slips function to anchor the tool in the well. This is an important feature to eliminate movement of the tool inside the wellbore during operation. Movement of packing elements would increase rubber wear.

- Lower Collapse Function
    - Similar to the upper collapse function, the lower is an emergency mechanism used if the tool is such down-hole.
    - The design is based on a custom straight-pull mechanism that will be active when the packer and slips are set. The same straight-pull force of 10 tons will be required to collapse this function.

The tool has a center bore that runs through all components, except the lower collapse function where a flapper valve is installed. This design allows for fluid flow from the coiled tubing, trough the center bore and out of the stimulation ports into the formation zone as illustrated in figure 16.

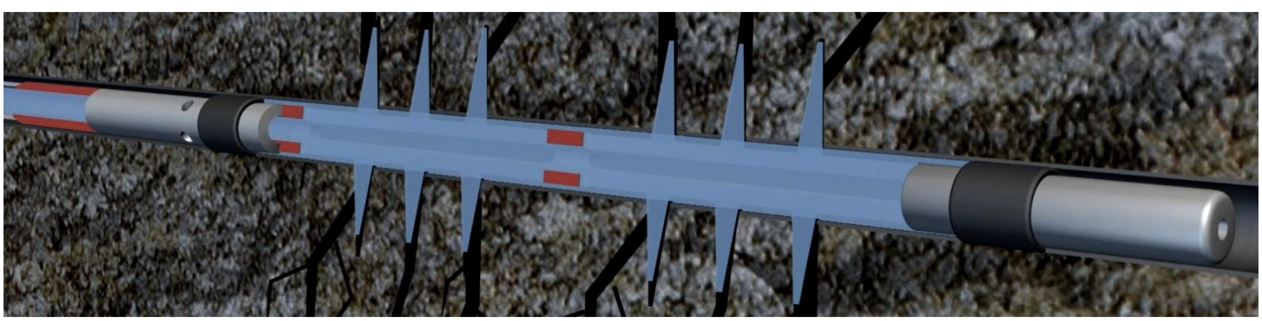

Figure 16 – Stimulating zone with hydraulic pressure and proppants through CT

Application and Working Environment

The basis working environment for the Zonal Isolation Tool will be North-American unconventional onshore production wells. Typically, these wells are drilled in reservoirs formations of hard shale and dolomite where the geological permeability is extremely low (>0.1 mD, PTTC, 2011). In such formations intervention techniques like hydraulic fracturing is often required to make production of hydrocarbons possible. During the lifetime of a well drilled in tight oil- and shale gas reservoirs, stimulation operations may be repeated when the pore channels start closing and causing the production to slow down. The operation procedures for the Target Intervention Zonal isolation tool are similar for both tight oil- and shale gas reservoirs.

The specifications of North-American unconventional wells differ depending on which oil company that is responsible for the field and also the properties of the reservoir formations. A typical well drilled in formations with shale and dolomite may produce hydrocarbons directly to surface from a liner hanger through a 4 ½ in. liner connected to the lowest casing and a 4 ½ in. tie-back string without the use of any additional production tubing or completion string as normally used in for example the North Sea. Figure 17 shows an illustration of the main parts of such a well (Angman, P, Andreychuk, M, 2012).

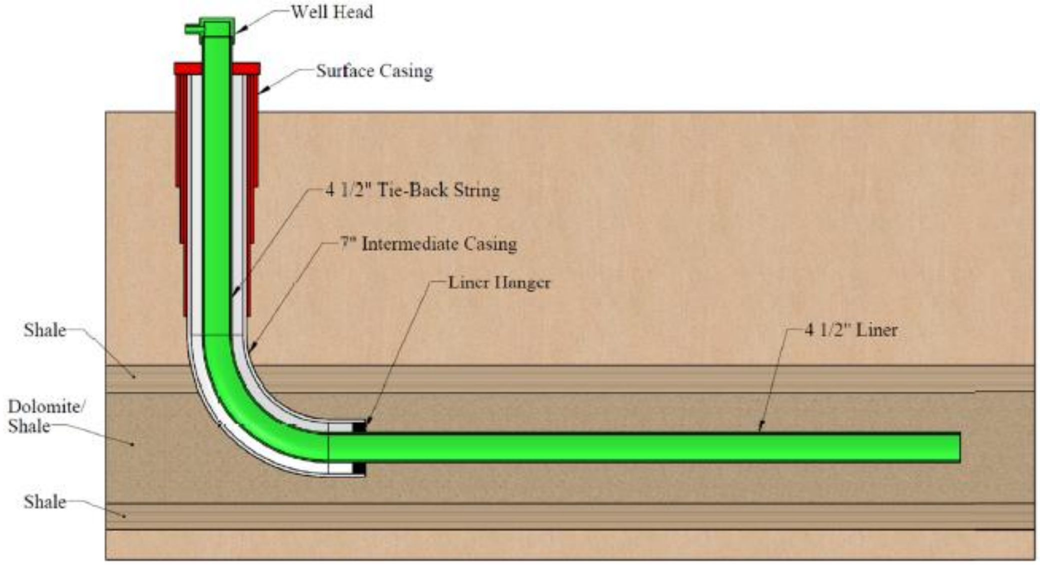

Figure 17 – Typical North-American Unconventional Well (17)

3.4 Critical aspects of Tool Operation – Zonal Isolation Tool

There are several critical aspects that need to be considered in relation to development of the Zonal Isolation Tool. Component failures may occur during operation causing reduced tool functions or in worst case a complete tool breakdown. Each component should have a criticality index that identifies the significance of the component function on the total tool function. The index should also consider the causes of possible failures related to each component. Criticality indexing will be discussed later in the thesis (chapter 7.4).

The most extreme down-hole conditions the tool will see are temperatures of 150 °C and pressures of 10 000 psi. In order to make the tool capable of withstanding such operating conditions it is important to design the components with the correct tolerances and with the proper material. Design and thorough testing and analysis of all components in the Zonal Isolation Tool are therefore essential in order to avoid failures caused by deterioration mechanisms.

One of the most critical aspects in relation to operation of the Zonal Isolation Tool is erosion due to injection of stimulation fluids containing sand and acids. Moreover, the run-in-hole process where the tool is moved inside the wellbore to locate perforated zones may cause significant mechanical stresses and impacts on the tool. Large mechanical forces between moving components can cause extensive wear of components and ultimately damage the functions of the tool.

All operational parameters that possibly can cause a failure are important to consider during the design and development phase of the Zonal Isolation Tool. These parameters are also essential to take into account when developing the operation procedure. For example, the tool should not be run down-hole for longer time intervals than what is specified in the tool specifications. Otherwise, packing elements and seals may be damaged severely damaged due to chemical erosion.

Failure - Root Cause

It is important to identify the root cause of failure in order to be able eliminate the failures. The root cause of failure is typically found within the three categories; design, manufacturing and operation (Markeset, 2012):

- Design and Construction: 60-70%
- Operating Procedures: 25-30%
- Maintenance: 10-15%

Possible failure mechanisms for the Zonal Isolation Tool

The failure mechanisms that may affect the functions of the Zonal Isolation Tool can typically be categorized into the following:

Design	
Failure root cause	**Possible consequence**
Tolerances designed too loose	Rotating parts may experience a "wobbling" movement causing misalignment and vibration
Misinterpretation of operating conditions	Extensive mechanical wear due to wrong choice of material properties and treatment.
Inadequate testing of components	Operating lifetime may be miscalculated causing component to fail unexpectedly.

Manufacturing	
Failure root cause	**Possible consequence**
Improper manufacturing process	Components may be manufactured from the wrong material or improperly assembled causing reduced lifetime of components
Wrong interpretation of machine drawings	Components may be manufactured with the wrong tolerances, thread pitch, etc.

Operation	
Failure root cause	**Possible consequence**
Environmental specifications exceeded	Products exposed of operation conditions that exceed the maximum specifications causing extensive component deterioration
Poor ergonomics of the operation process	Operators taking short cuts in the operation process causing improper performance

Table 3 – Possible failure mechanisms for the Zonal Isolation Tool

Erosion

Erosion is a form of material wear and one of the main concerns in the oil and gas industry. For example during drilling and intervention operations, the use of fluids under high pressures, mechanical impacts and harsh environments are common factors that may cause erosion. Typically, the grade of erosion is measured as a specific weight loss due to material removal form the surface (Arefi, 2003). The effect of erosion depends on parameters such as velocity, particle characteristics, angle of impact, temperature and material type.

Erosion is one of the most significant concerns regarding tools operating with frac fluids. As the Zonal Isolation Tools is run with coiled tubing and allows flow through the center bore, internal erosion can become an issue. Velocity (V) of impacting erosive particles is one of the main factors in erosion phenomenon (Arefi, 2003). Generally, research on the relationship between erosion rate and velocity of erosive particles show a constant rate (E_r):

$$E_r = constant\ V^n$$

The angle of impacting erosive particles to the exposed surface is another important factor in erosion phenomenon.
It is shown that erosion increases with temperature (Neilson and Gilchrist, 1968). In addition to increased temperatures in down-hole operations, the effect of the erosion process caused by fluid flow involves a significant rise in temperature because of friction.

The choice of material type and material treatment is essential in order to reduce the effect of erosion to mechanical components in the Zonal Isolation Tool. Different materials have different mechanical properties. The erosion behavior of brittle materials is different from the behavior of ductile materials in the sense that brittle material may be more resistant to glancing impacts than to normal impacts, whereas for ductile materials, it’s opposite (Arefi, 2003).

3.5 Procedures and Check Lists Needed for Tool Development

Procedures are essential tools in any efficient organizational work structure. Procedures may include instructions and guidelines for administrative processes such as purchase and sales as well as technical procedures for operation and maintenance. Furthermore, HSE-procedures should be a part of any organization, especially in manufacturing and maintenance industries.

This section presents all the current procedures that are going to be developed by Target Intervention for the Zonal Isolation Tool. The master thesis will focus on the two main procedures related to operation and maintenance:

- *Procedure Tool Operation*
- *Procedure Tool Maintenance.*

Procedures and Check Lists for the Zonal Isolation Tool

There are procedures related to all parts of development, production and operation of the Zonal Isolation Tool. The following is a brief introduction off all the procedures:

<u>DESIGN</u>

- Type of procedure: Process procedure for development and design approval
- Contents: Checklist for approval of machine drawings

<u>MACHINING</u>

- Type of procedure: Process procedure for labeling/tracking components
- Contents: Documentation control list

<u>PURCHASE</u>

- Type of procedure: Process procedure used for purchases
- Contents: Quotes PO (production order) and approval Receiving inception

<u>ASSEMBLY, DISASSEMBLY AND FUNCTION TEST</u>

- Type of procedure: Technical procedure – *Procedure Tool Assembly*
    - Assembly and QA (quality assurance) test
    - Step-by-step assembly instructions with 3D illustrations
- Contents: Checklist – *Checklist Tool Assembly QA*
    - Tool log including documentation and tracking of each individual tool

SHIPPING/RENT

- Document type: Checklist – *Checklist Rental*
- Contents:
  - Including important checkpoints in relation to specific customer requirements.
  - Tracking control
  - Basis for pricing

PRE-OPERATION

- Document type: Checklist - *Checklist Pre-Operation*
- Contents:
  - Setup of tool for specific job and well data
  - Contents: Important checkpoints – specific for each job (for example: number of stimulation ports, packer size, and well spec.)
  - Setup of straight pull collapse

POST OPERATION

- Operation log – *Job Log*
- Data from the GUI (graphical user interface) is collected and all tool documentation updated.
- All operational data and tool data is included in this procedure.

OPERATION - *Procedure Tool Operation* (Master Thesis)

- Type of procedure: Technical procedure
- Contents:
  - Description of how the tool should be used in operation. Including collapse and release functions, as well as troubleshooting tools.

MAINTENANCE – *Procedure Tool Maintenance* (Master Thesis)

- Type of procedure: Technical procedure
- Contents:
  - Inspection and maintenance activities
  - All requirements and additional procedure are included

Section II

Operation Procedure

This section includes a presentation of the development of the operation procedure.

- **4 Development of Operation Procedures - Introduction**
- 4.1 Introduction
- 4.2 Benefits of Using Operation Procedures
- 4.3 Human factors
- 4.4 Development and Implementation
- 4.5 Writing and construction
- 4.6 Review and approval
- 4.7 Document control
- 4.8 Document format

- **5 Operation Procedure - Zonal Isolation Tool**
- 5.1 Planning and Development

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4 Development of Operation Procedures

This chapter covers the most important aspects related to development for general operation procedures. It includes a discussion of possible benefits as well as important aspects that should be considered during the procedure design and development phase. In addition, procedure structure and layout as well as how it should be written and reviewed are reflected upon.

4.1 Introduction

An operation procedure is a set of written instructions that document or describe a routine or activity conducted by a single operator, a team or an entire organization. The main purpose of developing and using operation procedures is that they ensure system quality by providing individuals with the necessary information to perform a job properly. The procedures document how to perform the activities within a certain job, for example, technical activities such as calibrating and controlling equipment as well as processes for maintenance (EPA, 2007).

By developing a standard set of instructions in the form of a procedure, the variation and insecurity regarding the related job activities are minimized. The level of detail in the procedure should be sufficient to allow personnel with limited experience or knowledge regarding the procedure to successfully perform the activities of the job. Basic understanding of the operation and application would be required (EPA, 2007). If the procedure is easy to follow, even a personnel change would pose minimum challenges. However, in order to verify the requirements for performing the activities of the job, a section describing the required personnel qualifications should be included in the procedure.

4.2 Benefits of Using Operation Procedures

Activities related to a repetitive job should be performed while guided by an operation procedure. This can possibly increase the efficiency of the overall process and make less room for errors or miscommunication. Moreover, a standard procedure can be used for personnel training as it provides clear instructions on how the activities should be performed. In addition, operation procedures can be used for reconstruction of job activities when historical data are being evaluated for current use or as checklists when supervisors are inspecting the process followed by a certain procedure (EPA, 2007).

In general, the benefits of operation procedures related to job activities are that they reduce the required work effort and increase the process quality. However, if not written correctly or not followed properly, an operation procedure will be of limited value. Therefore it is essential that the writing of the procedures are carefully reviewed and re-enforced during the procedure design and development process.

4.3 Human factors

Considering human factors are essential when developing an operation procedure. Humans have a very multi-disciplinary culture. People are different in sizes, shapes and personalities. Thus, designing procedures suited for humans may be a challenging task. The study of human factors strives to deal with the complexity of individuals by using information about how humans move and behave. It also studies human psychology to provide data on such things as human error rates, learning and training, and human decision making. Further, the anthropometry concerned with the physical feature of people like height and movement is related to the study of human factors (Chapanis, 1996).

4.4 Development and Implementation

In order to create an efficient operation procedure it is important to construct a plan for development and implementation. There are seven steps that can work as the basis for development and implementation of operation procedures (Pennstate Collage Homepage, n.d.):

1. **Planning**
    - Analyze the activities that have to be done to complete a process.
    - Identify how the operation procedure can improve the process?
2. **First Draft**
    - Develop a list of the process activities in a structured step-by-step order.
    - Identify the content of each activity.
3. **Internal Review**
    - Discuss and get input from workers that will use the operation procedure.
    - Update the procedure if required.
4. **External Review**
    - Involve technical advisors with experience related the process and discuss the procedure.
    - Update the procedure if necessary.
5. **Testing**
    - The procedure must be tested by performing the steps according to the instructions in the procedure.
    - A supervisor should follow the process and review the sequence of activities.
6. **Final draft**
    - Make a final draft of the procedure with updated information from analysis and reviews.
7. **Training**
    - A training procedure may be required to properly implement the procedure
    - All workers related to the current process should get the proper training and information related to the use of the operation procedure.

