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Abstract

When coiled tubing (CT) operations are performed from floaters there is relative motion between the sea bottom and the topside equipment placed on the vessel deck. Some of the CT equipment is placed in a heave compensated tension frame (ACTF) that hangs in a tower structure on the vessel deck to keep constant distance to the well head. The reel placed on the vessel deck keeps constant coil tension during the operation by spooling coil on and off the reel to compensate for vessel motions. The result is that the strains induced in the coil when it is bent over the reel are repeated in each cycle (one cycle=vessel moving up and then down). This reduces the fatigue life of the exposed parts of the coil drastically.

This thesis explores the possibility to reduce the fatigue problem by replacing the gooseneck placed on the injector, which traditionally guides the coil, with a guide pipe that goes all the way from the reel to the injector placed in the ACTF. The guide pipe will have a much larger bend radius than the gooseneck and eliminate the need for spooling excess coil on and off the reel to keep constant coil tension when performing CT from floaters, by changing its bend radius with the vessel motions.

The guide pipe behavior during 3m heave was guesstimated and the strain behavior was compared with a comparable standard CT case. As the need for reeling coil on and off the reel was eliminated, something that induced a strain variation of up to almost 2% in every cycle, it was expected to get an increase in coil life. The estimated strain variation in each cycle was reduced to under 0.2 % when the guide pipe compensated for the relative motion by changing its bend radius. The result after the simplified calculations where factors as pipe ovality, surface and internal material defects and welds were not accounted for; was an increase in estimated number of tolerated cycles from about 300 to about 2000.

In addition to increasing the coil life, the improved coil conditions could expand the operational window and/or make more use of monohull vessels for performing CT operations possible. It is also assumed that the technology with small adjustments can make CT operations in the Arctic more feasible than with the existing technology as the CT will be protected from ice spray.

The hypothesis after this literature study is that a standard steel pipe with an inner layer of polymer can be used as guide pipe. Steel pipes are available and known to handle the expected loads and the polymer reduces the force needed to pull the coil through the guide pipe and minimize coil damage. The most promising polymer candidate found is a 70-80% polytetrafluorethylene (PTFE) and 20-30% polytetrafluorethylene (PEEK) composite. More research and practical experiments are needed to validate the hypothesis.

After one round of risk analysis a rig up and operation solution assumed to be feasible were found, this is called solution 2d and is illustrated from page 89 to 93. A significant amount of work remains, however, in order to conclude that the suggested solutions are feasible in real life.

Preface

Some challenges were met during the preparation of this thesis since estimation of fatigue damage caused by plastic strains is not standard procedure and none of the fatigue experts I contacted wanted to start me on the matter after I had presented the case for them as they considered it to be too comprehensive.

In addition to this, the concept I had to work with was very vaguely defined and the people who had worked the most on the matter earlier were no longer available. But with guidance and unlimited access to the private library of my mentor at Rolls-Royce, Per Gunnar Bjoland, expertise knowledge on how CT operations are performed today which Frode Bjørkheim willingly shared and input on the practicality of my rig up and operational suggestions from Kjell Inge Torgersen and Jens Myklebust, solutions were found. I am also very grateful that Ove Tobias Gudmestad wanted to be my mentor at UiS, as he was the best mentor I could ever ask for.

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1 Background

This chapter is based on conversation with F. Bjørkheim, API (1996) and the references listed below the figures.

1.1 Basics about Coiled Tubing (CT)

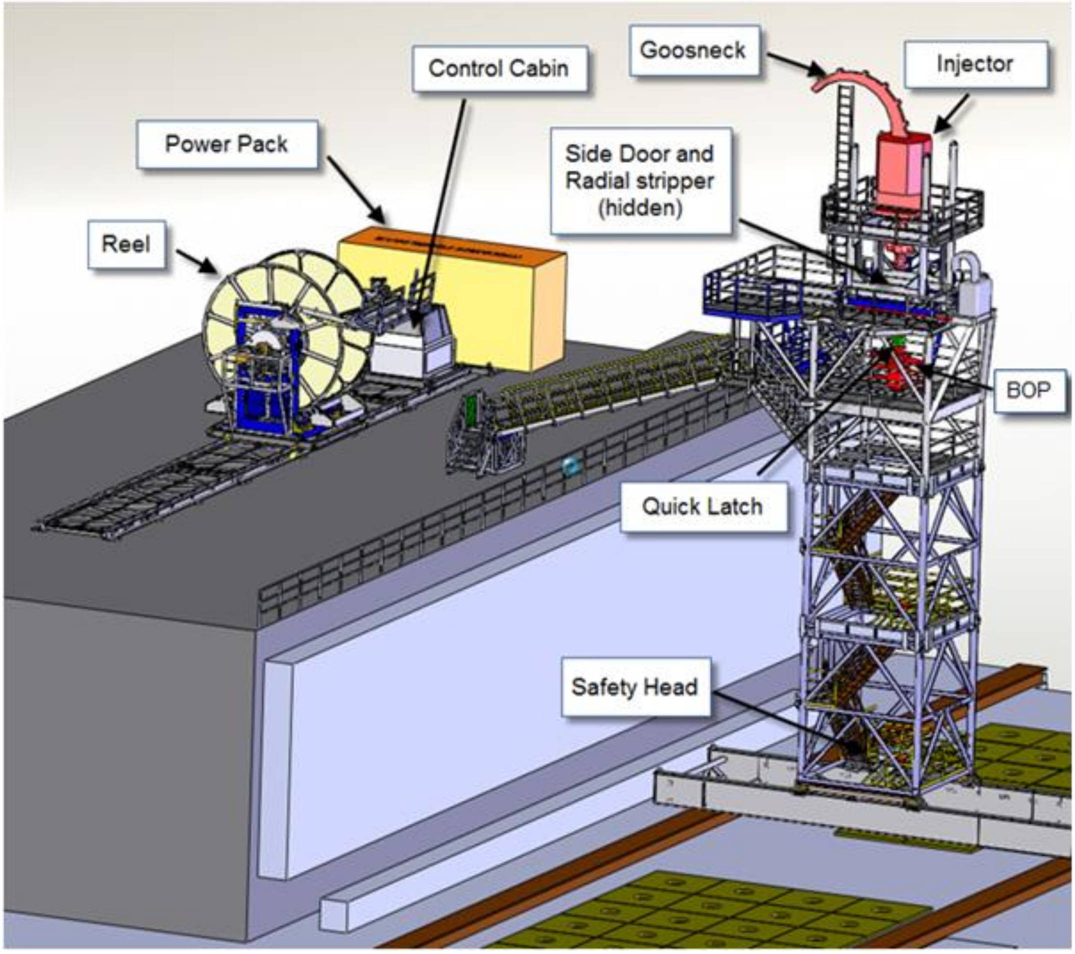


Fig 1.1 Example of CT rig on a permanent installation (RRMS)

Coil tubing is well intervention where one uses a continuous pipe. The continuous pipe called coil is coiled up on a reel and during operations the coil is guided into the injector over a gooseneck, see figs 1.1 and 1.2. The injector then drives the coil down in the well. The injector (and the other power consumers) is powered by the power pack and the operation is controlled from a control cabin. A tower structure or jacking frame is normally used to achieve the required height to stack the equipment and insert the tool. To make it possible for the coil to move in and out of a pressurized well one has two strippers placed under the injector that controls the well pressure during operation. In figure 1.1 a radial and a side door stripper are used, the stripper types may wary, but is has to be two of them for safety reasons. The main components in a stripper are two sealing rubber elements that are forced against the tubing by adding hydraulic pressure; some are assisted with the well pressure for easier sealing.

Under the strippers one has a blowout preventer (BOP) as a secondary barrier. This BOB have several functions that are initiated if needed; it can seal against the open bore, cut the tubing, hold the tubing and seal around the tubing. The first two functions are often performed by the same valve so that the total amounts of valves are three; the BOB is then called a triple BOB. Under the BOB there is usually made some room for risers that connect the upper BOB and a shear seal BOP (also called safety head). The shear seal BOP works independently of the upper BOP and is located as close as possible to the x-mas tree. Its function is to cut the tubing and seal the well in emergency situations. In fig 1.1 the safety head is located on pipe deck level, the x-mas tree is hidden because it is located one floor down.

Before lowering a tool into the well, the injector, with the strippers connected, is skidded to the side. Then the tool is lowered down through the upper BOP down in the riser section over the shear seal BOB. The x-mas tree controls the well pressure at this time, with a double block barrier (two closed valves) normally a swab valve and a hydraulic master valve. The down hole safety valve (DHSV) placed in the well can act as a secondary barrier against well pressure. After the tool is in place the injector and strippers are mounted on the upper BOB. After this some tests are performed to make sure that it is safe to pressurize the upper section (section between x-mas tree and injector) the upper section is normally filled with seawater, to equalize the pressure in the well before opening the x-mas three valves (the barriers against the well). Then the x-mas tree can be opened to let the tool pass.

After operation, and out of hole with CT and tool, the sequences are reversed when it comes to barriers. Inflow tests are performed on x-mas three valves to have required barriers in place before the pressure in the riser is bled off and injector and strippers can be latched off, skidded to the side and the tool string removed (and replaced if necessary).

On the reel there is placed a device called the spooling/counterhead that keeps track of how much coil is spooled out and a universal tubing integrity monitor (UTIM) keeps track of the deflection history of the different sections of the coil.

Fig 1.2 CT operation on a permanent rig (RRMS)

The principle of coiled tubing in the oil industry has been the same since the first functional CT unit was developed in 1962 (ICTA, 2012). But there has been an evolutionary development parallel to the development in drilling technology that has provided longer and more complex wells. Advantages with CT compared to wireline are that CT can be used in deviated wells and that it is possible to transport fluid and gas inside the coil. Examples of coiled tubing operations are flushing (cleaning), pumping nitrogen down the coil to lover the density of the oil so that is rises, milling (opening blocked wells) and fishing for lost objects.