4.5 Writing and construction

Clarity is an essential key factor for developing a good procedure. Generally, the instructions should be written in a simple step-by-step format that is easy to read. Redundant descriptions of functions or technical logic should be left out of the procedure, as this may confuse more than it aids. The operator of a certain type of equipment or system should only be provided the information necessary to be completely sure about what is required to properly carry out the activity. Essential information would be how to operate the system or equipment, how it is expected to operate or function and how to deal with possible errors or failures. A flow chart can be a helpful tool to illustrate the procedure as it is carried out. This shows all the actions undertaken in the procedure in a dynamic view.

The flow chart presented in figure 18 is a troubleshooting procedure which is a part of the operation procedure developed for the Target Intervention Zonal Isolation tool. It shows the sequence of activities that can be performed if the electrical communication with the tool is lost.

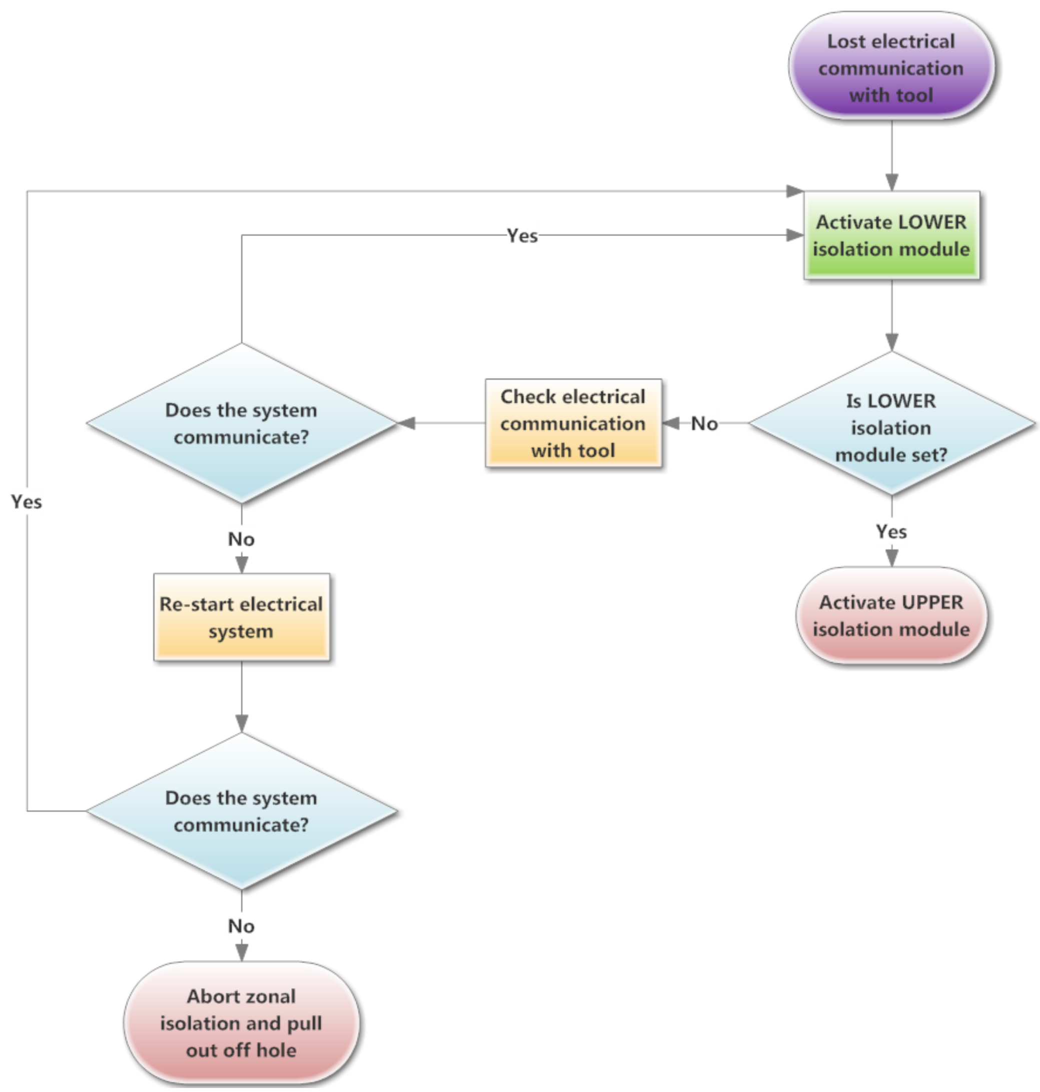

Figure 18 – Example of a flow chart representing a process for dealing with lost communication with a zonal isolation tool

If a procedure is difficult to explain in words, illustrations and figures may be used. Language should not be too complicated. Training of operation crew will be an excellent tool before a procedure is to be followed.

Generally, the best practice during development of an operation procedure would be to include both the writer and the operator in the development phase. As people tend to be supportive of what they contribute in developing, involving the operator could make the final product more complete, useful and accepted (Grusenmeyer, n.d.). Moreover, the operator will have the necessary practical experience and can therefore contribute with essential information related to the actual operation. However, practical experience with the process is not always required in order to develop a clear and accurate procedure. By following simple guidelines for development of procedures and using information and knowledge from experienced sources, the writer can be more than qualified to create a well-functioning procedure for almost any operation.

4.6 Review and approval

Before finalized, the operation procedure should be validated by certain qualified individuals. Reviewers should have sufficient knowledge and experience with the process in order to approve the procedure. Testing a draft procedure on someone other than the writer would be helpful to verify that the sequence of activities is appropriate and to check if the procedure is easy to follow. As part of the quality assurance, operation procedures should be systematically reviewed to ensure that they remain current and appropriate for the operation (EPA, 2007).

Change is something that the writer of a procedure needs to keep in mind during the development process. Design of systems, equipment or user interfaces may be updated or changed as new technology develops. The writer of the procedure should allow for updates and re-approvals that will be required when any significant change of activities or designs occur. It is essential that the operation procedure always remain current in order to be useful.

For certain process activities, checklists can be a useful tool in order to make sure that the procedure is followed properly (EPA, 2007). As an operation process is carried out, some steps in the procedure may require the use of a checklist to document the completed actions. The procedure may refer to the use of an attached checklist for a certain activity that requires extensive description and quality assurance. Table 4 is an example of a part of a simple checklist that could be used before run-in-hole of the Zonal Isolation Tool.

	Description of Activity	**Status:**	**Note:**
1.	Cable head connector has been pull- and pressure tested		
2.	All tool functions have been tested and verified operational		
3.	All sensors are functioning, check readings from GUI		
4.	Emergency collapse functions are adjusted to the required loads		

Table 4 – Example of a simple checklist

4.7 Document control

The final document containing the operation procedure should be systematically stored in the database of the company responsible for developing the procedure. In order to keep track of different documents and updated versions, a systematic numbering system should be developed as a tool for identifying and controlling the documents (EPA, 2007). A standardized document notation with specific document information should be included on all pages of the operation procedure (see table 5).

Table 5 – Standardized document notation

Short Title/Doc. #
Revision #:
Written by:
Date:
Approved by:
Page 1 of

- **Short title/Doc. #:** Serve as a reference designation.
- **Revision #:** Update if the operation procedure are changed
- **Date:** Date of issue
- **Written by:** Name of the writer of the procedure
- **Approved by:** Name of the person responsible for approving the procedure/update
- **Page 1 of:** Important when checking if the document is complete and

4.8 Document format

The operation procedure layout and format may be modified as required by the current process. Included in the document, activities such as data processing and evaluation, risk assessment and auditing of equipment operation are required. Further, steps related to initiating, coordinating and recording the activity should be included in the procedure (EPA, 2007). In general, the steps should be design to fully suit the specific activity.

The document should include a description of the current activity and purpose. Standards or general information as well as unusual terms should be defined in in the introduction. Further, required equipment, personnel qualifications and safety measures should be included. If additional procedures are required to facilitate the operation, these should be cited. Such procedures may be attached or referenced to where it can be located. Quality assurance (QA) and quality control (QC) activities related to the operation procedure must also be included to ensure that that the activities are being performed properly.

A generalized operation procedure format should contain five main elements (EPA, 2007):

1. <u>TITLE PAGE</u>

    - Procedure title
    - Summary of procedure
    - Document ID
    - Date of issue
    - Revision
    - Organization Name/Number
    - Signatures

2. <u>TABLE OF CONTENTS</u>

    - Reference to certain sections in the procedure
    - Structured list divided into chapters and sections

3. <u>PROCEDURES AND DEFINITIONS</u>

    a. Limits and requirements to the use of the procedure including general precaution

    b. Definitions of acronyms, abbreviations, or specialized terms used in the procedure

    c. Health and Safety Warnings with identification of possible hazards and critical steps in the procedure

    d. Cautions indicating activities that could result in equipment damage.

    e. Personnel qualifications/responsibilities/experience required by the user.

    f. Equipment and Supplies needed for the operation.

    g. Procedure describing all the relevant steps.
        - An example from one of the steps of the operation procedure developed for the zonal isolation tool is presented in figure 19:

    h. Data and Records Management identifying required calculations, reporting, and data storage information.

Step 3: Run in hole to identify first zone

1. Perform a double check on upper and lower isolation module positions
   i. Both isolation modules are re-tracked
      - Slips are re-tracked
      - Packers are re-tracked
      - Bleed-off valves are in **open** position
2. Activate CCPL and identify casing collars during RIH.
   i. Monitor both electronic and mechanical depth counters to ensure accuracy. Correlate depth with mechanical counter on reel.
3. Run in hole to detect the lowest perforated zone and stop RIH.
4. Run past lowest zone by sufficient margin
5. Slowly pull up the tool and utilize CCPL to locate the perforations in the first zone.
   i. Confirm location of perforations and move the tool over the detected perforated zone.

Figure 19 – Part of the operation procedure for the zonal isolation tool

4. QUALITY CONTROL AND QUALITY ASSURANCE

- Designed to allow self-verification of the quality of the procedure.
- Checklists may be used as quality control (QC)

5. REFERENCES

- Any additional procedures or documents should be fully referenced

5 Operation Procedure - Zonal Isolation Tool

The operation procedure for the Target Intervention Zonal Isolation Tool has been developed based on theoretical and practical experience from the well intervention industry. All steps have been thoroughly discussed and analysed to ensure an optimized operation procedure. During design and development of the tool, practical solutions to fast and effective assembly of mechanical components as well as electrical terminations have been emphasized.

As discussed in the previous chapter, clear descriptions and systematic presentations of the steps within the operation procedure are critical aspects. All the activities and steps in the final procedure have been formulated in a clear, step-by-step order so that any person knowledgeable with the general concept of the procedure easily can follow it during operation of the tool.

It should be noted that the procedure will strictly consider the operation of the Zonal Isolation Tool. All procedures related to for example rig-up of coiled tubing installations, run-in-hole technique, and pumping of fracturing fluids, etc. are provided by other service suppliers and the responsible oil company.

Chapter 4 includes the background theory of the parts included in this chapter and may be used as cross-reference.

5.1 Planning and Development

The operation of the Zonal Isolation Tool starts once it has arrived on the production site. The tool will be divided into three modules which is the upper isolation section, the stimulation ports section and the lower isolation section. Assembly of the modules are done prior to installation in the CT rig-up. All operational parameters and requirements from the customer are determined in advance (e.g. different packer element sizes and length of stimulation ports section).

In general, there will be only one operation procedure (with additional procedures enclosed) to facilitate the operation of the Zonal Isolation Tool. However, if the customer has special requirements, some procedures may be modified slightly. The following includes a presentation of the general structure of the operation procedure, as well as discussion of the procedure planning and development phase. Each activity and sequential procedures are discussed.

Procedure Contents

<u>1. Title Page</u>

The title page includes the name of the procedure and the document number that will be registered in the company procedure database. An executive summary of the operation procedure roughly describes the structure and the purpose of the procedure (i.e. how it should be used). The information table includes a revision index, the date of issue, name of the author, the person who has reviewed the procedure and the person who has approved it. The title page also includes information about the company such as, name, address, telephone number, organization number and e-mail address. It is important that all information on the title page clearly indicates that this is the current operation procedure for the Zonal Isolation Tool.

2. Contents

The table of contents may be used for quick reference for locating information and to denote revisions or changes made only to certain parts of the operation procedure.

3. Tool Description

The section describing the tool should contain a simple figure of the Zonal Isolation Tool that can be used to identify the modules of the tool. A list of the mechanical and electrical specifications as well as operational specifications is included. Important aspects are:

- Number of tool re-sets/zones
- Coiled Tubing Size (variable)
- Maximum stimulation pressure
- Maximum pressure atmospheric chamber
- Treatment time

The tool has been developed based on these (and other) specifications and requirements that need to be considered prior to operation. If the customer has special requirements, the specifications list must be updated to suit the requirements.

4. Rig-up in Coiled Tubing Installation

All general precautions presented in this section must be noted by the operator before initiation of the tool operation. To make the descriptions in the procedure steps as clear and short as practically possible, all preparations applicable to multiple parts of the operation is described in this section. Recommendations of type of grease and lubrication are important to follow, as these are selected to meet the operational requirements of the tool. Special instructions to preparation of electrical wires and conductors are also included.

5. Operation Procedure

STEP 1: PREPARE COILED TUBING

The CT must be prepared to fit the cable head connector. As CT specifications such as wall thickness, OD, material composition, etc. can vary from operation to operation, it is important that all requirements from the customer are met. The cable head connector is based on a slips connection principle, which makes it compatible with a range of CT sizes. Preparation of the CT is critical to ensure that the O-ring seals in the connector will seal internal stimulation pressure during operation. The process includes measuring the ovality to check if there is deviation from an approved circular shape (limits are noted in procedure). A special rounding tool may be used to shape the end of the CT to ensure a proper shape. Next, the end fitted into the connector need to be straight. Finally, the CT surface must be cleaned and all sharp edges removed.

STEP 2: RIG-UP PROCESS BEFORE RUN IN HOLE

This step includes the final installation activities to make the tool ready to run in hole. Installation of the Coiled Tubing equipment are done by an external company and all necessary equipment and systems required by the stimulation process will be ready when the tool arrives. Termination of electrical connections is designed with "plug-and-play" plugs. Highlighted illustrations in the attached assembly drawing show how the terminations installed. Connection to the cable head connector is also illustrated in the assembly drawing. Slips gripping force are determined based on tests and calculations (values noted in procedure).

To ensure that the connection of the CT is properly done, a plate-pull-test to maximum expected workload must be performed. It is essential to make sure that the load does not exceed the maximum recommended load on the connector. The slips gripping force must be re-torqued after the pull test according to the given specifications. Next, a pressure test of the connection is required to ensure proper seal. Testing must be done to maximum expected pressure or according to the current well operation program.

Finally, all electrical functions and sensors must be tested to verify the operability of the tool. This includes a test-run to fully set and un-set position on both the upper and lower isolation module. Further, the function of all sensor readings and electrical impulses are verified from the GUI (graphical user interface).

STEP 3: RUN IN HOLE TO IDENTIFY FIRST ZONE

Before the tool can be run in hole a double check must be performed on both isolation modules. The check includes to verify that both modules are re-tracked (i.e. the slips, packer and bleed-off valve are in un-set position). Otherwise, this will be noticed as the expanded packer will prevent the tool from entering the well. The CCPL is then activated and used to monitor the process. It is important to observe and correlate the mechanical depth counter on the CT reel with the readings from the CCPL.

The location of the lowest perforated zone in the well is noted in the well log. This will be used as a guide during detection. Once this zone is located the tool should be run past the perforations by a sufficient margin. This is important as the CT will lie like a spiral in the well after run in hole, and several meters must be pulled back onto the reel to make the tubing straight and capable of dragging the tool up the well at controlled speeds. To locate the first perforated zone, the tool must be slowly pulled up the well while readings from the CCPL will indicate when the position of the tool is correct.

STEP 4: ACTIVATE LOWER ISOLATION MODULE

Before the lower isolation module can be activated, all operational parameters must be confirmed according to specifications (i.e. temperatures and pressures). It is essential that the lower isolation module is activated first. This is because it contains the anchoring slips section which locks the tool inside the casing. Once the isolation module is activated, the bleed-off valve will run to its closed position. The GUI will confirm the position by automatically counting the revolutions from the roller-screw and converting it into distance. A screenshot of the GUI is presented in figure 19.

The bleed-off valve is designed to close before the packer and the slips are set to ensure that all pressure from below the tool is sealed during stimulation. The packer and the slips sections must be set with a force of 3.5 tons to fully isolate the zone. The setting force is indicated by the GUI. If there is any natural hydrostatic pressure in the well below the tool, a flapper valve in the lower section will release this pressure through the tool and out of the stimulation ports.

STEP 5: ACTIVATE UPPER ISOLATION MODULE

The upper isolation module is activated the same way as the lower module. It must be noted however that this module does not have a slips section. The packer is set with the same force of 3.5 tons. After both modules have been set and the zone is isolated, the down-hole parameters must be checked (i.e. temperatures and pressures below, over and between the packers).

STEP 6: STIMULATE THE ZONE

During stimulation, external companies have own procedures of operation. However, it is important that the operator monitors important aspects including flow rates, temperature and pressure, stresses and strains.

STEP 7: UN-SET UPPER ISOLATION MODULE

The upper isolation module must be un-set first as the lower module anchors the tool. It is important to let the bleed-off valve open fully to bleed off any differential pressure trapped between in the isolated zone. Open valve position must be confirmed before un-setting the upper packer element. When the upper isolation module is fully re-tracked (indicated on the GUI) the procedure can continue.

STEP 8: UN-SET LOWER ISOLATION MODULE

The lower isolation module is un-set exactly the same way as the upper. Again however, the slips in this module must be fully re-tracked in addition to the bleed-off valve and the packer.

STEP 9: RE-POSITIONING TOOL TO A NEW PERFORATED ZONE

Before re-positioning the tool to a new zone, it is necessary to wait 2 minutes for packer elements to fully re-track the elastic deformation. Utilize the CCPL to locate the next zone to isolate and position the tool. The operation procedure should be repeated until the targeted number of zones is reached. With the last zone treated and the wellbore clean the tool can be pulled out of the well and up to surface for maintenance.

Figure 19 – Graphical User Interface – Target Intervention AS

6. Possible Sources of Failure

One of the possible failures that can occur during operation is when electrical communication between the tool and the control system is lost. Electrical interfaces, wires or components may also be damaged making activation impossible. The other main failure mode may be that the tool is stuck in hole. This can be caused by sand being trapped around the tool, locking the isolation modules in set positions. It may also be caused by a mechanical problem such as damage to the roller screw, bearings or bleed-off valve making the modules unable to re-track.

The possible sources of failure are included in the operation procedure along with a troubleshooting procedure and possible actions that may solve the problem. The troubleshooting procedure is also illustrated in a flow chart to make it easier for the operator to identify the source and find a possible solution.

7. Packer and Slips Emergency Collapse Function

This is an additional procedure included in the operation procedure, only used if the tool is unable to re-track the isolation modules when set. It should be noted in the procedure that the collapse functions are not reversible when collapsed, and that the tool must be pulled out of the well to re-activate the mechanisms.

There are straight pull emergency collapse functions in both the upper and the lower module of the tool. However, both mechanisms have completely different designs as discussed earlier in the thesis. Nevertheless, the activation of the mechanism is based on the same similar principle. By pulling the coiled tubing with a predetermined force of 10 tons, the shear-pins in the upper collapse mechanism will break and thus making is possible to collapse and mechanically re-track the upper isolation module. The same procedure applies for the lower collapse function. Unlike the upper mechanism, this has a custom designed, spring loaded mechanism.

When both emergency collapse functions have been activated and the isolation modules are re-tracked, it should be possible to pull the tool out of the well and perform the required maintenance. If the tool is still not possible to move, the release function must be used.

8. Release Function

The release function is the final solution if a tool is stuck in hole. All other solutions must be attempted before this function is utilized. The mechanism is called a ball-drop release, where a metal ball is dropped through the CT and landing in a ball seat to cut a designed weak point in the tool. This will however only loosen the part of the cable head, leaving the rest of the tool stuck in the well. Fishing will be a solution to get the tool back out of the well. However, that is not a part of the current operation procedure.

Note: *A drafted operation procedure is included in the appendix.*

Section III

Maintenance

This section covers general aspects of maintenance and maintenance management.

- **6 Maintenance**
- 6.1 Maintenance Program Design
- 6.2 Critical Aspects of Maintenance
- 6.3 Factors influencing maintenance programs

- **7 Maintenance management**
- 7.1 Traditional management techniques
- 7.2 Preventive Maintenance Management
- 7.3 Predictive Maintenance
- 7.4 Condition monitoring
- 7.5 Development of a condition monitoring system
- 7.6 Implementation of a condition monitoring system
- 7.7 Condition monitoring techniques
- 7.8 Benefits of Condition Monitoring

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6 Maintenance

This chapter includes an introduction to the critical aspects of maintenance and maintenance programs. Before developing a maintenance procedure, it is essential to consider different factors related to these topics.

6.1 Introduction

Maintenance is defined in the NORSOK Z-008 standards as: “a combination of all technical, administrative and managerial actions, including supervision actions, during life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function”.

During the life time of practically any item, certain maintenance activities must be performed in order to achieve the expected function of the item. The specific activities are grouped into the general maintenance categories; preventive and predictive maintenance (i.e. retaining life time of an item) and corrective maintenance (i.e. restoring life time of an item).

There are different aspects of maintenance in relation to for instance safety, performance, quality, environment and life span of an item. However, the main purpose of maintenance is generally to reduce business risks (Markeset, 2012). The key factors that can influence business risks are unreliability and loss of quality. By introducing efficient maintenance programs, these factors can be compensated for. Maintenance programs will intend to improve reliability and quality, which are both correlated with each other, as illustrated in figure 20.

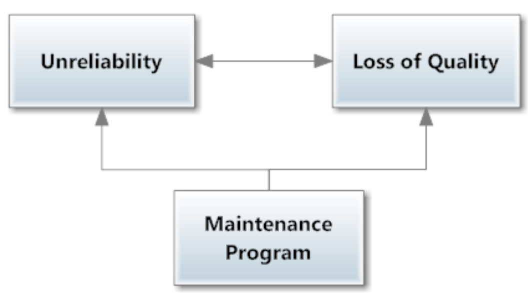

Figure 20 – Maintenance compensating for unreliability and loss of quality (20)

Recourses such as material, documentation, information and organization are all essential inputs to any maintenance process. All maintenance activities must be defined and required equipment must be available before any action is taken. High-quality maintenance procedures with adequate information and documentation are necessary in order to ensure proper maintenance. The outputs of a successful maintenance process should be reduced risk and improved reliability and availability.

6.2 Maintenance Program Design

The design of maintenance programs starts with understanding and defining the function and performance of the related item and the current operating environment. Next, analysis of the reliability, availability, maintainability and safety of the product is performed. Also a risk analysis must be conducted. During all parts of the design phase, critical aspects such as safety, environment, sustainability and return of investment should work as guiding measures. All parts of the maintenance operation phase forms integrated maintenance solutions and result in effective asset and production management. The main steps of the maintenance program design phase are presented in figure 21.

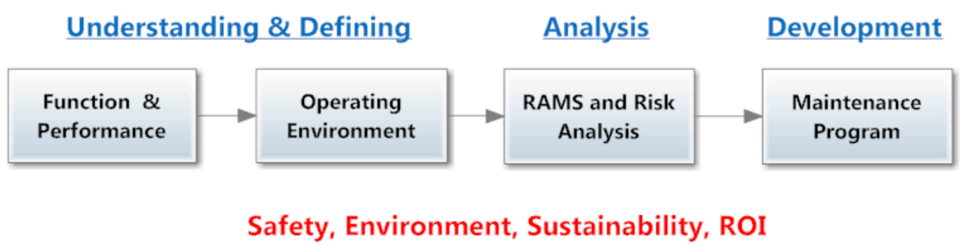

Figure 21 – Maintenance program design phase (21)

The important questions that need to be asked when developing a maintenance program are (Markeset, 2012):

- Why do we need maintenance?
  - Health and safety related
  - Environment related consequences
  - Economic consequences (cost, capital destruction, uninterrupted productions, etc.)

- What is maintenance and what processes, technology, knowledge and resources does it involve?
  - Describing system state and behaviour

- When should you do maintenance?
  - Predicting system state and behaviour

- How should you do maintenance?
  - Controlling system state and behaviour

- Who should do the maintenance?
  - Qualified and trained personnel

- Where should maintenance be performed?
  - Safety in relation to health and safety should be considered

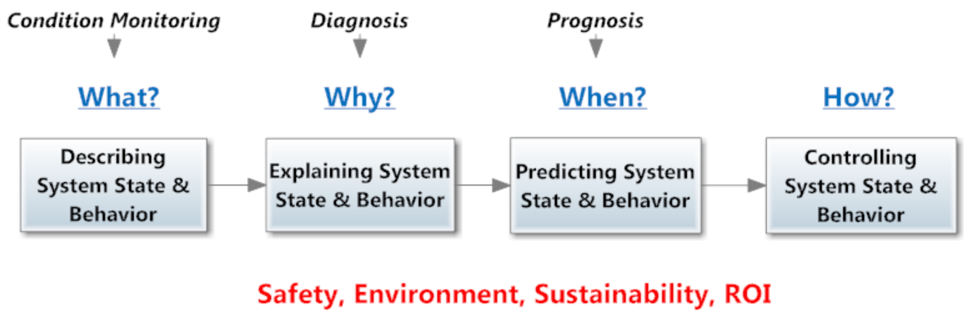

Figure 22 – Maintenance operation phase (22)

6.3 Critical Aspects of Maintenance

Effective and efficient maintenance programs are characterized by successful production of intended results and thorough use of resources such as time and energy. All activities included in a maintenance program must be designed to suit the actual products that at some point will require maintenance. Moreover, the design of work spaces and products must also allow for maintenance actions to be performed properly. Hence, maintenance programs are influenced by several factors making it essential to take all possible parameters into account during design and development.

Reliability

The reliability of any component is defined as the probability that it will perform its required function without failing under given conditions for an intended period of operation (Markeset, 2012). Reliability can be expressed in terms of MTTF (i.e. mean time to repair; how long the product will function before a repair is required) or failure rate (i.e. the frequency of component failure, e.g. failures per day).

In order to achieve optimal reliability, maintenance programs must be designed with state of the art technology that is able to restore complete product function after maintenance. However, high reliability may result in high costs for both product design and maintenance design.

Maintainability

During design of a product there are important aspects that should be considered in relation to maintenance activities. Simplicity, accuracy, safety, efficiency and effectiveness of maintenance actions are all important aspects that should be reflected in the product development, design and installation process (Markeset, 2012). Generally, maintainability is a measure that reveals how maintenance activities are performed with respect to all these aspects.

As maintenance is a term related to the actual repair or service activities, maintainability is a design parameter intended to reduce required maintenance time and cost as well as improving the safety of the maintenance activities. High maintainability will result in reduced downtime, efficient repairs and optimal product availability causing that the product meets the requirement set by the user.

Ergonomics

As discussed, products need to be reliable in terms of function and at the same time be easy to maintain. In addition to these requirements, the development of maintenance activities and processes must consider the characteristics related to ergonomics.

The ability of a person to carry out certain activities is highly influenced by the design of the work space and the maintenance job content. The practice of ergonomics considers safety and efficiency in the work environment. In relation to system design, ergonomics take into account the factors of human anatomy, physiology and psychology. To ensure safe operations, the design of man-machine interfaces is also essential.

The guiding philosophy is “fitting the job to the man”, meaning that job tasks should be designed to suit the characteristics of the worker (Bridger, 1995). For example, space requirements for body movement required by certain tasks are considered as an ergonomic issue during design of maintenance systems. Ergonomists should work as part of the design teams and contribute during the design of maintenance systems. Proper work space design along with correct design of activities will ensure high maintenance performance. Furthermore, proper system design should avoid the exposure of dangerous moving objects and extreme environmental conditions to humans.

Maintenance Strategy

The significance of proper maintenance increases with the importance of delivering improved product quality, availability and performance. Maintenance programs have the intention of improving system performance in relation to return on investment and health and safety related issues. In order to develop an efficient and effective maintenance program, the maintenance strategy must consider important aspects such as (Markeset, 2012):

- Environment related consequences
- Economic consequences
- Installation and commissioning
- Training
- Documentation
- Spare parts and warranty
- Remote monitoring and surveillance – tracking of products
- Upgrading and modifications

Maintenance programs should be based on a process view comprising cross-functional activities that that together creates value for the customer (Markeset, 2012). Rather than viewing maintenance as a function focusing on individual activities, emphasis on common goals and integration of activities with the aim of creating values are important aspects of a successful maintenance program. The development of a maintenance program should comprise theoretical and technical knowledge together with practical experience. By involving persons with all these capabilities, development and implementation of the maintenance program would become effective. Other factors that may influence the maintenance strategy are (Markeset, 2012):

- Maintenance objective
- Internal resources
- External resources
- Geographical location
- Statutory requirements
- Designed product support
- Technical characteristics

The need for maintenance of any machine, equipment or system should be decided during the design and manufacturing phase. The designers should get input from people with operational experience in order to know what kind of conditions the product is going to be exposed of. Important choices such as material properties, thread pitches and lubrication are essential to consider ensuring the reliability of the product. Furthermore, the designers should consider the products maintainability (Markeset, 2012).

6.4 Factors influencing maintenance programs

Besides being related to product reliability and quality, maintenance programs are influenced by other external factors including human errors, accidents and statutory requirements, see figure 23 (Markeset, 2012).

Humans are the main resource of any business, thus also the main liability. The direct influence caused by human errors on maintenance programs is typically related to design, development and implementation. Furthermore, human errors may also influence maintenance activities in terms of actual performance and quality assurance.

Humans are responsible for the design of all processes and system components, and are therefore often also the root cause of error in case of failure or accident. Designers must consider inputs based on experience, knowledge and existing data when developing new systems. However, unexpected errors are not possible to take into account during design. Thus, specific maintenance programs must be developed in order to deal with unforeseen errors, and procedures and maintenance plans must be available when they occur. Maintenance techniques and procedures are discussed later in the thesis.