1.2 Coiled Tubing From a Vessel

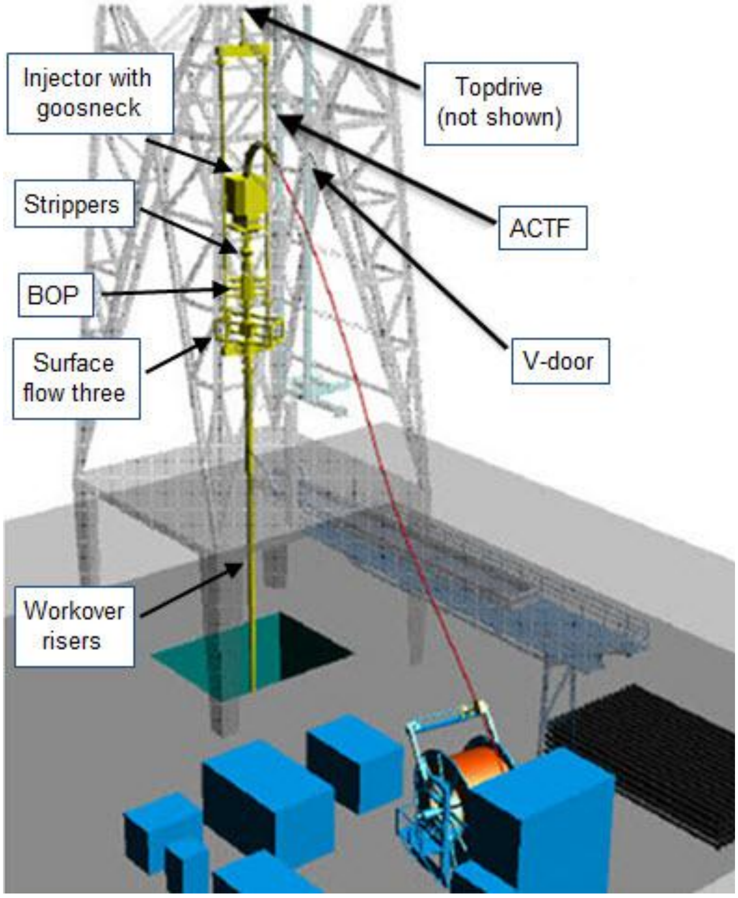


Fig 1.3 CT on a floater (Furberg, 2002)

Fig 1.4 Topdrive (Foremost, 2012)

There are more and more subsea wells because of, among others, increasing depths and increased focus on costs. Traditionally semisubmersible drilling rigs are used for both drilling and maintenance of the subsea wells. When CT operations are performed from floaters there is relative motion between the bottom hole assembly placed on the subsea well and the topside equipment placed on the vessel deck. Another difference is that the upper section between x-mas three and injector is very long because the x-mas tree is located on the sea bottom. Workover risers are normally installed to connect the x-mas tree to the surface flow three. The surface flow three is then connected to an advanced coiled tubing tension frame (ACTF), se fig 1.3. The ACTF provides a safe working window for the surface equipment and facilitates winches, injector lifting table etc. for equipment handling. The

ACTF is connected to the topdrive installed in the tower (fig 1.4).The topdrive heave compensate the tension frame by moving relative to the tower during the vessel motions, hence constant tension is kept in the stack of workover risers.

The reel keeps constant coil tension by spooling the excess coil on and off the reel with the topdrive motions. The result is that strains are repeated in each cycle (one cycle= topdrive moving up and then down one time).

All the extra equipment and man-hours needed to perform CT operations from a floater ad tremendously to the expense of performing a CT operation. The operation is also very weather dependent because of the relative motion between intervention vessel/rig and the well, this is further discussed in chapter four. In addition the relative motion increases the risk for incidents amongst the crew that have to rig up and support the operation outside the control cabin.

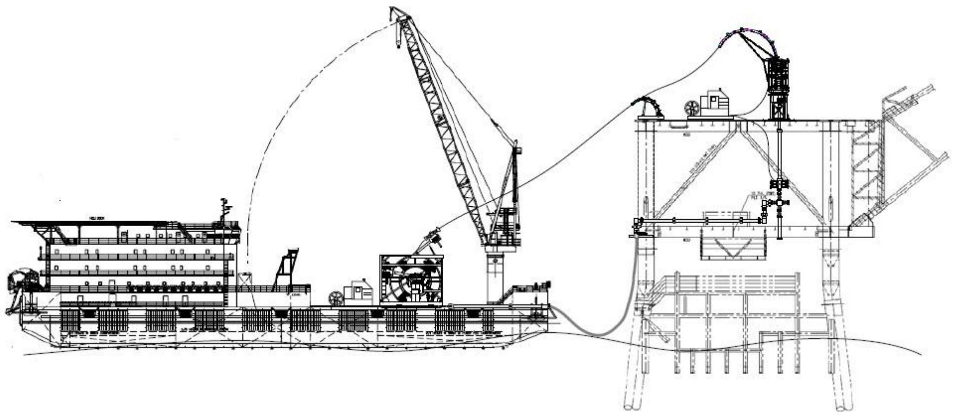


Fig 1.5 Example of a CT operation supported from a Vessel (Long et al., 2011)

Figs 1.5 illustrate another way of performing a CT operation from a floater. This way of rigging up for a CT operation is chosen when there is an insufficient amount of deck space available on the permanent installation or the available cranes does not have the capacity to lift the reel. The issue of relative motion between reel and gooseneck are the same.

According to Cann and Poldevaart (2004) regular well maintenance gives accelerated production, increased ultimate recoverable reserves (URR) and reduced operating cost. At present subsea wells have a lower URR and lower production rate because well interventions cannot be performed as often as it should because of weather conditions, or is not performed as often as it should because the cost and/or risk exceeds the benefits achieved.

2 Optimalizing CT Equipment for Floater Operations

2.1 General

The goal is CT equipment which is optimized with respect to health, safety and environment (HSE) that function as optimal as possible. The design needs to be optimized in relation to risk, functionality, reliability, availability, maintainability, supportability, costs, installation and need for modification to fit the different operations and sites. (Markeset, 2010)

To optimize the installation time and risk during installation the installation process must be evaluated early in the design phase (this is done in **chapters seven and eight**). Component size, shape, weight and center of gravity must be considered when determining number of lifts and placement of lift points, this have to be done at a later stage as the concept was not mature enough to evaluate these aspects at the time of writing.

There are challenges due to necessary technology qualification and testing when implementing new equipment or procedures. The financial risk is normally high with new technology. The possible benefits new technology and/or methodology induce must be considered higher than the financial risk in order to apply the new technology. A cost-benefit discussion can be found in **chapter nine**.

Examples of possible benefits in this case are:

- Extended lifetime of the coil
- Increased weather window for operations
- Better HSE results
- Possibly more use of monohull vessels (lower day rate and faster mobilization)
- Equipment more suitable for Arctic climate

In **chapter one** is was found that when considering CT operations from floaters coil fatigue and marine riser installation were potential areas of improvement. In this chapter two concepts are presented that possibly solve these issues. The theory of fatigue is presented in **chapter three** after some general material theory to have some background for the material discussion in **chapter six**. **Chapter four** gives some general background knowledge relevant for the discussion in some of the other chapters and **chapter five** presents the situation in the Arctic as the CiC concept solve some of the issues that will be met when CT operations are to be performed there.

2.2 Coil Fatigue

2.2.1 Coil in Coil

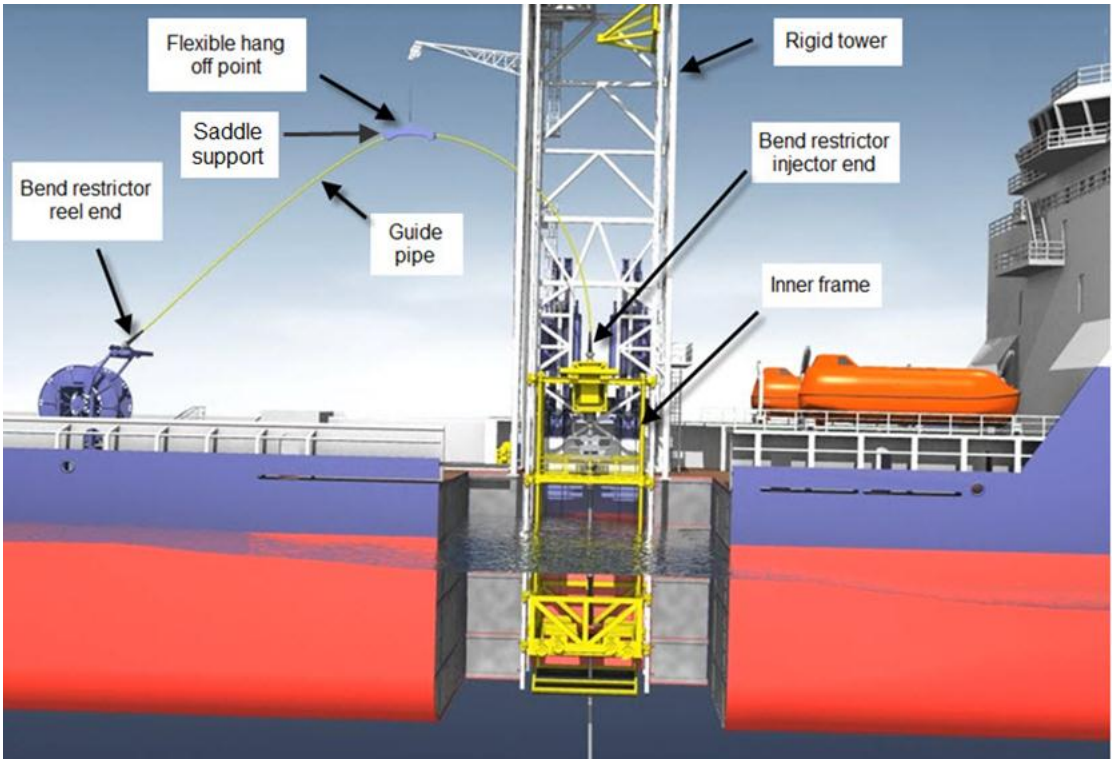


Fig 2.1 Rough Principle (RRMS)

The coil in coil (CiC) concept discussed in this thesis is developed by Rolls-Royce Marine Stavanger; the principle is illustrated in figure 2.1. In this figure a ship is used as an intervention vessel. A rigid tower structure is fastened to the deck and an inner frame (as in fig 2.1) or a tension frame (as in figure 1.3) with the necessary CT equipment installed is placed inside the rigid tower. The inner frame/tension frame is heave compensated as discussed in chapter 1.2; hence it keeps constant distance to the sea bottom. All equipment placed on the deck move with the wave motions relative to the equipment inside the tower.