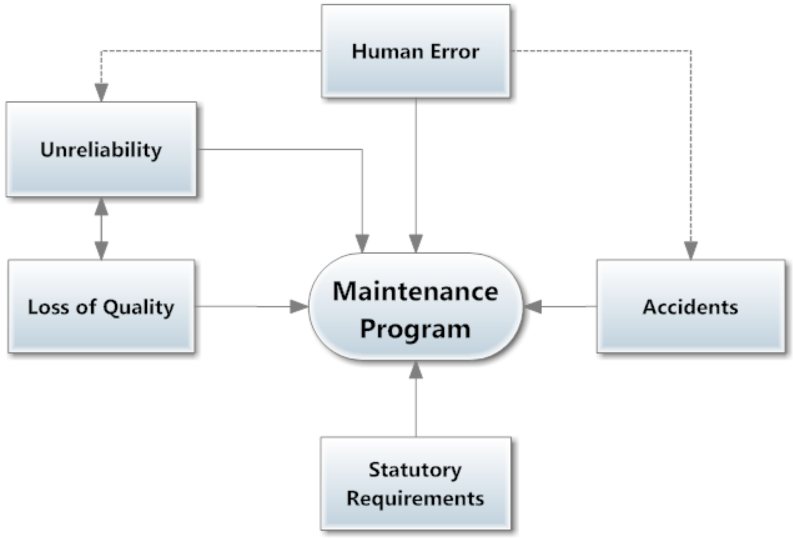

Figure 23 – Factors influencing maintenance programs

Generally, the complexity of technology and introduction of automation in manufacturing companies have converted activities performed by humans from being "hands-on" related to gradually involve less practical activities such as controlling and supervising. The result of such computerization has revealed less required man-hours and reduced operational risks leading to accident. Moreover, human natural errors caused by fatigue or misinterpretations are eliminated, thus improving overall system reliability.

7 Maintenance management

"Maintenance management deals with business management skills used for integrating: man, machine, technologies, etc. in line with corporate policies and objectives" (Markeset, 2012).

Maintenance operations and costs are essential topics for all manufacturing companies. The guiding philosophy is to keep the maintenance costs as low as possible, yet at the same time carry out efficient high-quality maintenance activities. In order to achieve these goals, the maintenance management must be well-organized and efficient. Surveys from the early 1990's of maintenance management effectiveness indicated that one third of all maintenance costs were wasted because of pore maintenance structure (Mobley, 1990). One of the main reasons for this was that required repairs and maintenance operations were not planned properly due to lack of operational data that could be used to calculate the actual need for maintenance or repairs on systems machinery and equipment.

Senior management has had a tendency to ignore the importance of maintenance operations on total system efficiency and instead regarded it as an unfortunate cost (Mobley, 1990). This has probably, among other things, been caused by limited knowledge of maintenance engineering and the importance of regular maintenance activities. Because technically competent engineers not necessarily have developed managerial skills, well-organized maintenance management programs where activities are scheduled and properly defined are essential in order for a manufacturing company to be efficient (Markeset, 2012). Further, inspections of maintenance activities as well as management processes must be controlled by the maintenance management itself.

Today, modern monitoring equipment and improved maintenance and repair tools have maid maintenance operations more efficient and easier to predict. Computer-based instrumentation such as microprocessors and sensors used to monitor operating conditions have made it possible to predict optimal repair and maintenance intervals and thus reduced the impact of maintenance operations on the total manufacturing system. However, along with the more advanced maintenance systems comes the importance of establishing a well-organized maintenance management system.

7.2 Traditional management techniques

Traditionally, two maintenance management techniques have been utilized in manufacturing companies: run-to-failure and preventive maintenance (Mobley, 1990). Run-to-failure is a reactive management technique based on performing maintenance or repairs only when machines, equipment or systems fail to operate. Only basic preventive maintenance activities, such as lubrication and minor adjustments are done. Because no maintenance is scheduled or planned the management of a run-to-failure based manufacturing facility must be able to respond to all potential failures that may occur. Consequently, spare parts or equipment must be available instantly to avoid unnecessary downtime of machinery.

Generally, run-to-failure is the most expensive maintenance management technique. It has high spare parts inventory cost and high overtime labor cost. Moreover, waiting for repairs to be completed means high machine downtime and low production availability (Mobley, 1990). Analysis of run-to-failure maintenance management have shown a significantly higher maintenance cost than for scheduled or preventive maintenance management techniques like preventive and predictive maintenance management.

7.3 Preventive Maintenance Management

Scheduling maintenance activities and repairs have proven to lower the time spent on repairs and maintenance activities as well as associated labors cost. Accordingly, downtime of equipment and machinery and lost production time has been minimized (Mobley, 1990). Preventive maintenance tasks are generally based on hours of operation. This is illustrated in figure 25, showing a basic illustration of reliability and the mean time to failure (MTTF) of a product. In the early stages of operation the product has high failure rate. This may be caused by improper installation or production failures. During the "useful life" period only random failures may occur, yet the general probability of failure is relatively low. As the product wears out towards the end of its lifetime, the failure rate increases significantly with time.

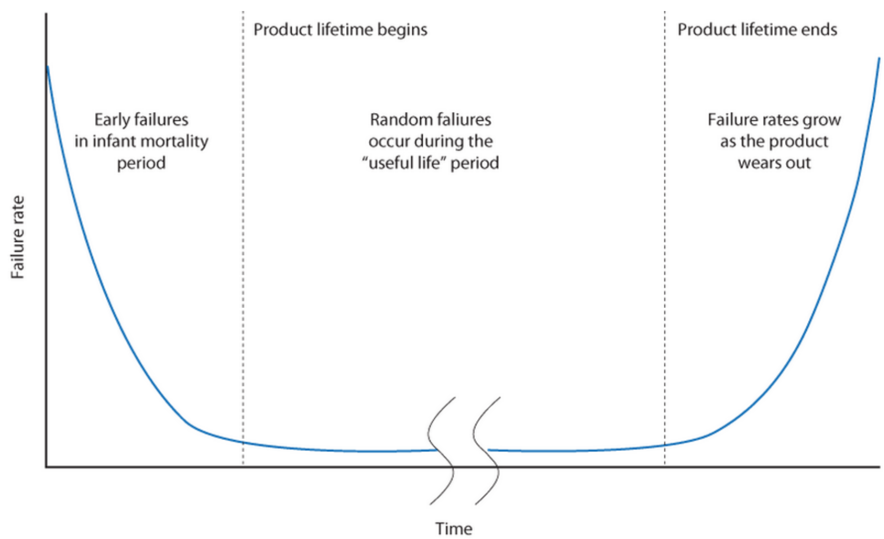

Figure 24 – The "bathtub" curve shows product failure rates at given life-cycle points (24)

Generally, all preventive maintenance programs are based on the assumption that a product will degrade within a typical classification time frame (Mobley, 1990). However, different operating conditions and specifications are essential to take into consideration when scheduling the maintenance activities. For example in the oil industry, high temperatures and pressures in conjunction with abrasive particles (e.g. sand, debris) may decrease the lifetime of seals and valves in down-hole drilling equipment. Thus, the implementation of a preventive maintenance program will vary depending on the different conditions.

7.4 Predictive Maintenance

If maintenance activities in preventive maintenance programs are scheduled to be performed too late and a machine suffers an unexpected breakdown, the maintenance personnel must act immediately and correct the failure. The repair labor time and cost of such unplanned repairs of unexpected failures will most likely exceed the maintenance budget by a significant margin. Moreover, the downtime of machinery will be longer due to inspections, troubleshooting and waiting for spare parts.

Predictive maintenance is a condition-driven preventive maintenance program where errors can be identified and fixed before the actual failure occurs (Mobley, 1990). This means that the maintenance actions can be scheduled to be performed when it is most convenient for the production/operation process. As availability of spare parts, tools and staff will be prearranged, repairs can be made in a period when it will have the least impact on the production/operation itself. Figure 26 illustrates the difference in uptime and waiting/repair time between run-to-failure maintenance management and condition based predictive maintenance management.

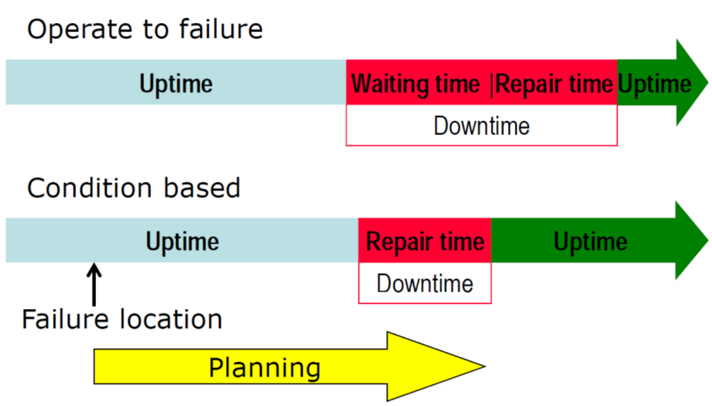

Figure 25 – Effect of condition monitoring (25)

Different from preventive maintenance programs where average-life statistics are used to schedule maintenance activities, predictive maintenance programs are based on systematic monitoring of the actual operating condition of machinery, systems and equipment. Different monitoring techniques and cost-effective tools provide sufficient data on operating conditions that the maintenance personnel use as a basis for developing optimal schedules of maintenance activities and repairs (Mobley, 1990).

7.5 Condition monitoring

Condition monitoring is a major component of predictive maintenance. It is a generalized process for observing the mechanical state of machines or equipment used to measure the changes in operating conditions (Markeset, 2012). The demand for condition monitoring systems has increased as efficiency and resource constraints have become some of the primary features of most companies. Increased complexity of technological systems as well as extensive automation of production processes has made the importance of equipment reliability more vital than ever.

In order to assess the condition of a machine, a comparison of past and current operational data must be performed. The instruments and software required in a condition monitoring system are determined by the type of machine or equipment and the specific needs to take measurements of critical components (Rao, 1996). The recent development of huge platforms for data storage and advanced software analysis tools have to a large extent improved the traditional condition monitoring systems. Instruments and are easier to operate and the efficiency of failure analysis has been significantly improved with the introduction of knowledge-based and expert systems (Rao, 1996).

Understanding of the deterioration mechanism and finding the correct techniques to detect failure processes are essential aspects of a successful condition monitoring program. Maintenance management must utilize the proper monitoring techniques in order to develop a system for failure prediction in real time (Markeset, 2012). Failures can be caused by different mechanisms such as wear, fatigue/stress and corrosion/erosion. The speed of the failure process varies depending on several aspects including design, material composition and exposure. However, similar to all normal mechanical failure modes is that they degrade at a speed directly proportional to the specific severity (Mobley, 1990). Figure 27 shows the general degradation processes that can occur for a component and the associated recommenced condition monitoring techniques.

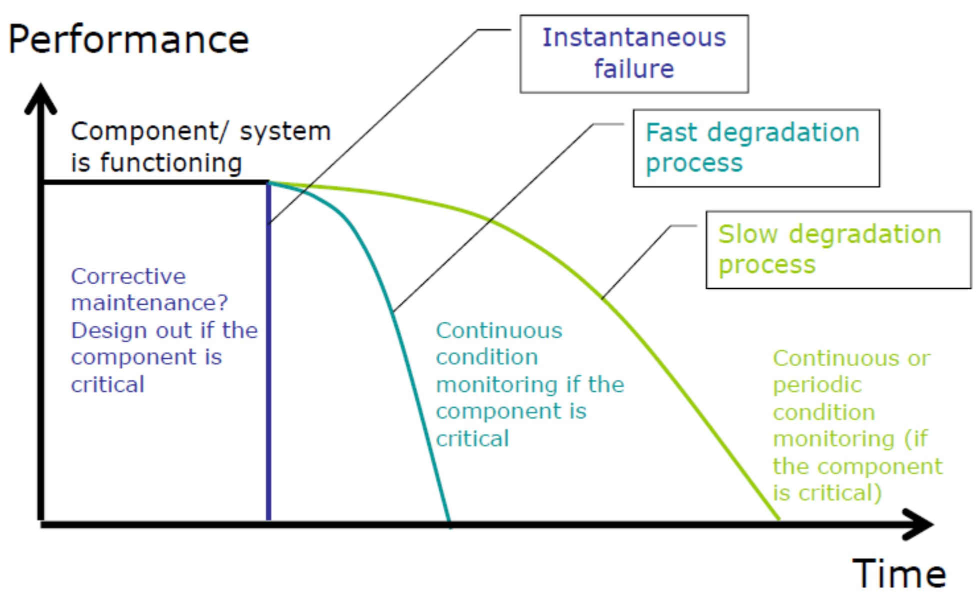

Figure 26 – Speed of failure process

7.6 Development of a condition monitoring system

Similar for all types of monitoring systems the structure of the design involves three major components; measuring, diagnosing and informing (Kumar, 1990).

Figure 26 – The three major components of a monitoring system (26)

Monitoring of equipment condition requires the use of physical sensors to measure the equipment performance. Together with comprehensive software programs and microprocessors, the sensors are often part of a complex monitoring system. The risks of failure associated with complex systems are often substantial. In down-hole operations the conditions can be harsh and sensors may be exposed to vibration and shock in addition to corrosive and abrasive fluids. Therefore, it is important to keep the designs of monitoring systems as simple and reliable as possible. Location and choice of sensors and termination of electrical wires must be considered in order for the monitoring system to function properly, enable replacement and run throughout the required lifetime.

Diagnosing involves the use of input data received from sensors. Instruments and software programs based on microprocessors interprets the raw data and algorithms convert readable output for the operator (Kumar, 1990).

Informing is an important aspect of the monitoring system design. One vital part of the informing aspect is to determine how to inform (Kumar, 1990). Sensor readings and diagnoses must be clearly expressed and easy to interpret by the operator through a display. The information is used

During design and development of a condition monitoring system, it is essential to determine which parameters to monitor and how they should be monitored (Markeset, 2012). Like for all effective systems, condition monitoring systems are based on important aspects such as links between cause and effect and benefits versus costs.

Cost → Risk → Benefits (One can't be changed without affecting the others). Increase benefits, reduce cost, increase risk (Markeset, 2012).

Other features presented in the "Handbook of condition monitoring" by Rao (1996) are:

- When the mechanical condition of a machine or equipment is changed and a possible failure is evolving, the monitoring system must respond rapidly with a warning.
- The measurements being taken of a certain system must be clearly related to the condition of the system.
- The condition of a machine or equipment is predicted by analysis of measurements and recorded data. Thus, it is essential that a system is developed for measuring and recording data.

- In order to determine the condition of a machine or equipment, comparisons of current measurements against predefined standards or existing measurements must be made.
- Cost effectiveness is essential for all condition monitoring systems.

As stated earlier, products will degrade within a typical classification time frame (Mobley, 1990). When developing a condition monitoring system it is therefore important to consider the distribution of failures illustrated by the “bath-tub” curve in figure x. As individual components have different specifications, all will be represented by specific curves expressing the respective failure rate. For example bearings will have a high failure rate in the early life due to latent design failures followed by random failures in the useful period. O-ring seals made of rubber will on the other hand have few failures in early life and in the useful period, but have a steep curve in the wear-out period.