What is different from traditional CT:
The gooseneck is replaced with a device which function is to restrict bending at the injector entry point. A device with the same function (but not necessarily equal) is placed on the reel end. These two bend restrictors are connected with a pipe with an inner diameter larger than the coils' outer diameter, here called the guide pipe. The guide pipe serves the function the gooseneck traditionally serves (guiding the coil into the injector). The guide pipe is supported and hung from a point above the reel and gooseneck by a component called saddle support; the flexible hang off point might have to have the possibility to move to some extent with the heave motions. Constant tension is kept in the coil by the guide pipes change in bend radius with the vessel motions. Since the guide pipe will have a much larger bend radius than the gooseneck and the need for spooling coil on and off the reel with the heave motions is eliminated the fatigue problem is assumed to be reduced.

The design is in an early concept stage. How to rig up, which guide pipe material could be used and details on the design of new components have not been considered at all, at least not in any traceable way. **The main goals for this thesis are;** to find a feasible rig up suggestion and a promising material candidate, get some numerical values on the effect the CiC solution could give and evaluate if it is probable that it is worth taking the design solutions further.

2.3 Riser Rigup

As mentioned in chapter one it is more difficult (if possible at all in some areas/periods of a year) to rig up workover risers from a vessel to the subsea tree. Where CT from a vessel is considered the depths are often quite considerable. This means that even if the weather conditions allow rigging up a riser stack long enough to connect the vessel to the subsea well it is an extremely expensive operation. A principle for a possible solution is illustrated to show that work is done to solve this issue, but the scope of the thesis would have been too wide if more work should have been done on this.

2.3.1 Riserless Coiled Tubing

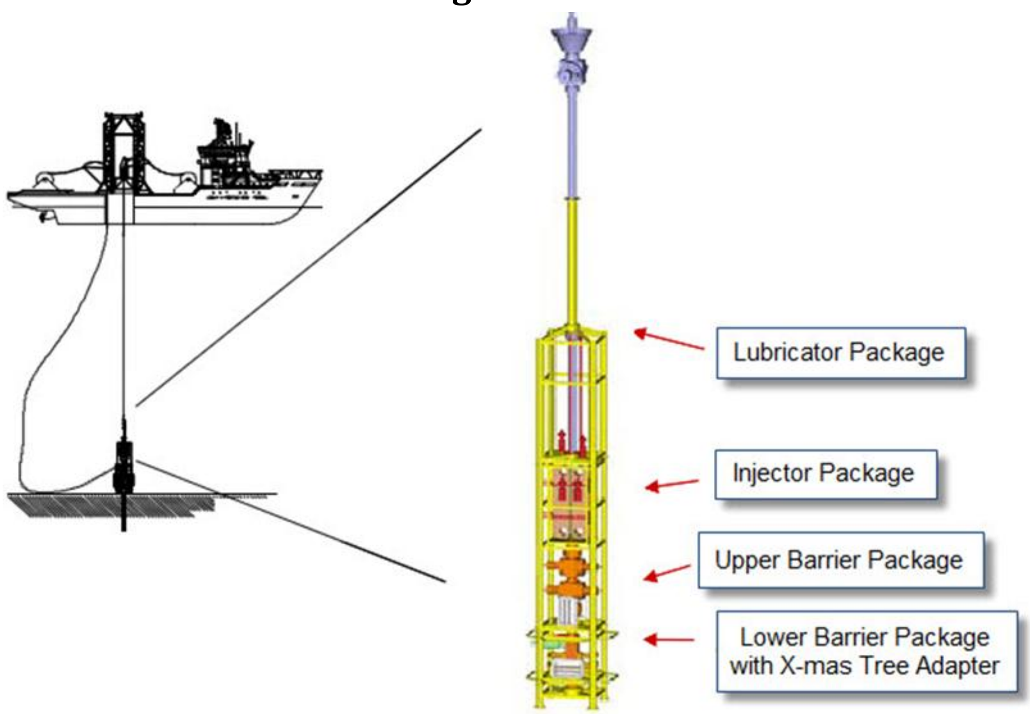


Fig 4.2 Example of riserless coiled tubing (Hoen and Håheim, 2004)

In riserless coiled tubing the coil is run in the open sea as shown in figure 4.2. This has been done and is very cost effective compared to rigging up a riser stack when one exceeds a certain depth. On the downside one has no barrier against spillage of the coil content should the coil fail during operation. Therefore it is extremely important to dimension the coil correctly; much work remains to be able to accurately evaluate the loads on the coil in the open sea under different conditions.

3 Material Theory

This chapter is based on Callister (2007) and the other references mentioned below the figures.

3.1 Metals

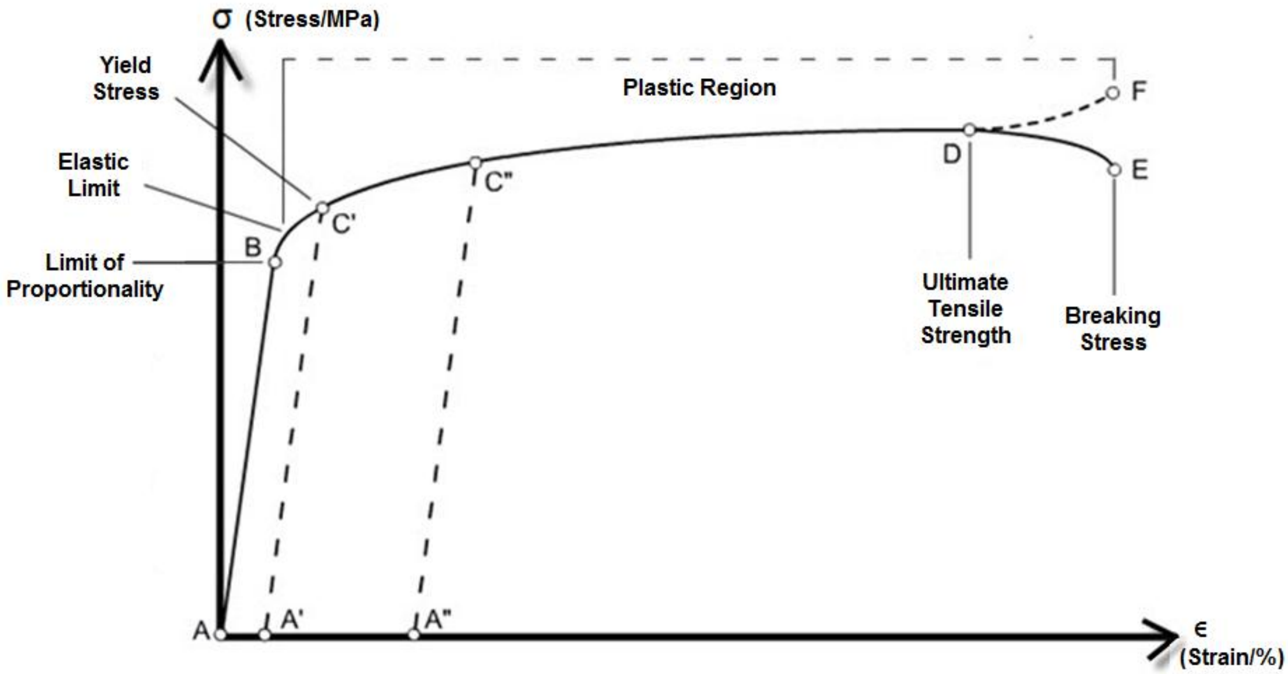


Fig 3.1 Stress-Strain diagram for a ductile material

As long as the imposed stress is below point B, the proportionality limit, stress is described by Hookes law as $\sigma=E*\varepsilon$ if the material is elastic. E is the modulus of elasticity, a property of the given material. A high E indicates a high resistance against deformation; hence the interatomic bonding forces are strong and/or many. ε is the strain, a uinitless measure of the amount of deformation. Materials as gray cast iron, concrete and plastics does not have a linear elastic region. Then a tangent or secant method is used to determine E.

When the applied load induce a stress level above the yield stress (σ_y) the material beginns to deform plasticaly. Stress below this point does not inflict any permanent reordering of atoms in the structure. The stress is completely relieved as the load is removed and the metal goes back to its original shape. For some merals such as steel and aluminium the yield point C` (fig 3.1) is not easily defined, σ_y is then commonly set as the stress level reached when the strain is 0.01 or 0.02, one then often write $\sigma_{0.01}$ or $\sigma_{0.02}$ respectively.

The ultimate stress, σ_u, is the maximum stress level that can be applied before failure.