Section IV

Maintenance Procedure

This section includes important aspects related to the development of maintenance procedures.

- **8 Maintenance procedures**
- 8.1 Development and Implementation of the Maintenance Procedure
- 8.2 Planning tools - Critical Path and Gantt Diagram
- 8.3 Health, safety and environment (HSE)
- 8.4 Criticality indexing of Components
- 8.5 Performing Diagnosis
- 8.6 Maintenance Activities
- 8.7 Function testing after Maintenance

- **9 Maintenance Procedure - Zonal Isolation Tool**
- 9.1 Planning of Maintenance
- 9.2 Procedure Contents
- 9.3 Additional procedures

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8 Maintenance procedures

The main purpose of developing a maintenance procedure is to ensure productive and efficient maintenance. This will reduce the number of unanticipated accidents during operation, reduce the time and resources required be maintenance activities and thus also increase the overall system efficiency. The basis for this chapter will be important aspects to include in maintenance procedure related to down-hole intervention tools used in the oil and gas industry.

The maintenance procedure are typically be separated in two main categories; the work procedure (i.e. the sequence of activities, and the maintenance process plan (i.e. critical path and time constraints). Both categories are essential for the procedure to ensure an efficient maintenance process. Included in the maintenance procedure there should also be a part concerning health, safety and environment (HSE).

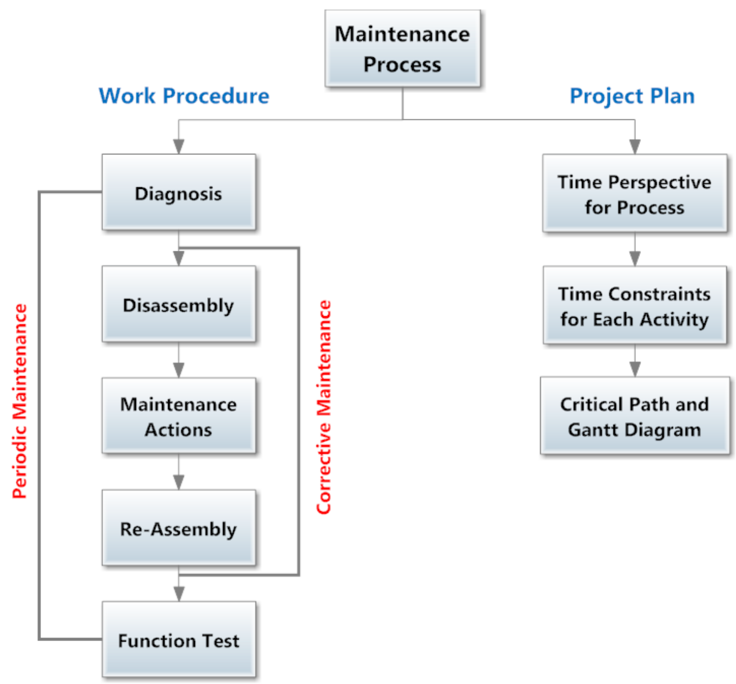

Figure 27 – The guiding maintenance process structure (27)

The work procedure includes the actual maintenance activities that should be performed. Diagnosis and function tests are related to periodic maintenance activities, while disassembly, maintenance actions and re-assembly are related to corrective maintenance activities (see figure 30). Nevertheless, disassembly of components may also be part of periodic maintenance activities (e.g. full inspection of tool components).

Additional procedures may be required apart from the main procedure to facilitate during the maintenance process. Problems may occur during the maintenance process, and troubleshooting procedures and inspection documents will be required. Furthermore, checklists can be helpful to keep track of the sequence of actions during the maintenance process. The main procedure will refer to the additional procedures once problems occur, thus keeping it easy to follow.

General elements in the development of a maintenance procedure

1. Planning of maintenance
    - Planning of periodic maintenance
    - Planning of corrective maintenance
    - Planning tools: Critical path and Gantt diagram
2. Health, safety and environment (HSE)
    - Use of safety equipment
    - Working environment
    - Tool for risk analysis of activities - Safe job analysis (SJA)
3. Criticality indexing of components
    - Why use risk based maintenance approach
    - Risk-based approach
4. Diagnostics
    - Measuring equipment and inspection reports
    - Analysis of tool/equipment
    - Diagnostics during periodic maintenance
    - Diagnostics during corrective maintenance
    - Failure mode and effect analysis (FMEA)
5. Maintenance actions
    - Equipment used during assembly and disassembly
    - Disassembly
    - How to perform actual maintenance and repairs
    - Assembly
6. Function testing after maintenance
    - Verify that all functions are working

8.1 Development and Implementation of the Maintenance Procedure

A maintenance procedure must contain clear instructions on all the activities included the maintenance process. It is important that the procedure is easy to understand to ensure efficient utilization. Redundant descriptions and instructions may be confusing rather than helpful for the maintenance personnel that is going use the procedure. Generally, the maintenance procedure should work as a guiding tool throughout the entire maintenance process, and facilitate the maintenance personnel.

Planning of Maintenance Activities

For most down-hole tools used in relation to production of oil and gas, both periodic and predictive maintenance strategies needs to be included in maintenance procedures. The periodic maintenance activities are based on systematic inspections and corrections that are determined during the design of the tool. For example all seals must be replaced after each stimulation job.

The predictive maintenance activities are based on monitoring and tracking of the mechanical and electrical components in the tool. Calculated lifetimes of electrical motors and harmonic gears will be the guiding basis when deciding when maintenance activities should be performed. Corrective maintenance activities must be done if damage of components or production failure is detected during inspection and diagnostics (e.g. thread damage or incorrect tolerances from manufacturing).

It is important for all maintenance processes that HSE measured are taken into account in procedures. A safe job analysis should ensure that all maintenance activities are approved by maintenance management, that all required safety equipment is available and that the work area is ergonomically designed and safe. It is essential that safety is highly prioritized. The designer of the maintenance procedure is required to include all the essential safety measures in the procedure. It is also necessary that a proper time schedule is established and all sufficient resources are available. Ultimately, it is the person or team in control for the maintenance activities are responsible for following up the safety instructions in the maintenance procedure.

During design of maintenance procedures there are different tools for planning maintenance activities, including the critical path method and the Gantt diagram. It is essential that all activities related to the maintenance process are included in a structured time schedule the procedure. The most critical components should be defined by a criticality index also included in the maintenance procedure. This must be used as the basis for developing the critical path and the scheduling process. Further discussion of planning tools and criticality indexing are done later in the thesis.

Planning of Periodic Maintenance Activities

Periodic maintenance activities can be planned during the design process of most down-hole intervention tools. This makes it possible to schedule the maintenance activities and plan for sufficient time. It will also ensure that all the required equipment and work space are available when maintenance must be done. The maintenance plan must identify when and how often maintenance should be performed. On certain components, preventive activities may be required to ensure equipment reliability. As part of the periodic maintenance activities, equipment diagnosis and function tests are the two main activities. These will be discussed later in this chapter.

Planning of Corrective Maintenance Activities

Because corrective maintenance concerns repairs that turn out to be required due to unexpected failures or breakdowns, it is essential that a maintenance procedure is properly developed and contains the appropriate tools for troubleshooting and clear job instructions. The maintenance activities that are required once a component fails unexpectedly are often difficult to define directly after the failure occurs. Usually, thorough inspections and diagnosis are required before the failure can be identified and proper maintenance activities assigned. The maintenance procedure should include additional procedure for diagnostics and troubleshooting inspections.

Certain common failures can often be defined during development of products. However, as these failures may occur when it is least expected, planning of corrective maintenance activities are difficult to do in advance. Common failures may be caused by for instance inappropriate assembly process or manufacturing faults, which ultimately can cause different components to fail unexpectedly.

8.2 Planning tools - Critical Path and Gantt Diagram

Maintenance activities associated with well intervention tools will have different criticalities depending on factors like safety and performance quality. However, time constraints are always an important issue related maintenance activities. Because the current product will be out of operation as long the process is enduring, the maintenance activities must follow the time schedule closely. Therefore, it is essential that all the maintenance activities are identified and planned with great care to ensure that adequate time and resources are available during the maintenance process. The Critical Path method is often used to identify the critical activities of a maintenance process. The steps in the method are presented in figure x (Endrerud, 2010).

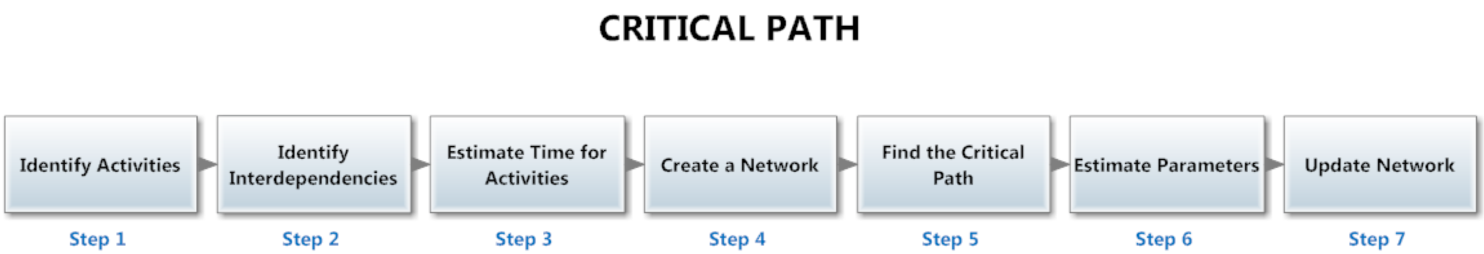

Figure 28 – The Critical Path Method flowchart (28)

Step 1: Identify Activities
The first step of the critical path method is to from a work breakdown structure of the maintenance activities. This is done to separate the activities in order to identify the individual specifications.

Step 2: Identify Interdependencies
Several activities in the maintenance process are related to each other, meaning that one activity cannot be performed before another is finished (i.e. interdependency). For example, greasing of threads must be done before components can be mated together.

Step 3: Estimate Time for Activities
The time required by each maintenance activity will be determined by a combination of calculations, tests and experience. The criticality of the maintenance activities is also important to consider in this step. Time must not be a stressing factor during critical activities, as accidents or improper maintenance may occur.

Step 4: Construct a Network
The maintenance activities should be represented in a time schedule (Gantt diagram). In this schedule, the relation between the activities should also be illustrated. The critical path should also be defined in the schedule. Methods for construction schedules will be further discussed later in the chapter.

Step 5: Find the Critical Path
The critical path it the sequence of activities that takes the longest time and is therefore critical for completion of the project. The time it takes to complete the activities on the critical path is the same time as the entire project will take. There are no possibilities for slack in any of these activities, as any delay would affect the entire project. However, the sequence of activities in the critical path may be changed if other activities outside the path are changed.

Step 6: Estimate Parameters
The parameters related to the start and finish times for each activity must be calculated based on the time each activity will take. Some activities have more slack than others, meaning that the start and finish times for these can be adjusted in the network. The activities on the critical path are not possible to change as they are directly affected by each other.

Step 7: Update Network
During the maintenance project it may be necessary to update the network of activities. If for example unexpected time delays occur due to damaged maintenance equipment, the time schedules for some activities may have to be shortened. A new critical path may occur.

Gantt Diagram

A Gantt diagram is a schedule that illustrates the maintenance project time frame. Figure 33 shows a basic diagram constructed in Microsoft Project. The red columns represent the critical path in the project while the blue columns are regular activities. The arrows between the activities represent the predecessor activities.

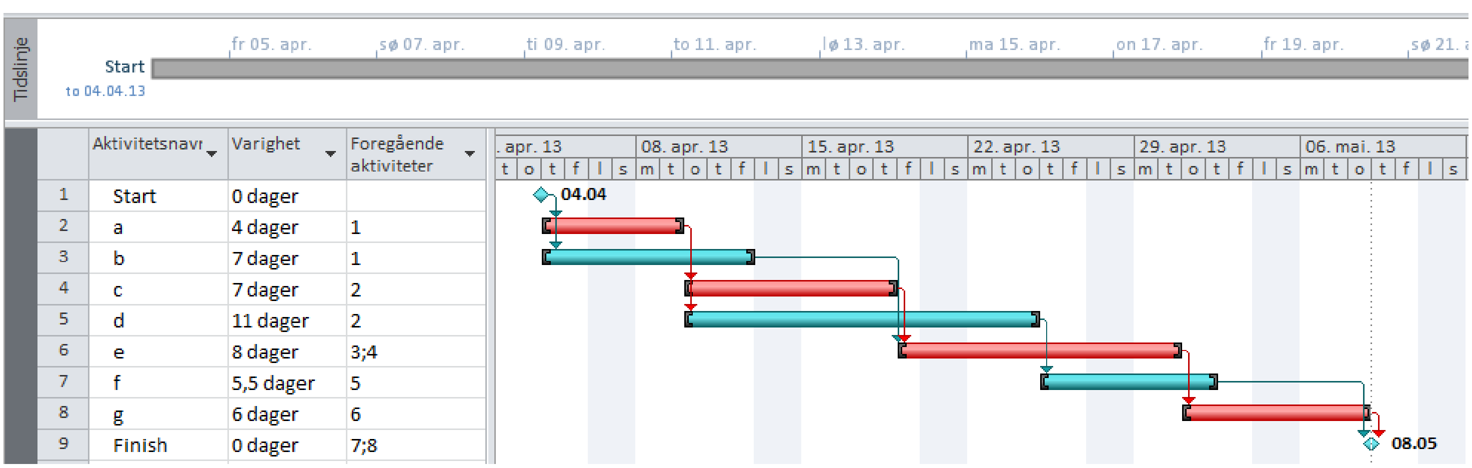

Figure 29 – Gantt diagram constructed in Microsoft Project.

8.3 Health, safety and environment (HSE)

In the HSE-plan all requirements associated with maintenance activities must be included.

Safety equipment

Analysis and identification of all maintenance activities as well as work environment and space must be considered when selecting required safety equipment. The designer of the maintenance procedure must take into account all the possible hazards and associated safety equipment when writing the activity instructions.

Examples of safety equipment used during maintenance of well intervention tools:

Possible Hazard	**Safety Equipment**
• High noise level	*Hearing protection*
• Chemical splashes	*Protective glasses, eyewash and safety shower*
• Grease and oils	*Protective gloves*
• Falling components	*Safety shoes*

Working environment and Maintenance Equipment

Investigation of the work space where maintenance activities are preformed is important to discover possible risks of injury. Ergonomics is an important part of the HSE-plan because it considers the design of the work space and the maintenance equipment. Noise levels, lighting conditions and body movement are examples of important aspects that have to be analysed to ensure a safe work environment during the entire maintenance process. Moreover, it is essential that the work space is kept clean (e.g. oil spills are removed) and that the maintenance equipment are systematically stored after use.

Equipment used for maintenance activities have the potential to create safety hazards if not used correctly (e.g. using grinders and securing load in lifting equipment). The maintenance personnel must be aware of all the risks that may be associated with the use of current maintenance equipment. Furthermore, datasheets for all chemicals need to be easily available at the maintenance facilities. This is important to have at hand if treatment of an injury caused by chemical spill would be required.

Typically, HSE-analysis of working environment and maintenance equipment would be performed together with a safety representative. This person has the main responsibility of overseeing that the HSE-regulations are followed throughout the organization. Inspections of safety equipment and maintenance equipment and activities should be done regularly to ensure that the HSE-regulations are followed.