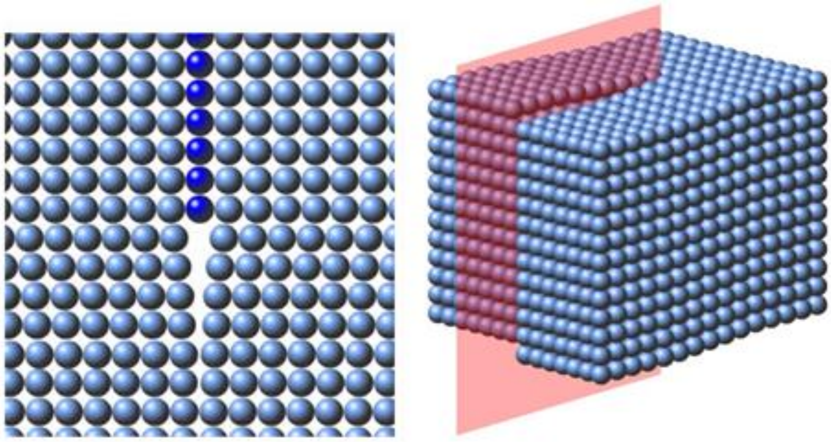


Fig 3.2 Left; edge dislocation and right; screw dislocation (esa, 2012)

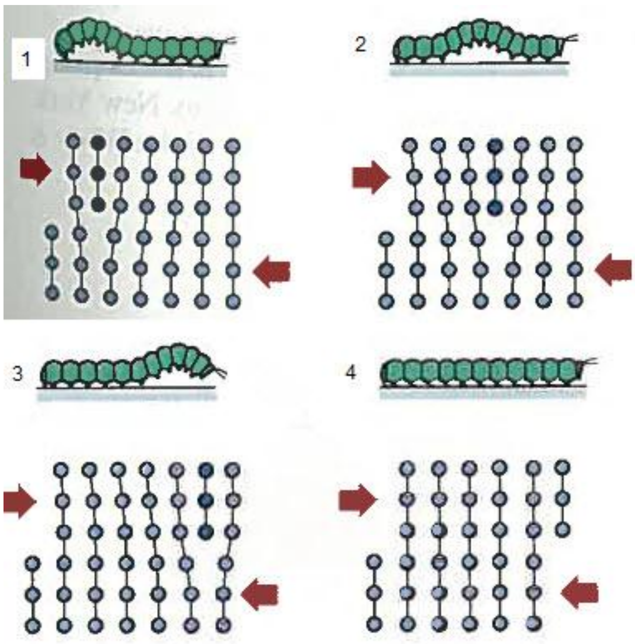


Fig 3.3 Dislocation movement (Callister, 2007)

A load beyond the elastic limit (σ_y), gives plastic deformation. In the plastic region when load is removed only the elastic part of the strain goes back. This is illustrated by the paths A' to C' and A'' to C''. At atomic level this means that there is movement of atoms away from their equilibrium positions and creation and movement of imperfections in the crystal stricture called dislocations; the two types of dislocations are illustrated in fig 3.2. Fig. 3.3 illustrates the principle of edge dislocation movement. Edge dislocations move in the shear stress direction and screw dislocations move perpendicular to the stress direction. Depending on the crystal structure certain planes are preferred planes for atomic movement. These are called slip planes and get a higher shear stress concentration than other planes.

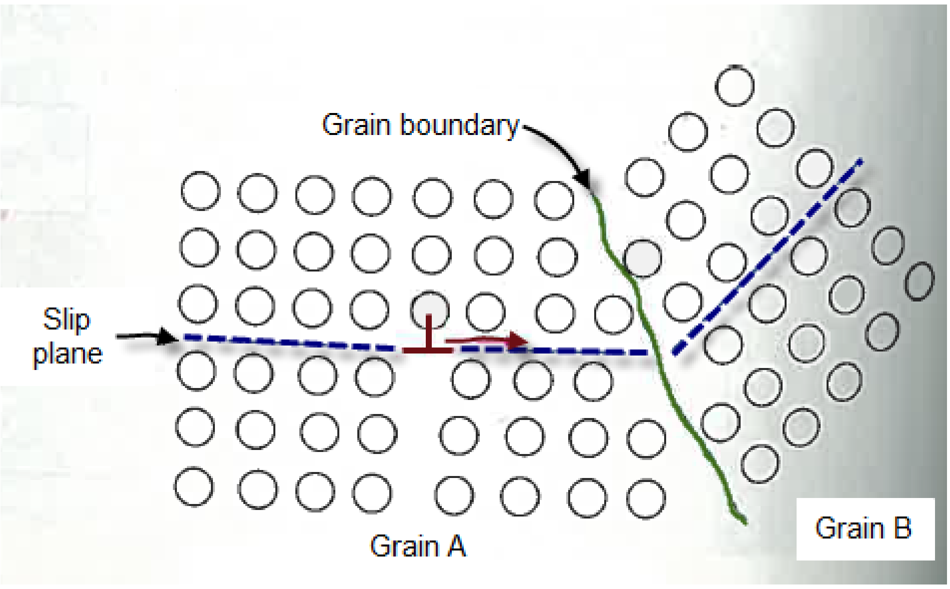


Fig 3.4 Grind boarder as pinning point (Callister, 2007)

Even if all grinds in a metal have the same crystal structure (this is not always the case) the grinds have different orientations. This makes the path of the slip planes discontinuous as illustrated in figure 3.4. More energy is needed for further movement as the dislocation reaches a grind boarder. Hence grind boarders serve as pinning points (barriers) against dislocation movement, the force that must be applied to further move and create new dislocations increase. The result is increased yield strength, hardness and tensile strength, and a decrease in ductility. This is called strain or work hardening.

The crystallographic misalignment between grinds creates a varying amount of extended distance between atoms along the border compared to the “ideal” distance inside the grain; if the distance exceeds a certain limit the atomic bounds cannot be completed. When an atom is not bounded to the maximum number of neighboring atoms, it is in a higher energy state. Because of all the missing bounds along the grind borders, the term grind border energy is used. Metallic structures with large grinds have lower total grind boarder energy than a structure consisting of small grinds because the total grind boundary area is larger in a fine grinded metal. An atom “wants” to complete its bonds to get in a lower energy state. When energy is applied, during, for example, welding, the atoms start to vibrate (more than they do in room temperature). If the energy gets high enough they might move, or diffuse. The result is that stresses and dislocations are gradually resolved, new grinds forms and over time some grinds grow on the expense of others.

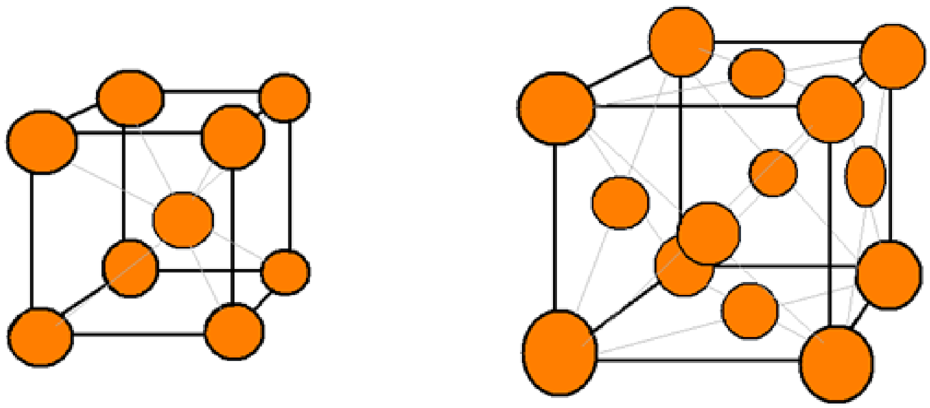


Fig 3.5 Left; Body Centered Cubic (BCC) and right; Face Centered Cubic, FCC

The diffusement velocity depends on:
-Temperature (higher temperature gives higher velocity (the probability that an atom will move increases with temperature))
- Quantity and type of defects (examples: vacancies, available space in the structure, ease the process and grind boarders function as start points for new grinds)
-Chrystal structure, se fig 3.5 (as an example: atoms diffuse at a rate of hundred times faster in the open body centered cubic structure (BCC) than in the face centered cubic structure (FCC) (Gunn, 1997))
-Diffusion mechanism (substantial; through the structure and interstitial; i.e. between the “main atoms”, we have a combination of these mechanism’s, the dominating type depends on crystal structure and composition)

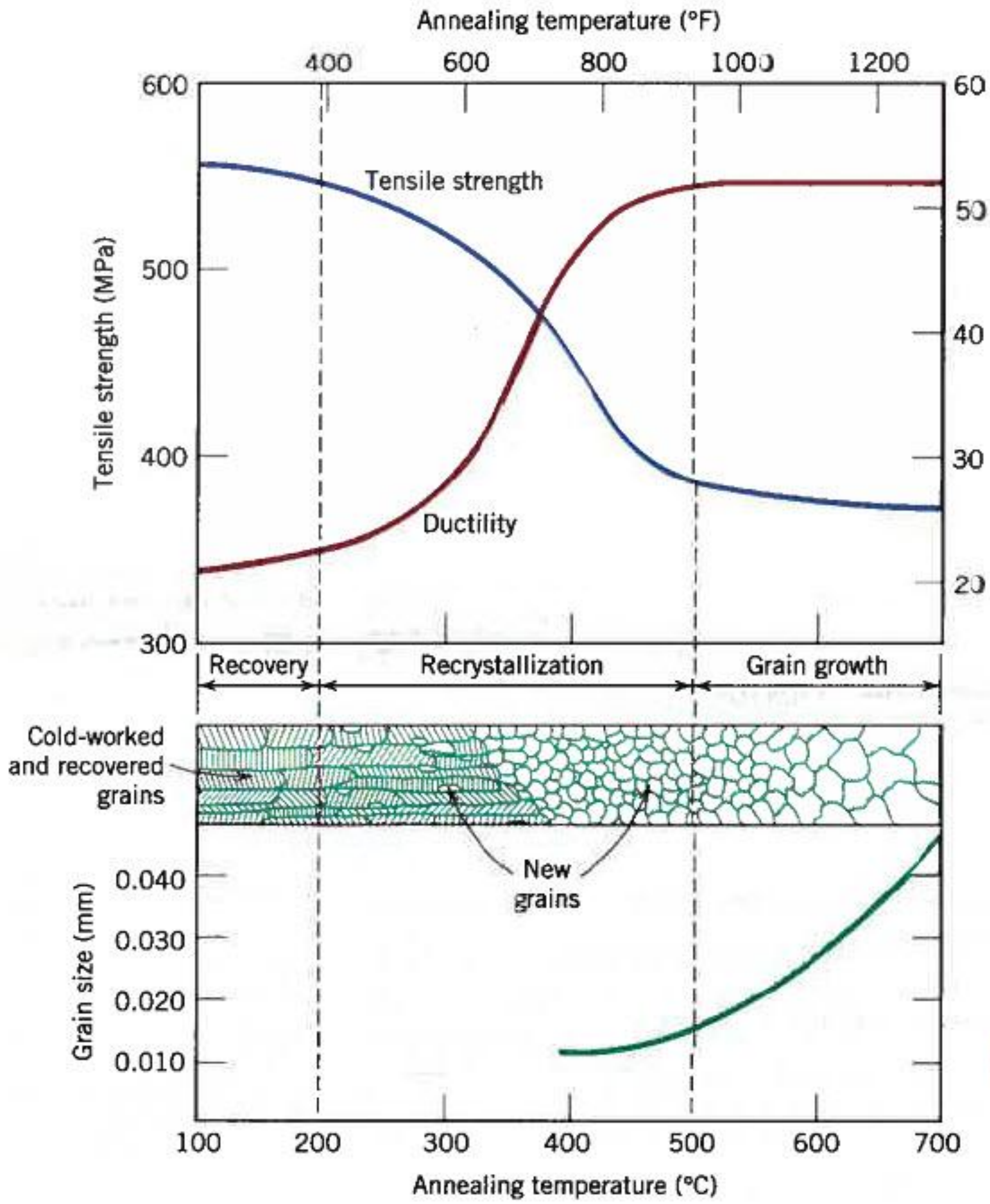


Fig 3.6 Connection between tensile strength, ductility and grind size (Callister, 2007)

The principle of annealing is illustrated in fig 3.6 for a brass alloy; the annealing time is in this example is one hour. The figure shows that the tensile strength sinks and the ductility increases as the dislocations resolve and new grinds form. The intention is to achieve the balance between tensile strength and ductility that is considered optimal for the purpose of the material; one cannot, as the figure shows, have both tensile strength and ductility on a maximum level simultaneously. As the grinds grow it gets easier for the dislocations to move and the tensile strength sinks and ductility increases. This happens slower in the grain growth process than in the recrystallization process and the ductility can only increase to a maximum limit. Had the temperature been lower more time had been needed to achieve the same and contrary.