Safe job analysis (SJA)

Prior to any maintenance activity it is essential to perform a SJA to identify, analyze and record the different activities and related risks related to the maintenance activities of a well intervention tool. The SJA should be separated into smaller activities, and each activity should be analyzed. Important aspects of the SJA are:

1. To include the steps involved in each specific maintenance activity and identify the requirements
    - Does the activity require certain training or competence?
2. To identify potential safety concerns and risks associated with each step
    - Falling objects
    - Penetration of sharp objects
    - Crushing between moving objects
    - Falls
    - Exposure to vibrating power tools, extreme temperatures, high noises, chemical liquids or fumes, etc.
    - Electrical power
    - Excessive body movement such as lifting, reaching, bending, etc.
3. To discuss the recommended actions or procedures that will eliminate or reduce the risk of injuries

The potential of injuries related to each specific maintenance activity should be represented with a given number based on a risk index (table x). The index is prepared on the basis of the consequences of the possible injuries and the probability that they will occur. For maintenance management one of the most important aspects in the maintenance planning process is to detect the criticality indexes for all activities in the maintenance process. Allocation of resources between the most critical activities in the process should be based on this criticality index. Further, the current risks should be evaluated against the provisions of The Working Environment act to ensure that all HSE-standards are followed.

Grade	Risk	Assessment
I	Insignificant level of risk	Activity is not critical
II	Tolerable level of risk	Activity must be performed with care
III	Undesirable level of risk	Activity should be carefully evaluated
IV	Intolerable level of risk	Possible that change of tool design is required

Typically, the SJA is documented in a form which includes:

- The current job title and number
- The names of all persons responsible for:
    - Undertaking the current job
    - Supervising
    - Performing the SJA

- The location of the current job
- The name of the responsible organization
- The job sequence
- A presentation of potential consequences and related risks
- Recommended risk assessment and procedure

An example of a SJA document is presented on the next page.

<table>
<tr><td rowspan="2">SAFE JOB ANALYSIS</td><td colspan="3">JOB TITLE: SJA No. ____________
Page of</td><td>DATE:</td><td>NEW:
REVISED:</td></tr>
<tr><td colspan="2">TITLE OF PERSON WHO DOES JOB:</td><td>SUPERVISOR:</td><td colspan="2">ANALYSIS PERFOMED BY:</td></tr>
<tr><td>ORGANIZATION</td><td colspan="2">LOCATION:</td><td>DEPARTMENT:</td><td colspan="2">REVIEWED BY:</td></tr>
<tr><td>SEQUENCE OF BASIC JOB STEPS</td><td>POTENTIAL CONSEQUENCES</td><td>RISK POTENTIAL</td><td colspan="3">RECOMMENDED RISK ASSESSMENT AND PROCEDURE</td></tr>
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8.4 Criticality indexing of Components

The criticality of components in a well intervention tool is typically determined by the actual function of the components. If maximum performance of a component is required for a tool to operate properly (e.g. motors in electrical tools), the criticality would be rated as high. Further, the function of components with respect to safety and environment should be considered. For example housings containing lubricating oil chambers should be closed so that no leakage occurs to the environment. The criticality index of a component should also consider the grade of component degradation. If a component is exposed of large flow rates of abrasive fluids containing sand particles the component would be regarded has critical.

The criticality index of components may be used during planning of the maintenance process. The degree of condition monitoring of components are often based on the criticality index.

Failure of critical components may be classified into four categories as represented in table 6 (Markeset, 2012):

Criticality Class	Risk of Failure	Maintenance	Criticality Distribution
IV	**Negligible Risk** Failure of component would not affect operation	Condition monitoring is sufficient	*41 %*
III	**Tolerable Risk** Component functions have degrading effect on operation	Preventive maintenance is recommended	*38 %*
II	**Undesirable Risk** The tool can be operated with reduced efficiency/function, depending on the extent of the component failure	Preventive maintenance is highly necessary	*20 %*
I	**Intolerable Risk** The tool will be impossible to operate if component fails. Failure may cause a safety hazard.	Redesign may required	*1 %*

Table 6 – Criticality Indexing

8.5 Performing Diagnosis

The purpose of performing diagnosis during maintenance is to identify failures and possible failure causes. This chapter will present different common diagnostic methods that can be used for diagnosing the condition of well intervention equipment.

Diagnostics are typically a part of the maintenance procedure. However, additional inspection reports are recommended to keep the activities structured. This will be discussed later in the chapter. As part of the inspection, a failure mode- and effect analysis, FMEA is presented as a tool to identify the potential failures and causes.

Common Diagnostic Methods

The most common diagnostic tool used for mechanical and electrical equipment are non-destructive testing, NDT. It is based on the use of test methods to examine components without damaging the function or shape. Non-destructive testing is a preventive technique used to verify the quality of the component and prevent failures from occurring.
Commonly used techniques are:

<u>Visual Inspection</u>

This is the simplest and most common method of non-destructive testing. Measuring equipment and cameras are often used during diagnosis (Hellier, 2001). However, small fractures and defects are not possible to identify by visual inspection and requires other, more advanced testing methods.

<u>Penetrant Inspection</u>

Penetrant testing is based on applying a penetrating solution to the surface of a component to identify the location of surface defects. The penetrating solution, often a red dye, will enter discontinuities in the component surface. After removing excess dye, a developer is used and the location of the defect will be visible, see figure 34. The method is used to inspect large components and to locate defects that may occur in the surface of the component such as cracks and pores (NDT Resource Center).

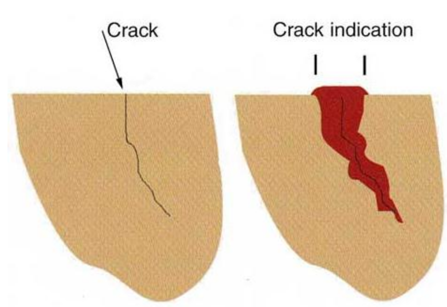


Figure 30 – Penetrant Inspection

Magnetic Particle Testing

Magnetic particle testing is done by first creating a magnetic field in ferromagnetic materials (i.e. materials that can be magnetized). Iron particles are then applied to the material surface. The magnetic field will force the surface to produce magnetic poles. Cracks or defects in the surface does not support as much flux as the undamaged material, thus some of the flux will be forced to run outside the surface attracting the iron particles and making a visible indication of the defect (NDT Resource Center)

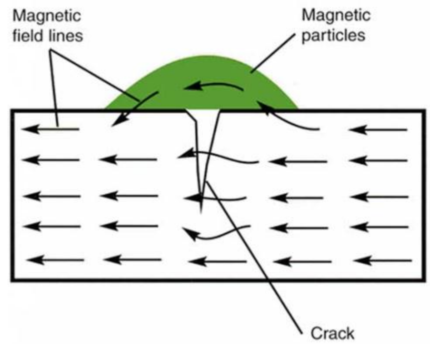


Figure 31 – Magnetic Particle Testing

Eddy Current Inspection

This method is based on the use of electromagnetism to detect surface and near-surface defects in conductive materials as well as measuring the thickness non-conductive coatings and sheet metal. A magnetic field is produced by an alternating electrical current that flows through a coil. The currents are called eddy currents, and travel in closed loops. Defects in conductive materials that are tested with eddy current inspection is detected by a visible change in the magnetic field inducing the current flow in the material. The current will be bent around the defect (NDT Resource Center).

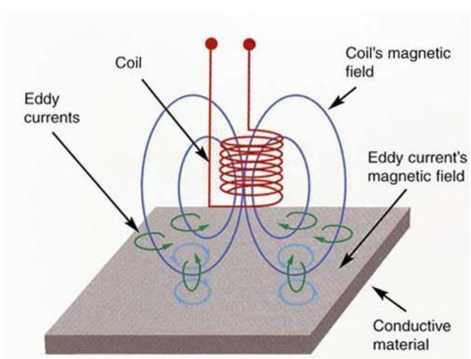


Figure 32 – Eddy Current Testing

Radiographic Testing

Radiographic testing is typically done by exposing the component to x-ray or gamma ray radiation. It is commonly used to detect internal defect in welds, castings or forgings. Detection of failures is indicated by a change in radiation absorption in the tested material. This is typically visualized on a shadow graph displayed on photographic film (The Engineering Toolbox).

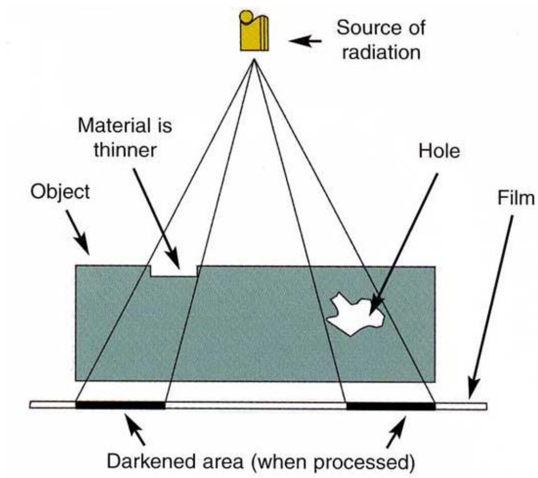


Figure 33 – Radiographic Testing

Inspection reports

Inspection reports are useful for documentation of the diagnosis process and for later identification of the failures that have been found during diagnosis of equipment. The report may be developed as an additional maintenance procedure with organized instructions related to the diagnosis process. This would be appropriate to make the diagnosis more structured if the inspected equipment consists of several parts.

It is essential for all inspection reports that identification of the associated equipment is easy. Labeling of all equipment components must be done properly. Serial numbers/ID-numbers should be printed on the component and easily located the inspection report to ensure quick component identification. Moreover, the current maintenance project should be referred by name and number the report.

It may be appropriate to include all the equipment components in the report, listed chronologically based on the criticality index, to verify the condition of each individual component. However, during a corrective maintenance process, identification of damages and failures may be filled into the report as they are identified. This may be more convenient because corrective maintenance activities usually are done for components that already have failed, and diagnosis of other components would be characterized as preventive maintenance.

The inspection report must be filled out by the mechanic during the diagnosing process. Symptoms and pictures of failures/damages must be filled into the report. A simple model of an inspection report is presented below:

Inspection Report

Job No.		**Serial number:**	
Customer			
Equipment			

Diagnostics

Component	**Diagnostic Technique**	**Symptom**	**Picture**

Performed By/Sign./Date:	

Failure mode and effect analysis (FMEA)

FMEA is used as a troubleshooting tool used for structured analysis of a system, device or process. It is used to identify possible failure modes and the causes and effects of these failures. The purpose of FMEA is to increase reliability and safety of a product by eliminating or reducing failures modes and the effects on the component. A plan will give more motivation for the maintenance mechanic during the troubleshooting.

The general steps in a FMEA (Aven, 2008):
- Identify components in the system
- Identify functions
- Identify failure mode
- Identify effects on other components
- Identify effect on system
- Identify measures
- Identify frequency of failures
- Identify failure mode classification

Failure will be prioritized after:
- The severity of the consequences
- The frequency of the failure
- How advanced the detection of the failure is

The table below is a brief example of a FMEA that could be used for analysis of components in the lower isolation module in the Zonal Isolation Tool.

FMEA Failure mode and effect analysis					**Equipment:** Zonal Isolation Tool	
Component	**Part nr.**	**Function**	**Failure mode**	**Failure cause**	**Effect on other components**	**Effect on system**
Lower isolation module						
Roller screw	01	Activating setting mechanism	1. Stuck – unable to move 2. Low efficiency	1. Broken threads 2. Insufficient lubrication	1. Unable to set isolation module	1. Tool unable to function 2. Reduced tool function
Electrical Motor	03	Supplying power to setting mechanism	1. Motor unable to start/run 2. Low efficiency	1. Lost electrical connection 2. Overheating	1. Unable to set isolation module 2. Increased setting time	1. Tool unable to function 2. Reduced tool function

8.6 Maintenance Activities

If the equipment diagnosis reviles a failure or a defect in any of the equipment components, maintenance activities such as repairs and replacements must be performed. The inspection report used during the diagnosis will only identify the failures or defects of certain components. It is the maintenance procedure that identifies the required maintenance activities.

Planned and structured maintenance activities are essential for the total efficiency of the maintenance process. Equipment disassembly, actual maintenance activities performed and equipment assembly are the main parts of the maintenance process.

This chapter includes a presentation of general maintenance activities that may be used to get damaged equipment back to its original operating condition. The maintenance activities discussed are the disassembly and assembly processes as well as how to perform actual maintenance activities.

Disassembly of Equipment

Several maintenance activities require that the major parts of the equipment must be disassembled. In order to make the process as efficient as possible, a disassembly procedure should be developed. This should be an additional procedure related to the maintenance procedure. The main purpose of equipment disassembly is to enable the maintenance personnel to perform all the required maintenance activities on all current components.

Which parts to disassembly should be pre-determined based on the required maintenance activities. This should also be specified in the procedure. For corrective maintenance activities, it may be sufficient to disassembly the damaged parts only. This may be done during the diagnosis as well.

The disassembly process may require special tools developed for certain components. All tools used in this process must be defined in the maintenance procedure. The required tools should be presented in a separate list in the procedure. In the maintenance process area, the location of the tools should be easy to discover, as well as instructions of use. Efficient maintenance activities rely very much on the structure and systematic layout of the work space. It is therefore essential that the maintenance procedure include clear descriptions of

Actual Maintenance Activities

After the equipment is disassembled and a diagnosis of the condition is completed, actual maintenance activities can be performed. These activities have the purpose of restoring the original function of the equipment, and may be separated into two main categories; repairs and replacements.

Depending on the extent of a failure or damage, a decision on whether a replacement is required must be made. If a component is badly damaged and repairs are either difficult or impossible, a

replacement of the component would be appropriate. Other factors such as time and cost must also be considered when deciding the maintenance activity. Standard components such as O-ring seals, bearings and bolts should always be replaced and not repaired. It is not worth taking the risk of machining standard components.
However, large components such as a cable head connector on a well intervention tool may be expensive to manufacture, thus also causing large maintenance costs in case of a replacement. If possible, failures and defects should be fixed. If the failures are caused by other factors than extensive wear, extreme operating conditions, etc. a re-design may be required.

Assembly of Equipment

After the maintenance and repairs are done, the equipment must be put together to its original form. If the equipment consists of several components, an additional assembly procedure similar to the disassembly procedure should be developed with clear instructions and illustrations. Specified torque forces required to assemble threaded connections, type of grease and lubrication, and termination of electrical connections are examples of instructions that should be included in the assembly procedure.

8.7 Function testing after Maintenance

After maintenance is complete, the equipment must go through a full function test to verify that all components have been restored properly. This is known as a FAT (factory acceptance test), and is required after equipment re-dress and assembly according to NORSOK. The test procedure must be approved by NORSOK and include acceptance criteria and a description of all tests to be carried out.

The function testing includes a test of all the functions of the equipment. To be approved, the equipment must be tested under the actual working conditions related to pressure, temperature and loads. Calibration of drivers, sensors and alarms, as well as a function test of safety systems is also required in the test. The current acceptance criteria must be included in the test procedure

9 Maintenance Procedure - Zonal Isolation Tool

The maintenance procedure for the Target Intervention Zonal Isolation Tool must be continuously developed throughout the mechanical and electrical design process. The construction process should be aided by persons with theoretical knowledge of maintenance operations and management, as well as persons with practical experience from current maintenance and operation activities in the oil and gas industry.

This chapter will include a presentation of the important aspects that need to be considered during the planning and development process of the maintenance procedure and the critical aspects related to the document design.

Initially, planning and development of the maintenance process is discussed, followed by a presentation of the procedure contents. This includes relevant HSE-information, critical component classification, and estimated time frames. Then, the actual steps of the procedure will be discussed chronologically. Finally, a brief presentation of the additional procedures is included.

9.1 Planning and Development

Maintenance of the Zonal Isolation Tool is scheduled to be performed at specific maintenance facilities. Only minor corrective actions may be carried out at the tool operation site. The entire maintenance process should be planned before the tool is sent to the customer, including both predictive and preventive maintenance activities. In the initial phase of tool operation, maintenance facilities will be located at the production/manufacturing shop in Norway. The specific location of the maintenance processes is determined by the required maintenance activities.

In general, the Zonal Isolation Tool should not be disassembled at operation site. The reason for this is that disassembly possibly can lead to critical components being exposed to damaging environments containing substances such as sand, dust, dirt, etc. Furthermore, it is undesirable to let personnel without the required training or knowledge about the particular maintenance process to perform any maintenance activities.

All tool components must have an ID-number and a material certificate that makes it possible to track where the components come from (i.e. batch), manufacturer, designer, etc. Spare parts must also be registered with number on a spare parts list. It will be preferred that one document belonging to each individual tool contains all certificates and an overview over the numbers of all components that the tools is made up of (including spare parts if replacements have been made). In addition, documentation of finished jobs, performed maintenance and approved/not approved function tests must be included. All documents must be signed (name, date).

Each individual component must be graded based on its criticality. The grading determines the criticality of the components on the total function of the tool and what type of maintenance that is required. Choice of material for components in contact with well fluids (i.e. H_2S) should determine if replacements of parts due to erosion/corrosion is necessary after a job (>30 settings).

Other important aspects to consider during the planning and development phase are:

- Identification of common failures through experience, knowledge and failure analysis.
- Provide good descriptions of the failures so that they can be easily identified by maintenance mechanics doing the machine diagnosis.
- Develop inspection procedures for common failures (i.e. troubleshooter).

Procedure Contents

<u>1. Title page</u>

The title page includes the name of the procedure and the document number that will be registered in the company procedure database. An executive summary of the maintenance procedure roughly describes the structure and the purpose of the procedure. The information table includes a revision index, the date of issue, name of the author, the person who has reviewed the procedure and the person who has approved it. The title page also includes information about the company such as, name, address, telephone number, organization number and e-mail address. It is important that all information on the title page clearly indicates that this is the current maintenance procedure for the Zonal Isolation Tool.

<u>2. Contents</u>

The table of contents may be used for quick reference for locating information and to denote revisions or changes made only to certain parts of the maintenance procedure.

<u>3. HSE-Information</u>

The health, safety and environment information provided in the maintenance procedure are based on a safe job analysis, SJA (see chapter 7.3).

Safety equipment:

- Safety glasses
- Safety shoes
- Gloves
    - Latex for handling fluids, oils, grease, etc.
    - Textile for handling maintenance equipment such as wrenches, lathe, drills, etc.
- Hearing protection when necessary (specified in procedure)

Target Intervention AS is are going to develop a safety handbook that will include safety information related to all physical activities performed by the staff. This handbook will be a supplement to the safety information included in the maintenance procedure.

4. Inspection and Maintenance

All steps must be thoroughly discussed and analysed to ensure an optimized maintenance procedure. During design and development of the tool, practical solutions to fast and effective assembly of mechanical components as well as electrical terminations must be emphasised. Estimated time frames should be identified for all maintenance activities.

The inspection and maintenance processes are similar for all the components (Cable Head Module, Upper Isolation Module and Lower Isolation Module):

STEP 1: DISASSEMBLE MODULE (Additional Procedure)

A disassembly procedure (*Procedure Tool Disassembly)* should be attached to the maintenance procedure. All steps must be illustrated with pictures showing the activities and thoroughly described in text. Tools required for the disassembly procedure should be presented in the general information section. All components must be placed in sections belonging to each module.

STEP 2: INSPECT COMPONENTS

Once all the components of the module have been disassembled, inspection can start. During this process, the maintenance personnel must use an inspection report attached to the maintenance procedure.

STEP 3: MAINTENANCE ACTIVITIES

All the required maintenance activities and maintenance tools must be identified and clearly described in the procedure.

STEP 4: ASSEMLBE MODULE (Additional procedure)

An assembly procedure (*Procedure Tool Assembly)* should be attached to the maintenance procedure. The layout and structure should be similar to the (*Procedure Tool Disassembly).* The assembly procedure should have a checklist that must be filled out during the assembly process.

Note: *A drafted maintenance procedure is included in the appendix.*

9.2 Additional procedures

To make the maintenance procedure as clear and practical as possible, additional procedures should be developed for different processes including tool disassembly and assembly. The additional procedures are only briefly discussed in this report.

- **Procedure Tool Disassembly**

  The disassembly procedure should be developed during the design of the Zonal Isolation Tool. It is essential that all mechanical connections and electrical terminations are defined in the procedure.

- **Procedure Tool Assembly**

  The assembly procedure is used both when the tool is assembled for the first time and after maintenance processes. The procedure should include general precautions that are important to consider such as appliance of grease, lubrication, lock-title, etc. An example of how a step in the assembly procedure may look is presented below:

	- Slide the valve into the valve housing - Connect activation rod - Use copper compound grease on threaded connection - Maximum torque: 6 NM

10 Summary and Conclusions

This chapter is a summary of the master thesis and a brief discussion of the project work. The conclusion discusses whether the main objective and the sub-objectives of the master thesis have been answered. Recommendations for further work are briefly discussed.

10.1 Summary

This project has been based on studying and discussing important aspects related to development of operation and maintenance procedures. Major parts of the report are background theory and knowledge obtained from my two years as a master student of Offshore Technology – Asset Management at The University of Stavanger.

The design of the Zonal Isolation Tool was changed several times during this project, and therefore the final prototype that was intended to be the basis for the operation- and maintenance procedures was delayed. Hence, instead of developing procedures that could not be used for current processes, the main objective of the thesis became to identify the critical aspects of developing procedures. By identifying these aspects and discussing the theories of both operation and maintenance, the report can be used as a guide when the final procedures are going to be developed in the future.

10.2 Conclusion

This report has identified several important aspects that need to be considered when developing procedures for operation and maintenance of the Target Intervention Zonal Isolation Tool.

A drafted operation procedure and a drafted maintenance procedure have been developed and attached in the appendix. The procedures are draft versions that should be used for further comments of procedures.

Techniques, tools and strategies used for maintenance processes and maintenance management have been identified in the report. Moreover, the critical aspects of general design and development of maintenance procedures have been discussed. General guideline for development of maintenance procedures has been defined.

In general, this report can be used as a guiding tool during development of future procedures.

12 References

Figure references:

(1) Craig Freudenrich, Ph.D. and Jonathan Strickland (n.d.) How drilling works [online] Available at: http://science.howstuffworks.com/environmental/energy/oil-drilling4.htm [Accessed: 04.03.13]

(2) Zhang, J., 2008. Pore pressure prediction from well logs: Methods modifications, and new approaches, Elsevier Earth-Science Reviews 108 (2011), 50–63.

(3), (4) King, G.E. (2009) Formation Damage – Effects and Overview [online] Available at: http://gekengineering.com/Downloads/Free_Downloads/Formation_Damage.pdf [Accessed: 14.05.13]

(5), (7), (8), (9) Pandey, A. K. (n.d.) Well stimulation techniques [online] Available at: http://petrofed.winwinhosting.net/upload/IAI/17-20mar10/Wellstimulationtech.pdf [Accessed: 12.03.13]

(6) Stewart & Stevenson - Coiled tubing units [online] Available at: http://www.stewartandstevenson.com/equipment/market/oil-gas/well-intervention-coiled-tubing/coiled-tubing-unit [Accessed: 12.03.13]

(10), (16) Target Intervention (2012) - Animation Video

(11) Samuel, M and Sendul, M (2003) – Stimulating the flow [online] Available at: http://www.slb.com/~/media/Files/resources/mearr/num4/stimulate_flow.pdf [Accessed: 06.03.13]

(12) TAM International (2013) – Animation Video [online] Available at: http://www.tamintl.com/index.php?option=com_content&task=view&id=220&Itemid=373 [Accessed: 12.04.13]

(13) Allison, Dave (2012) Self-removing EFDAs level stimulation access [online] Available at: http://www.drillingcontractor.org/self-removing-efdas-level-stimulation-access-14457 [Accessed: 18.05.13]

(14) Shuling Li, Cary Purdy, and Shiguo Wu, Halliburton (2012) - Pore Pressure and Fracture Gradient Prediction in Shale Gas Formations; Accounting for Complex Rock Properties and Anisotropies [online] Available at: http://www.onepetro.org/mslib/app/Preview.do?paperNumber=SPE-155540-MS&societyCode=SPE [Accessed: 15.05.13]

(15) Target Intervention AS (2013) – Zonal Isolation Tool

(17) Kobold – Provided Illustrative Figures

(20), (21), (22), (23), (25), (26), (31) Markeset, Tore (2012) – Lecture slides in MOM460 – Operations and maintenance management

(24) Engle, Paul (2010) - MTBF And Reliability - A Misunderstood Relationship In Solar Photovoltaics [online] Available at: http://electronicdesign.com/energy/mtbf-and-reliability-misunderstood-relationship-solar-photovoltaics [Accessed: 13.05.13]

(27) Endrerud, Ole-Erik.V (2010) – Bacheloroppgave om Utvikling av Prosedyrer

(30), (31), (32), (33) NDT Resource Center (n.d.) - NDT Method Summary [online] Available at: http://www.ndt-ed.org/GeneralResources/MethodSummary/MethodSummary.htm [Accessed: 03.06.13]

Literature:

1. Arefi, B.B. (2003) – Stimulation of Erosion in Drilling Tools for oil and Gas Industry (Master Thesis)
2. Aven, Terje (2008) – Risk Analysis – Assessing Uncertainties Beyond Expected Values and Probabilities, (John Wiley & Sons, Ltd) pp. 64-65
3. Bennion, D.B and Thomas, F.B (1994) – Underbalanced drilling of horizontal wells: Does It Really Eliminate Formation Damage? [online] Available at: http://www.reslab.com/media/34827/underbalanced_drilling_of_horiz_wells_does_it_really_elimina.pdf [Accessed: 09.03.13]
4. Biot, M.A., 1941. General theory of three-dimensional consolidation. J. Appl. phys. 12 (1), 155–164.
5. Bridger, R.S., 1995, Introduction to Ergonomics, McGraw-Hill, Introduction
6. Freudenrich, C and Strickland, J (n.d.) – How oil drilling works [online] Available at: http://science.howstuffworks.com/environmental/energy/oil-drilling5.htm [Accessed 16.04.13]
7. Hellier, C. J. (2001). Hanbook of Non Destructive Evaluation. McGraw-Hill.
8. Kumar, U. (1990) – Reliability analysis of a load-haul-dump machine: Chapter 5: Major components of the monitoring system, PhD thesis 1990:88D, Luleå University of Technology, Luleå, Sweden
9. Markeset, Tore (2012) – Lecture slides in MOM460 – Operations and maintenance management
10. Mobley, R.K. (1990) – An Introduction to predictive maintenance, New York: Van Nostrand Reinhold pp. 25, 38-40
11. NDT Resoruce Center (n.d.) Method Summary [online] Available at: http://www.ndt-ed.org/GeneralResources/MethodSummary/MethodSummary.htm [Accessed: 05.05.13]
12. NORSOK http://www.standard.no/PageFiles/961/Z-008.pdf

13. Pennstate College Hompage (n.d.) - Standard Operating Procedures: Development and Implementation [online] Available at: http://extension.psu.edu/animals/dairy/hr/tools-for-dairy-employee-supervisors/development [Accessed: 16.04.13]
14. Petroleum Online (n.d.) – Phases of Well Construction [online] Available at: http://www.petroleumonline.com/content/overview.asp?mod=4 [Accessed: 02.04.13]
15. Rao, B.K.N ed. (1996) – Handbook of condition monitoring, Chapter 2: Condition monitoring: the basics, Comadem Int., pp. 1-2
16. Samuel, M and Sendul, M (2003) – Stimulating the flow [online] Available at: http://www.slb.com/~/media/Files/resources/mearr/num4/stimulate_flow.pdf [Accessed: 06.03.13]
17. Shuling Li, Cary Purdy, and Shiguo Wu, Halliburton (2012) - Pore Pressure and Fracture Gradient Prediction in Shale Gas Formations; Accounting for Complex Rock Properties and Anisotropies [online] Available at: http://www.onepetro.org/mslib/app/Preview.do?paperNumber=SPE-155540-MS&societyCode=SPE [Accessed: 04.05.13]
18. Standard operating procedures: Development and Implementation [online] Available at: http://extension.psu.edu/animals/dairy/hr/tools-for-dairy-employee-supervisors/development [Accessed: 12.03.13]
19. Schlumberger (2013) – Oilfield Glossary [online] Available at: http://www.glossary.oilfield.slb.com/en/Terms/p/pore_pressure.aspx
20. TAM International (2013) – [online] Available at: http://www.tamintl.com/index.php?option=com_content&task=view&id=220&Itemid=373 [Accessed: 04.04.13]
21. Terzaghi, K., Peck, R.B., Mesri, G., 1996. Soil Mechanics in Engineering Practice, 3 rd Edition. John Wiley & Sons.
22. U.S. Environmental Protection Agency (EPA) (2007) – Guidance for Preparing Standard Operation Procedures
23. U.S. Energy Information Administation (2013) Shale oil and shale gas resources are globally abundant [online] Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=11611[Accessed: 12.05.13]
24. Zhang, J., 2008. Pore pressure prediction from well logs: Methods modifications, and new approaches, Elsevier Earth-Science Reviews 108 (2011), 50–

Appendix

Procedure Tool Operation –
Well stimulation with Target Intervention Zonal Isolation Tool

Document number: N/A – **Draft for Comments**

Executive summary:

This operation procedure includes a step-by-step description of a well stimulation process accomplished with the Target Intervention Zonal Isolation Tool.