3.2 Organic Chemistry

Organic chemistry is for someone that is not familiarized with the subject quite overwhelming with all the different subfamilies and the possible variations in composition and structure. A short discussion of some general theory is included to have some background for the material discussion later.

A polymer material is built up of chains that consist of repeated units/molecule(s) (called monomers) (derived from the Greek roots: poly (many), mer (part), mono (one)) (Reusch, 1999). The polymers are subdivided in different subfamilies depending on which elements the molecules include. Other than chemical composition of the monomers there are some other main factors determining the mechanical properties:

-dominating lengths of the chains, how the chains are branched and to what extent

-how the chains are arranged to one another

- extent of bounding between the chains

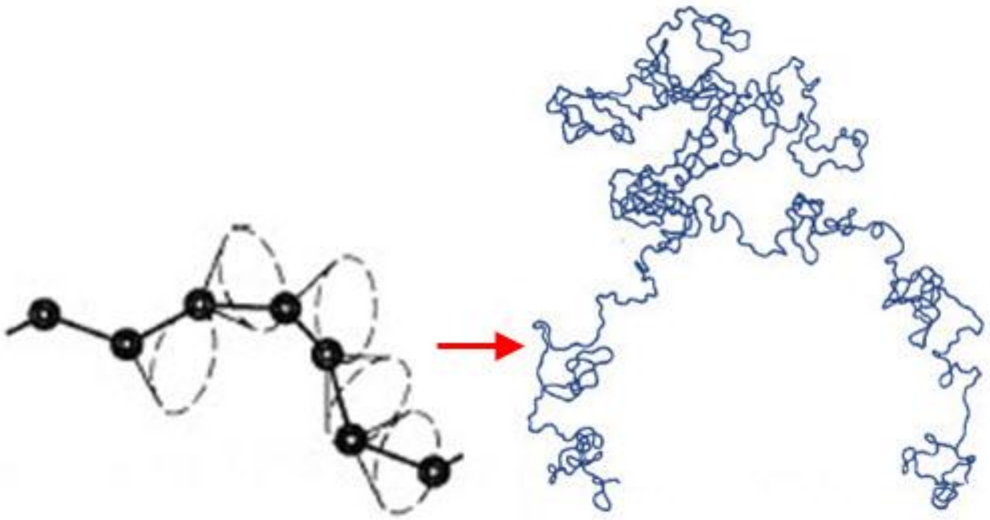


Fig 3.7 Possible chain molecule orientation (Callister, 2007)

Organic chemistry is defined as the chemistry of carbon as carbon is the backbone in most monomer units. Carbon allows 109 degree revolution of the bound (represented by the cones in fig 3.7). Fig 3.7 illustrates how the allowed twist angle between each monomer (represented by a black circle) result in a long irregular chain molecule. The molecule weight of polymers is given as an average since the molecule size wary with thousands of monomer units within the same material. This average value is based on number of molecules in each defined size interval and is mostly given as g/mol.

Longer chains generally mean increased melting point, viscosity and impact strength, but this also depends on other factors as the extent of bounding between the chains and degree of crystallinity.

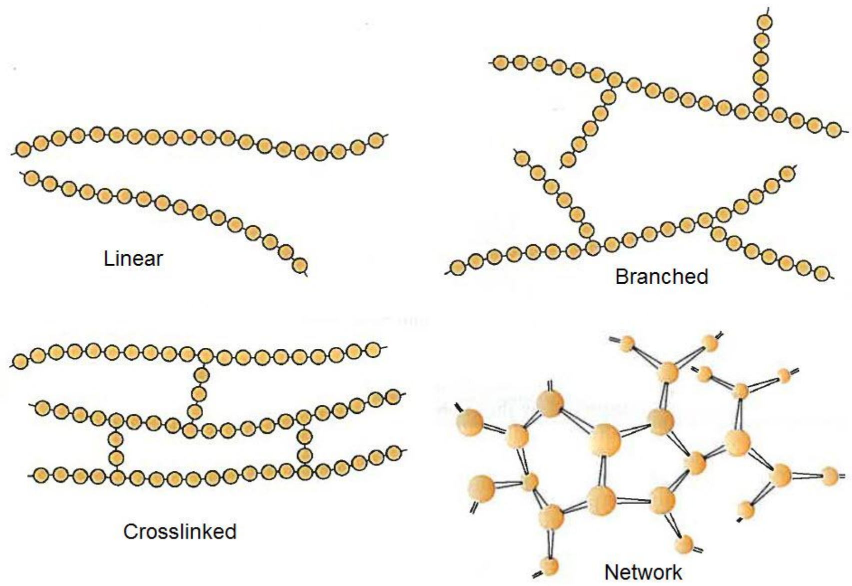


Fig 3.8 Polymer chains configurations (Callister, 2007)

Fig 3.8 shows some possible chain configurations (one must imagine the molecules to consist of more repeated units than shown (as yellow circles)). For the linear structure one can imagine the molecule in fig 3.7 tangled together with millions like it in an irregular way (amorphous structure). There is a varying extent of weak van der Waals bonds between the molecules. Crosslinks make the material tougher than a linear structure because the bounds between the chains are stronger. When the crosslinking become excessive the result is a network structure that has excessive bounding in three dimensions, the result is an even more rigid material. Branching decreases the packing efficiency, which lowers the density of the material. Crystallization is also gets more difficult. This is sometimes used to get a softer version of the material.

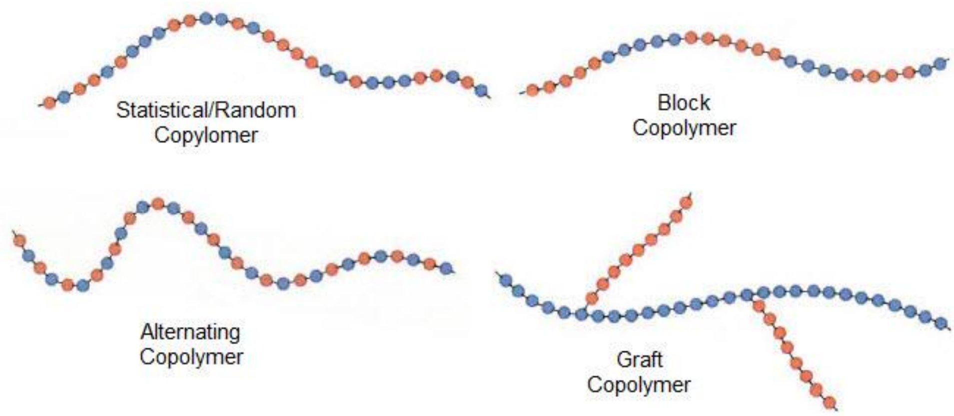


Fig 3.9 Copolymer composition (Callister, 2007)

As with metals one can mix different compounds to engineer the material to get specific properties that could not have been achieved with one component alone. The result is called copolymers. Some possible ways of composition is illustrated in fig 3.9 (red and blue circles represent different base units; it is possible to mix more than two base units).

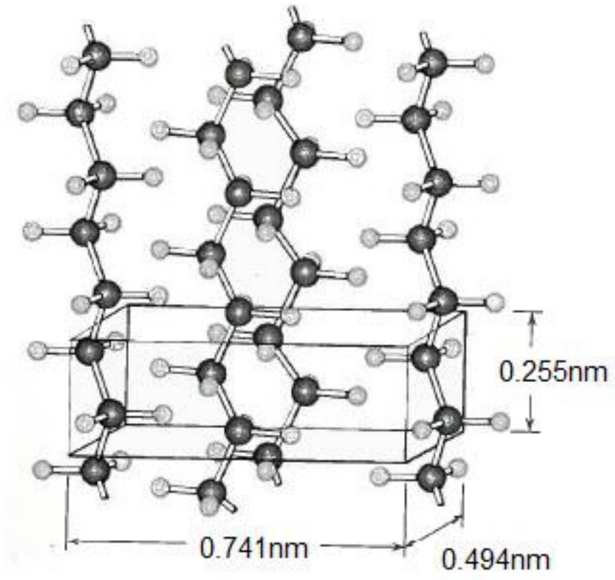


Fig 3.10 Unit cell (Callister, 2007)

When molecule chains orient each other in an organized manner in three dimensions it is possible to identify unit cells like the one showed in fig 3.10. The organized part of the structure is said to be crystalized. The crystalized structure is more rigid and this increases the tensile strength, hardness and resistance to heat.