01	11.04.13	First revision	Kenneth Høydal		
Rev Index	Issue date	Approval	Author	Review	Approved
Total number of pages					

1 Tool description

1.1 Specifications

Operational Specifications		**Comments**
Number of tool re-sets/zones	30	
Coiled Tubing Size	2 7/8"	Variable
Coiled tubing Material	100ksi	130ksi
Max stimulation pressure	**7.500psi**	
Max pressure atmospheric chamber	**15.000psi**	
Treatment time	**2hrs**	2hrs x 30 set/release
Max ambient operation temp.	**80°C (130°C)**	130°C ConocoPhillips NS
Min ambient operation temp.	**0°C**	
Max storing temperature	**40°C**	
Min storing temperature	**- 40°C**	
Max flow rate stimulation ports	**15bbl**	
Max pressure drop over tool	**750psi**	Under stimulation/frac operation (not bleed off/equalize)
Max diff. pressure over tool	**1.500psi**	
Vibration	5g (15-500 Hz), 20sweeps	**Design goal:** Sinus 10g (25 to 1000 Hz) Random 20grms (20 to 2000 Hz)
Shock	30g for 11ms (half sine)	**Design goal:** 30g, 11ms half sine – 100g, 6ms half sine – 1000g, 0.5ms half sine
Acid resistance	Yes	Standard 28% HCL with inhibitor
Ability to pump solids	Yes	Solid concentration:
H2S resistance	Yes	Low concentration. ConocoPhillips.: 60ppm
Gas	Yes	

2 Operation procedure

Step 1: Prepare Coiled Tubing
1. **Coiled Tubing Size** i. Make sure the CT is within tolerances by measuring the OD of the CT. ii. Maximum deviation from nominal OD = 0.4mm iii. Recommended deviation from nominal OD ~ 0.0mm 2. **Coiled Tubing Ovality** i. Measure the coiled tubing ovality ii. Maximum deviation from circular shape = 0.4mm iii. Recommended deviation circular shape ~ 0.0mm iv. If necessary, adjust the shape with special rounding tool. 3. **Coiled Tubing straightness** i. Make sure that the coiled tubing is straight in the section were the connector is to be assembled. 4. **Coiled Tubing seal surface** i. Clean the CT surface and remove all rust/dirt. Make sure that the CT surface is smooth and has no cuts or holes to ensure the O-rings in the connector seal properly. ii. Remove all sharp edges and round off the OD of the CT with a file.

Step 2: Rig-up process before run in hole

1. Terminate electrical connection
2. Connect to CT
3. Perform plate-pull-test to maximum expected workload.
    i. Make sure test load does not exceed the maximum recommended load on the connector. See assembly drawing for specifications.
    ii. Re-torque connector after pull-test according to specifications
4. Pressure test connection to maximum expected pressure or according to well operation program.
5. Test all electrical functions and sensor readings before RIH.
    i. Perform test-run to fully set and un-set positions on both upper and lower isolation module
    ii. Verify that all sensors are operational

Step 3: Run in hole to identify first zone

6. Perform a double check on upper and lower isolation module positions
    ii. Both isolation modules are re-tracked
        - Slips are re-tracked
        - Packers are re-tracked
        - Bleed-off valves are in **open** position
7. Activate CCPL and identify casing collars during RIH.
    i. Monitor both electronic and mechanical depth counters to ensure accuracy. Correlate depth with mechanical counter on reel.
8. Run in hole to detect the lowest perforated zone and stop RIH.
9. Run past lowest zone by sufficient margin
10. Slowly pull up the tool and utilize CCPL to locate the perforations in the first zone.
    i. Confirm location of perforations and move the tool over the detected perforated zone.

Step 4: Activate **LOWER** isolation module

1. Confirm that all operational parameters are ok according to procedure
   i. Check pressures and temperature and note.
2. Activate lower isolation module
   i. Activate lower isolation module and run until bleed-off valve is in closed position. Confirm bleed-off valve in closed position by checking revolution indicator in GUI.
   ii. Activate lower isolation module again and run until slips and packer are fully set. Confirm that packer and slips are fully set by checking torque indicator in GUI. **Set-force = 3.5 tons**

Step 5: Activate **UPPER** isolation module

1. Activate upper isolation module
   i. Activate lower isolation module and run until bleed-off valve is in closed position. Confirm bleed-off valve in closed position by checking revolution indicator in GUI.
   ii. Activate lower isolation module again and run until slips and packer are fully set. Confirm that packer is fully set by checking torque indicator in GUI. **Set-force = 3.5 tons**
2. Confirm that zone is fully isolated
   i. Perform check that all parameters on GUI are according to instructions.

Step 6: Stimulate the zone

1. Initiate stimulation process according to program
2. Monitor well parameters during the stimulation process
   - Pressures and temperature
   - Stresses and strains

Step 7: Un-set **UPPER** isolation module

1. Activate **UPPER** isolation module to open lower bleed-off valve and bleed off any differential pressure.
   i. Confirm that pressure is fully bled off before un-setting upper packer element.
   ii. Confirm no mechanical force on tool
2. Activate **UPPER** isolation module to un-set upper packer element
   i. Confirm that the upper isolation module is fully re-tracked before proceeding

Step 8: Un-set **LOWER** isolation module

1. Activate **LOWER** isolation module to open lower bleed-off valve and bleed of any differential pressure
   i. Confirm that pressure is fully bled off before un-setting slips and upper packer element.
   ii. Confirm no mechanical force on tool
2. Activate **LOWER** isolation module to un-set slips and upper packer element
   i. Confirm that the lower isolation module is fully re-tracked before proceeding

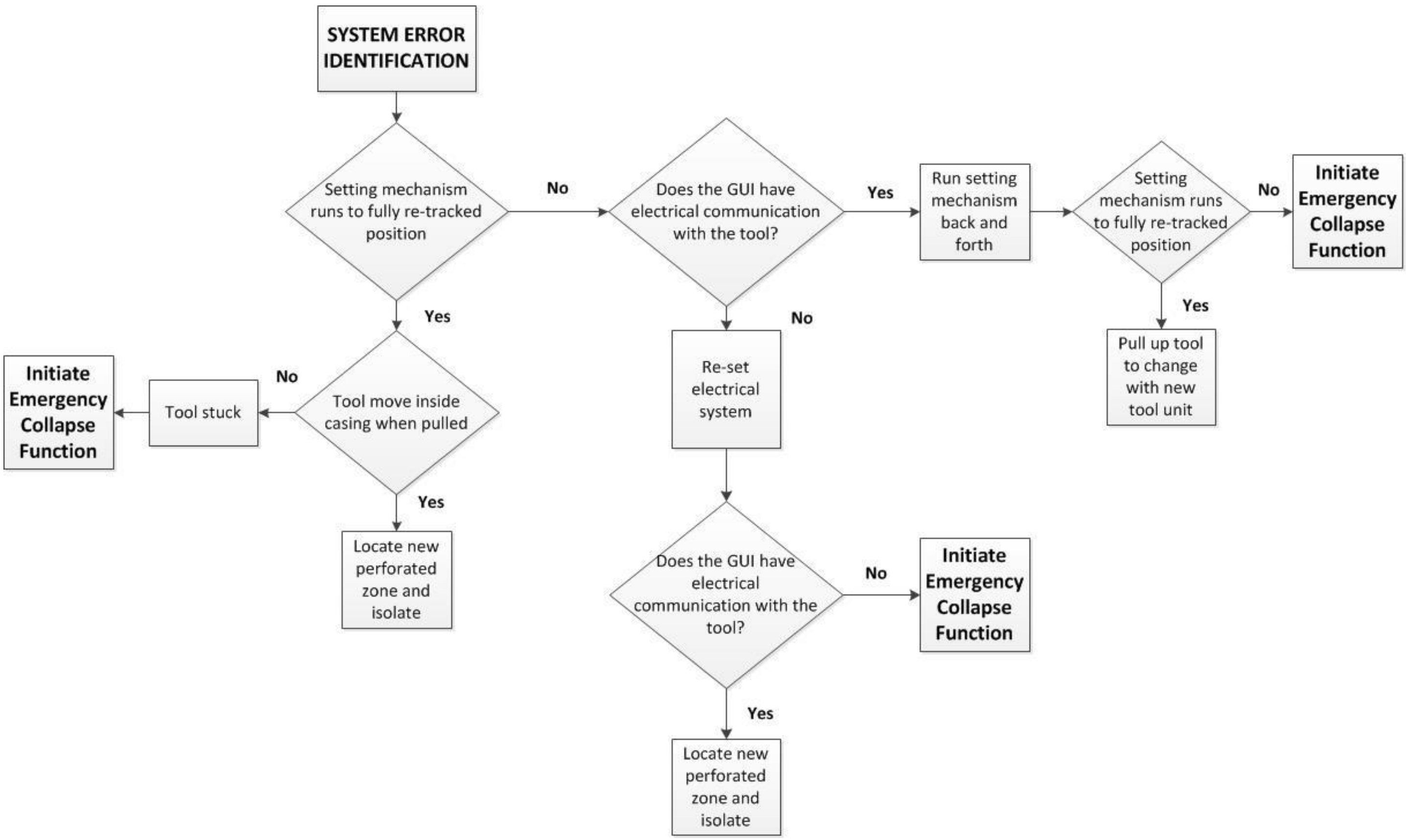
Step 9: Re-positioning tool to a new perforated zone

1. **Before re-positioning the tool to a new zone, wait 2 minutes for packer elements to fully re-track the elastic deformation in the packer element.**
2. Pull tool to locate next zone to isolate
3. Repeat operation procedure until targeted number of zones are reached
4. With the last zone treated and the wellbore clean, pull the coiled tubing and the tool to surface.

3 Possible sources of failure

3.1 System error identification

If encountering errors during operation, follow troubleshooting procedure:



FAILURE: Lost electrical communication with tool	
Error indication	**Actions**
1. No electrical communication/power between GUI/power supply and tool	1. Re-start electrical system a. If successful proceed operation b. If unsuccessful and tool unset (position) **Pull out of hole** c. If unsuccessful and tool set Initiate **Emergency Collapse Procedure**

FAILURE: Stuck in hole	
Error indication	**Actions**
1. Stuck in hole when slips and packer are fully re-tracked – moving tool not possible	1. Confirm that both isolation modules are re-tracked Try to run isolation modules back and forth to attempt to loosen the slips and packer If not re-tracked: Pump/circulate to try to work string free If not able to pull loose apply overpull in accordance to emergency collapse procedure to mechanically collapse slips/packer. Note: not reversible Initiate **Emergency Collapse Procedure** 2. Attempt to clean out potential debris/sand. a. If both isolation modules are fully re-tracked but pulling the tool is not possible. **3. Release.**

4 Packer and slips emergency collapse function

Emergency collapse procedure: Packer and slips emergency collapse
1. Note: not reversible when collapsed no turning back. 2. Initiate slips and packer collapse function i. Confirm required over pull (**in preparation check list**) to collapse slips and packer ii. Pull CT with sufficient over pull to activate the straight pull collapse mechanism

Module	**Collapse function**	**Load**
Lower packer/slips/valve	Straight pull collapse mechanism	Spring loaded to hold 10 tons (6.5 if set) of straight pull force
Upper packer/valve	Straight pull collapse mechanism	Shear pins holding 10 tons of straight pull force (shear force)

5 Release function

Release: Ball drop release (additional procedure)
1. Make sure that all emergency processes have been tried and followed according procedure 2. Ball seat (preparation check) 3. Follow additional procedure for release function

Procedure Tool Maintenance –
Target Intervention Zonal Isolation Tool

Document number: N/A – **Draft for Comments**

Executive summary:

This maintenance procedure should include a step-by-step description of the maintenance activities performed on the Target Intervention Zonal Isolation Tool.

01	11.04.13	First revision	Kenneth Høydal		
Rev Index	Issue date	Approval	Author	Review	Approved
Total number of pages					

1 Procedure Tool Maintenance

Note:

Read safety instructions found in HSE-handbook before starting maintenance operations.

1.1 GENERAL

a. Import data from Job Log into Tool Log. Review operational data and tool exposure.
   - Check whether any operational parameters has exceeded the specified maximum on any tool components
   - Check whether any components have exceeded maximum total exposure time

b. Perform a visual inspection of the assembled tool. Take note of any signs of damage.
c. Split tool into modules as shown in the next section
d. Follow attached procedures for disassembly and assembly of all modules.

1.2 HSE- Information

Required safety equipment (must be used at all times during maintenance activities):

- Safety glasses
- Safety shoes
- Gloves
    - Latex for handling fluids, oils, grease, etc.
    - Textile for handling maintenance equipment
- Hearing protection when necessary (use specified in procedure)

1.3 INSPECTION AND MAINTENANCE

CABLE HEAD MODULE

STEP 1: Disassemble Cable Head Module using *Procedure Tool Disassembly (must be attached)*

STEP 2: Inspect components (Cable Head Module)

Inspect following components and take note of any signs of damage. Fill out attached inspection report:

1. CONNECTOR
   i. Threaded connection
   ii. Slips teeth

2. CABLE HEAD
   i. Threaded connection
   ii. Electrical termination

STEP 3: Maintenance activities (Upper Isolation Module)

Use tool drawing and disassemble as shown in steps below:

1. ROLLER SCREW
   a. Check exposure parameters and determine if change is required

2. BLEED-OFF VALVE
   a. Change Seals and O-rings
      - Clean seal grooves with cloth. Apply degreaser.
      - Grease seal grooves, O-rings and backup-rings sufficiently before installation

3. BEARINGS
   a. Change Bearing Stack and Motor Bearings

4. PACKER ELEMENTS
      - Change packer elements after every run-in hole

5. ELECTRICAL COMPONENTS
   a. Check exposure parameters and determine if changes is required

STEP 4: Assemble Cable Head Module using *Procedure Tool Assembly (must be attached)*

UPPER ISOLATION MODULE

STEP 1: Disassemble Upper Isolation Module using *Procedure Tool Disassembly (must be attached)*

STEP 2: Inspect components (Upper isolation module)

See assembly drawing for details during diagnosis

1. Inspection document
    a. Fill out inspection form during diagnosis
2. Visual inspection
    a. Check for visible mechanical damage roller screw
        - Threads
        - *Lifetime calculation according to ISO 3408-5*
          20.000 working hours = 388235 rev.
          Tech. parameters: Expected lifetime: 90.000 rev. = 100 wells
    b. Check for visible mechanical damage on valve
    c. Check for visible mechanical damage on bearings
        - *Roller screw bearings rated for 1500 hours, 2700RPM rating, L10*
    d. Check for visible mechanical damage on slips
    e. Check for damage on electrical termination and wires

STEP 3: Replace components (Upper isolation module)

1. Replace seals and O-rings in bleed-off valve
2. Replace packer element
3. Replace electronics if required (based on lifetime)
    a. *Modem*
    b. *Motherboard*
    c. *Electrical wires*

STEP 4: Assemble Upper Isolation Module using *Procedure Tool Assembly (must be attached)*

<u>LOWER ISOLATION MODULE</u>

STEP 1: Disassemble Lower Isolation Module using *Procedure Tool Disassembly (must be attached)*

STEP 2: Inspect components (Lower isolation module)

See assembly drawing for details during diagnosis

1. <u>Inspection document</u>
   a. Fill out inspection form during diagnosis
2. <u>Visual inspection</u>
   a. Check for visible mechanical damage roller screw
      - Threads
      - *Lifetime calculation according to ISO 3408-5*
        <u>20.000 working hours</u> = 388235 rev.
        Tech. parameters: Expected lifetime: 90.000 rev. = 100 wells

   b. Check for visible mechanical damage on valve
   c. Check for visible mechanical damage on bearings
      - *Roller screw bearings rated for <u>1500 hours</u>, 2700RPM rating, L10*

   d. Check for visible mechanical damage on slips
   e. Check for damage on electrical termination and wires

STEP 3: Replace components (Lower isolation module)

1. Replace seals and O-rings in bleed-off valve
2. Replace packer element
3. Replace electronics if required (based on lifetime)
    a. *Modem*
    b. *Motherboard*
    c. *Electrical wires*

STEP 4: Assemble Lower Isolation Module using *Procedure Tool Assembly (must be attached)*