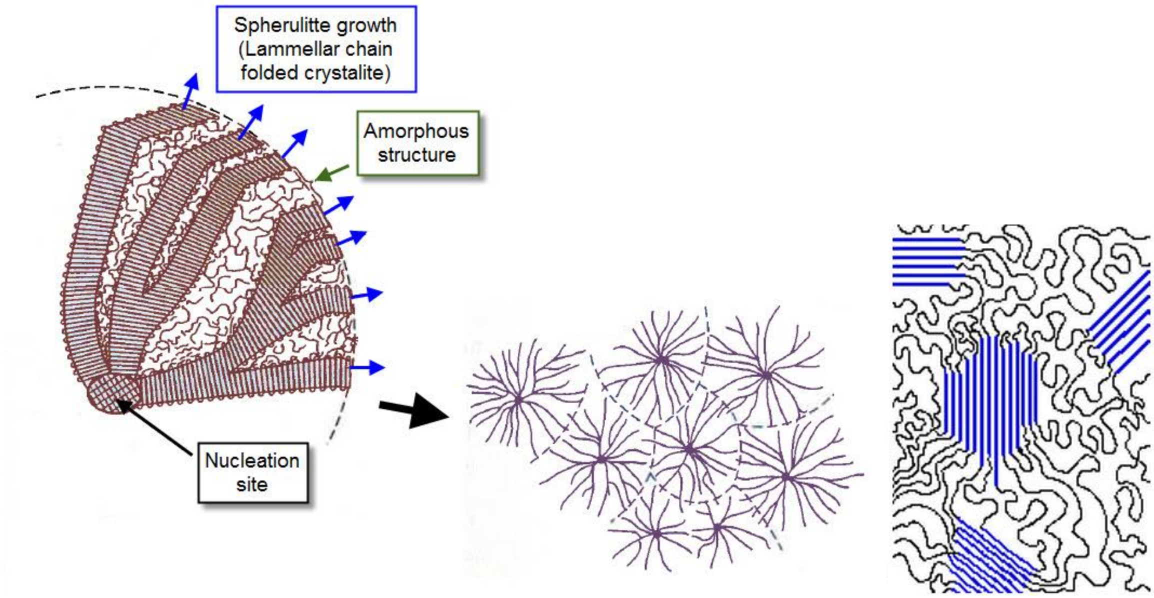


Fig 3.11 Example of partially crystallized structures (Callister, 2007 and Reusch, 1999)

Left in fig 3.11 shows how the crystal structure can “grow” spherulittes during hardening from a melt and form a partly crystalized structure. Another alternative shown right in the figure is fragments of crystal structure (blue) spread arbitrary around in an amorphous structure.

One rarely has only one type of molecules in the structure. Independent linear chains can coexist with branched and cross linked chains and fragments of crystalized structure.

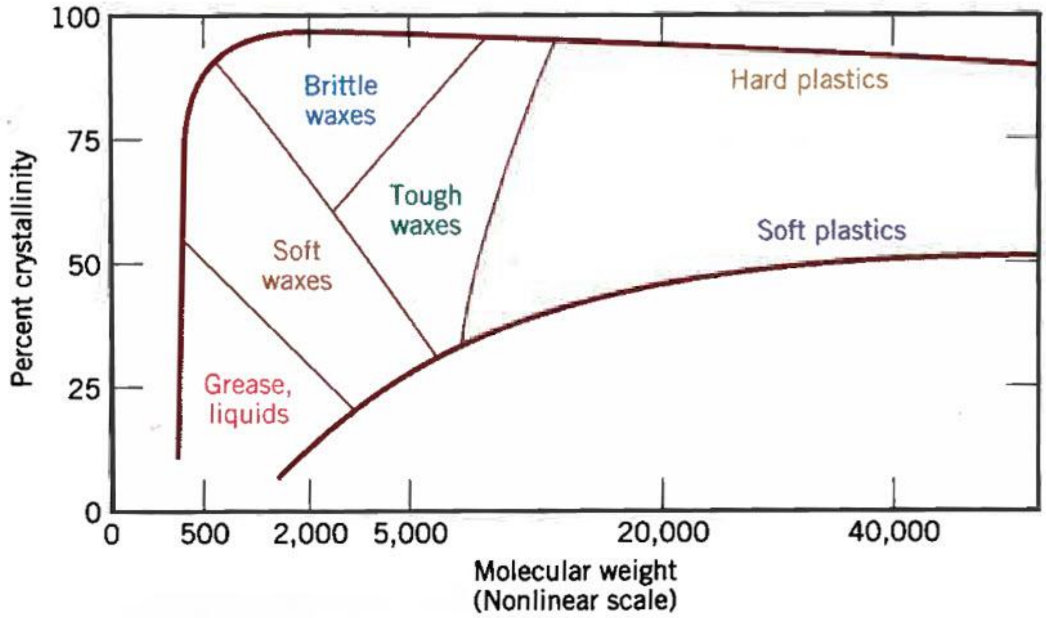


Fig 3.12 Degree of crystallinity and molecular weight (g/mol) influence on material texture (Callister, 2007)

From fig 3.12 one can see that increased molecular weight gives and more and more solid substances and increasing degree of crystallinity hardens the resulting material even more.

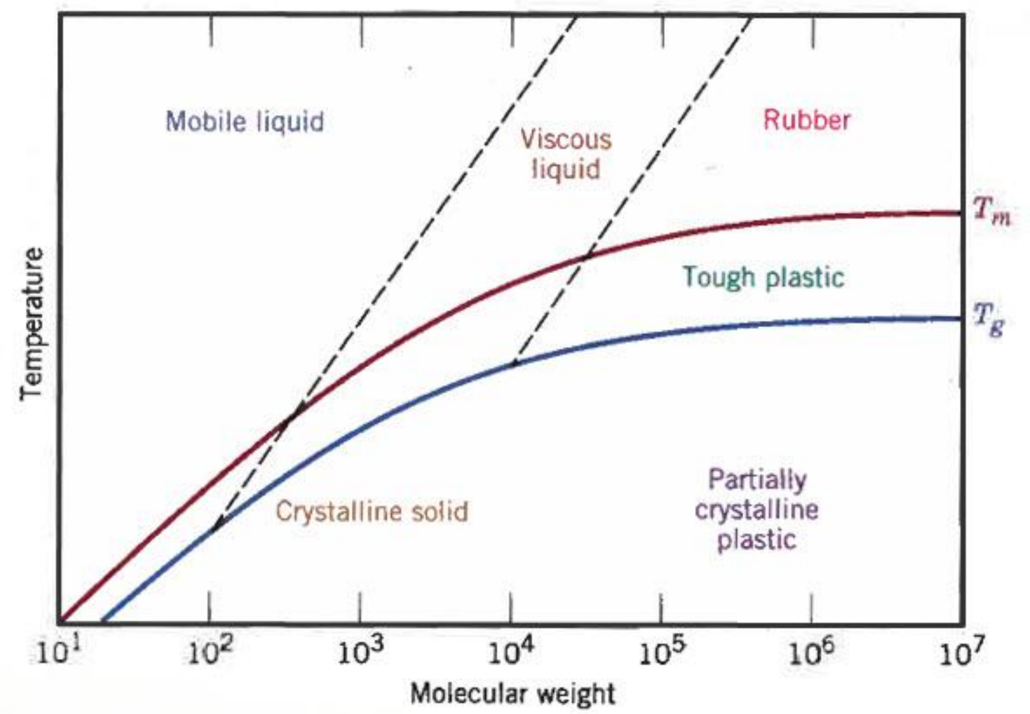


Fig 3.13 Molecular weight (g/mol) and temperature influence on properties (Callister, 2007)

Fig 3.13 illustrates how molecular weight and temperature correlate. T_m is the melting temperature where the form changes from a solid to a viscous liquid. T_g is the glass transition temperature where the polymer translate from a rubbery to more rigid state. Many polymers change properties drastically over a relatively short temperature interval, the temperature range at which the polymer material shall be used must always be checked against T_m and T_g.

3.3 Fatigue

Repeated loading under the ultimate stress limit might lead to failure; the process is called fatigue. In a paper by ASM International (2008) it is claimed that as much as 90% of all mechanical service failures are results of fatigue.

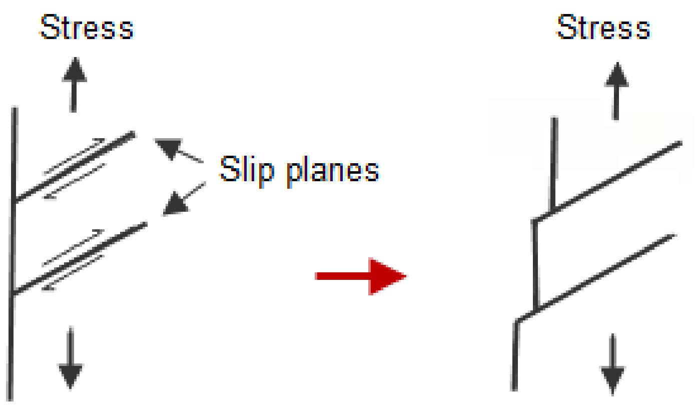


Fig 3.14 Development of surface defect by repeated slip (CMPT, 1998)

There are three stages; crack initiation, crack growth and lastly fracture. Surface and internal defects or other uniformities will create local stress concentrations. This shortens the time it takes for the first step to be a reality. Even if the structure is without defects of significance, fatigue cracks will be initiated if the load/cycle limit is reached. One way of getting crack initiation on a smooth surface is yielding on successive slip planes that lead to formation of notches and peaks at the surface as shown in figure 3.14. Fine grinds slows phase one because the grind boundaries have to be overcome for the continued atomic movements.

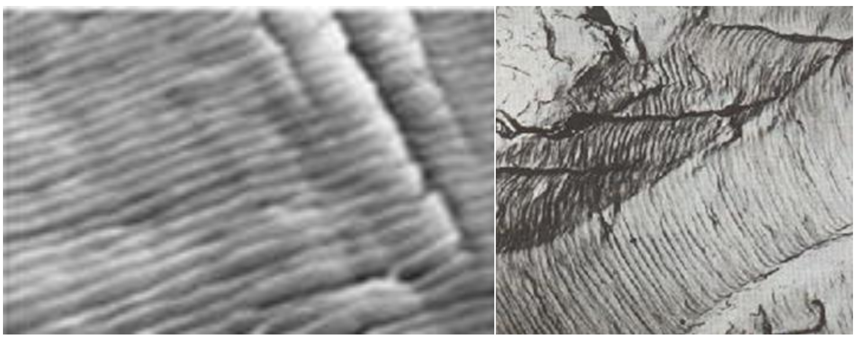


Fig 3.15 Left; striations and right; beachmarks (Madusanka, 2007 and Kelly, 2012)

Stage two can take time. Striations and beachmarks are characteristic, but not always formed in this phase. Beachmarks may be observed without microscope and are characteristic for materials that have been loaded cyclic and then had a pause. Each benchmark represents one work interval. The striations are much smaller and can only be observed with an electron microscope. The hypothesis is that each cycle creates one striation, that an increased stress level increases the striation width support this hypothesis. Fig 3.15 shows striations and benchmarks, they look quite similar, but the magnification needed to show the striations are much higher. There might be thousands of striations within one benchmark.

The stress level in the non-affected material increases as there is a decreasing amount of material to take the load and the stress concentration close to the affected area(s) increases. When the non-affected material no longer can withstand the applied stress there is a complete fracture. This happens fast and without warning. Fig 3.16 shows a rod that has gone through all three stages.

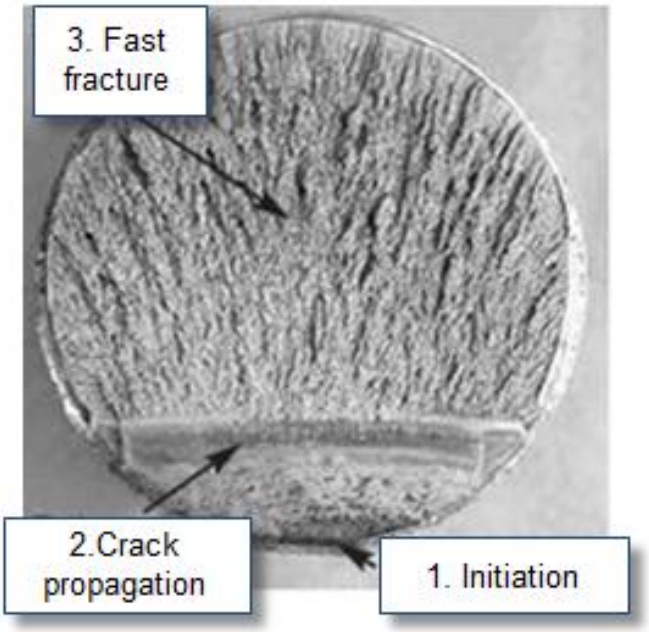


Fig 3.16 Fatigue fracture (Madusanka, 2007)

3.3.1 High Cycle Fatigue

When the strain induced per cycle is elastic a high number of cycles can be applied before failure occur, fatigue in the elastic area is therefore called high cycle fatigue. To estimate the numbers of cycles before failure in the elastic area S-N curves are often used.

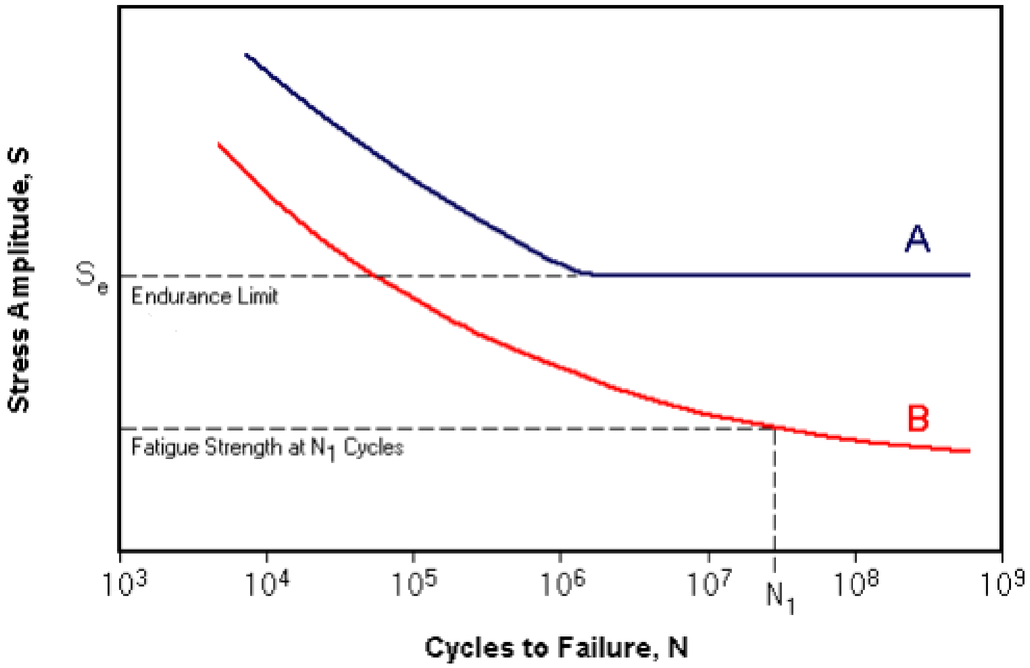


Fig 3.17 S-N (stress-number of cycles) curves (ux.uis, 2012)

There are two main types of curves, depending on if the material has an endurance limit or not. The two types are shown in fig. 3.17. Materials which have an endurance limit is represented by type A curve, examples are steel and titanium. As long as the applied load is below the endurance limit failure shall in theory not occur. Materials that do not have a defined endurance limit are represented with the B type of curve, this behavior is typical for non-ferrous metals and alloys such as aluminum and copper.

Before the endurance limit is reached the curves are drawn after this equation:

$$N = \frac{A}{s^m}$$

A and m are experimentally determined constants (CMPT, 1998). The value of the constants depends on the material considered, for steel m is in the range 3 to 5 depending on steel type and structure.

Surface or internal defects, uniformities in the material caused by for example welding or impurities will cause localized stress concentrations that reduce the fatigue life estimated by an S-N curve significantly. In high cycle fatigue weld geometry and initial defects are more important parameters than tensile strength and material ductility (Almar-Næss, 1985).

The values of the different constants vary for the same material and test loads because it is impossible to control all parameters with the same accuracy every time. The curves must be seen as a representation of mean data from several tests. As much as one half of the test specimens might fail at a stress level 25% below the curve that have been drawn as a result of average values (Callister, 2007).

In real life the loading often vary throughout the material life. There are different approaches on how to estimate the fatigue life in these cases. One simplified way is to sum up the cumulative effect of estimated load and estimated number of cycles with the actual load and compare against material capacity. This approach proposed by DnV gives an indication of the severity of service, but does not provide a measure of the residual capacity (Sriskandarajah et al., 2003).

3.3.2 Low Cycle Fatiugue

When the load exceeds the elastic limit, there will be plastic strain (ε_p) in addition to the elastic strain (ε_e), the total strain is $\Delta\varepsilon=\Delta\varepsilon_e+\Delta\varepsilon_p$. In this case much fewer load cycles are tolerated before failure and it is therefore called low-cycle fatigue. In low cycle fatigue tensile strength and material ductility are mostly the more important parameters (Almar-Næss, 1985).

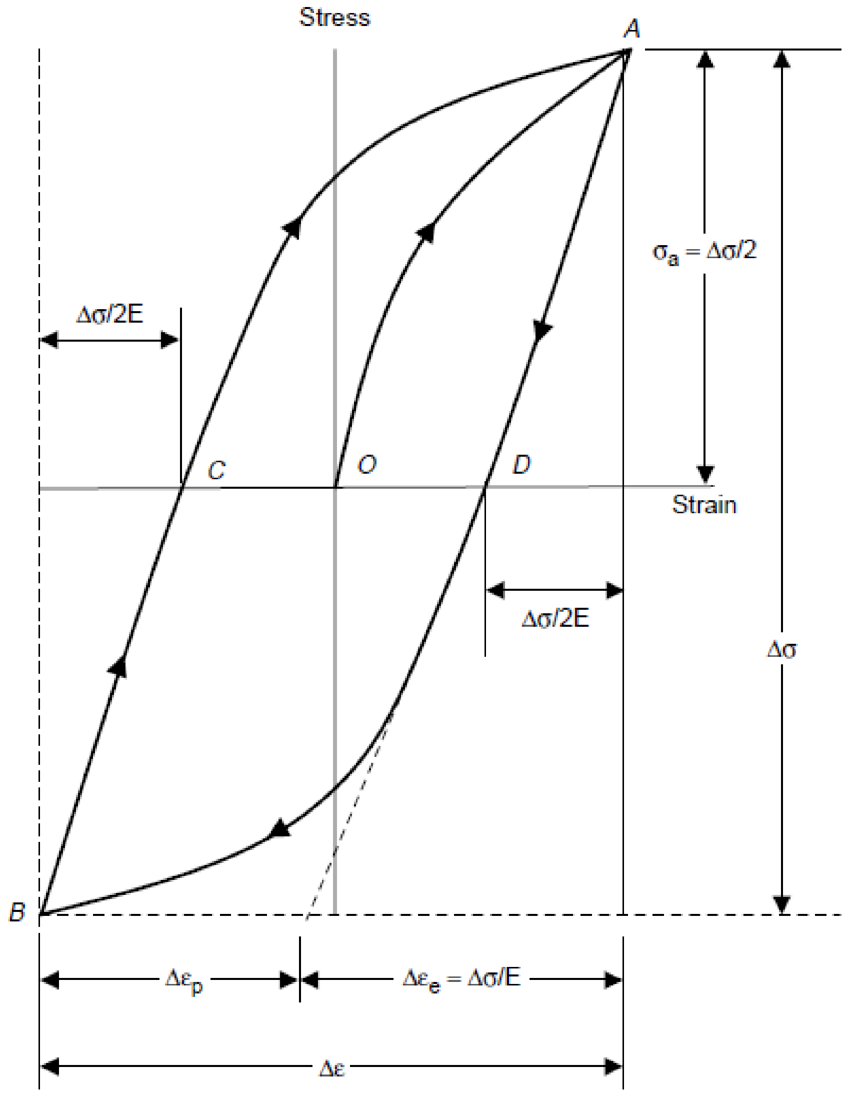


Fig 3.18 Hysteresis loop for cyclic loading (ASM International, 2008)

The strain-response relation in a load cycle in the case of plastic behavior can be graphically presented by a hysteresis loop as shown in figure 3.18. The area inside the hysteresis loop is equal to the work done/energy lost for one cycle. Point O is the unloaded start point. The component is stretched (tension force applied) whit a force that induce the stress σ_a at point A. During unloading the strain level follows the curve from A to D (if the complete load is removed). If the component is subjected to compressive stress after unloading, the strain response follows the curve from D to B. Releasing the complete compressive stress result in a stress level going from B to C. From C reapplied tensile stress cause the stress level to return to point A.

During plastic loading the material can work harden as described in chapter 3.1, low strength materials where σ_u / σ_y is above 1.4 tend to work harden. Metals that are initially hard on the other hand, typically σ_u / σ_y below 1.2, tend to soften. The softening is caused by rearrangement of an initially high dislocation density into more stable networks. This reduces the stress at which plastic deformation occurs. In both cases, the hysteresis loops shift with successive cycles by increasing (if hardened) or decreasing (if softened) the peak strain level σ_a. This does not go on through the entire material life, after a few hundred cycles the material attain a stable condition for the imposed strain.

The plastic strain range $\Delta\varepsilon_p$ can be plotted against cycles to failure after the Coffin-Manson relation (ASM International, 2008):

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f{}' * (2N)^c$$

ε_f' is the fatigue ductility coefficient, it is defined by the strain intercept at 2N=1. For many metals, ε_f' is approximately equal to the true fracture strain ε_f.

C is the fatigue ductility exponent; its value depends on the material. It usually varies between -0.5 and -0.7, a larger value of C indicate a longer fatigue life (-0.5 is favorable when put up against -0.7).

Cyclic straining tests must be made to provide data for calculating the Coffin-Manson coefficients (Sriskandarajah et al., 2003).

3.4 Cyclic Loading of Coil

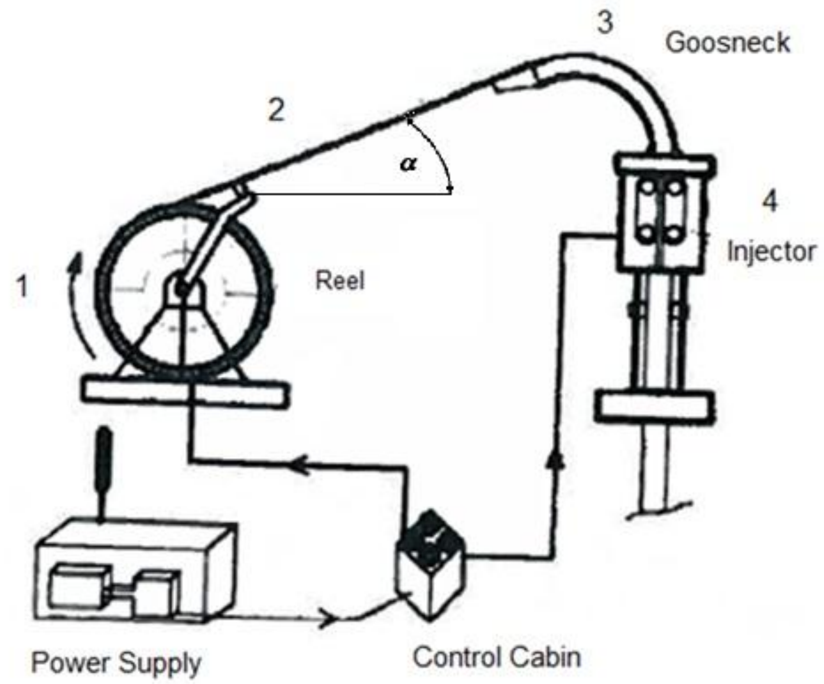


Fig 3.19 System overview (Inspired by API, 1996)

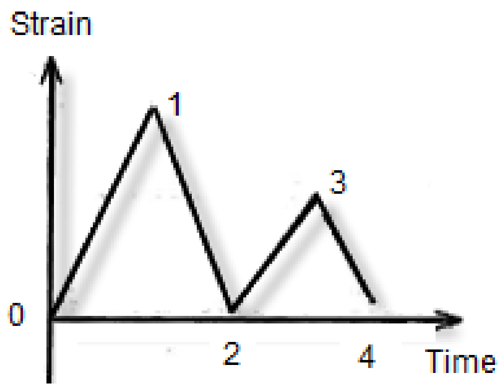


Fig 3.20 Coil strain (inspired by API, 1996)

Points 1-4 in figure 3.19 and 3.20 illustrate:
0-After stress revilement at the factory, before the coil is spooled on the reel there is no stress in the coil.
1- The coil is spooled on the reel; here we normally get the largest strain.
2-Almost all the strains are relieved between reel and gooseneck.
3- During bending over the gooseneck the strain level rise again, the strain magnitude depends on the gooseneck radius.
4-The coil is straightened inside the injector and pushed down in the well, there is significant, but not complete, strain relive.
The coil might be deformed again down in the well, but what happens as the coil reaches the well is outside the scope of this discussion.

4 Factors Influencing Fatigue Damage

If there is fatigue and how long it takes before fatigue damage occurs depends on several factors that are more or less interconnected, the most important are:

-The running speed of the coil

-Coil properties

-Internal pressure

-Gooseneck radius

-Physical environment

-Vessel motions

4.1 Running Speed

This subchapter is inspired from a paper by Yang et al. (1998).

Heave motion is assumed to be sinusoidal with origin at the top off the reel (where the coil spools off, se fig 3.19). Vertical motion due to heave is then described by (A is wave amplitude, f wave frequency and t is time):

$$y = A * sin(2 * \pi * f * t)$$

The velocity in the vertical direction is then (the derivative of y):

$$v = A * 2 * \pi * f * \cos(2 * \pi * f * t)$$

We have the largest velocity when $co\,s(2 * \pi * f * t) = 1$, then $v_{max} = A * 2 * \pi * f$.

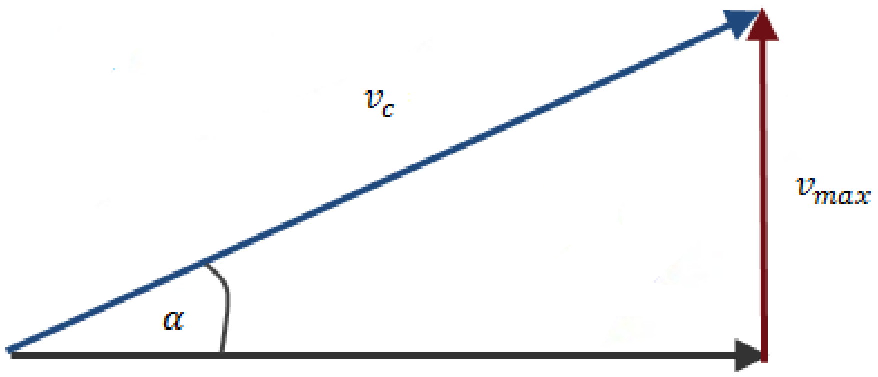


Fig 4.1 Critical running speed

The critical velocity when the inclination angle of the coil is α (the variation of α with the heave motion is assumed to be negligible) see figs 3.19 and 4.1:

$$\sin(\alpha) = \frac{v_{max}}{v_c} \rightarrow v_c = \frac{A * 2 * \pi * f}{\sin(\alpha)}$$

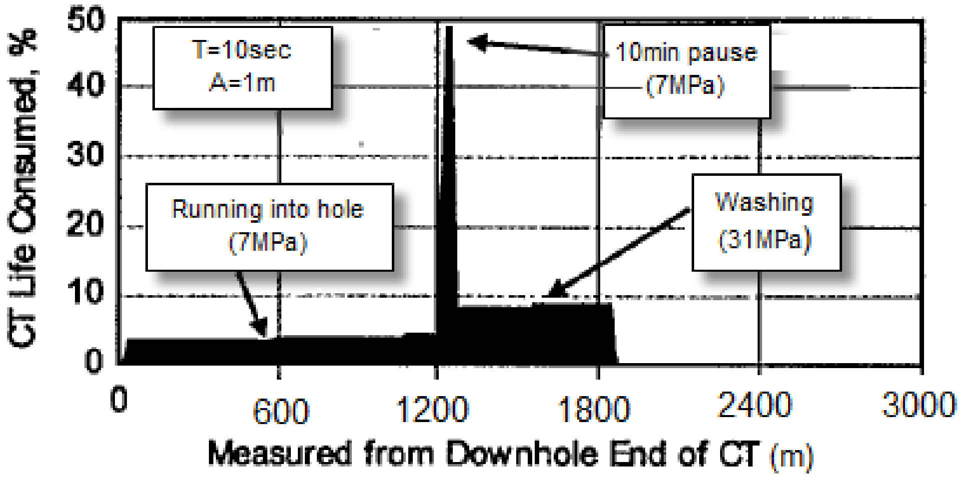


Fig 4.2 Effect a pause has on CT life (Yang et al., 1998)

If the running speed is equal to or greater than the critical speed there is no fatigue damage. The coil is then run faster than the heave motion so that the reel will never have to spool the same coil segment coil on and off the reel repeatedly. The worst case is if the operation for some reason stops, for example if the tool gets stuck. Then severe damage or even failure can occur in a few minutes. Figure 4.2 illustrates how fast the CT life is consumed during a pause. Therefore it is important to know what the critical running speed is at all times and take action if the critical running speed cannot be kept over a period of time.

4.2 Coil Properties

The most obvious properties are coil diameter and wall thickness. Larger diameter decreases the fatigue life (see fig 4.4) and increasing the wall thickness increases fatigue life (see fig 4.5) (Newman and Newburn, 1991). The outer diameter is determined by the operation that shall be done. 1-1/4" and 1-1/"2 are called "workhorses" in a presentation from King (2009), 1-3/4" and 2-1/4" goes in the category "larger work strings" and coils with a diameter greater than 3-1/3" are called "flowlines". Generally coil diameters have increased over the years as more complicated operations are carried out. This has been possible due to development in the field of optimizing the coils (ICTA, 2012). It costs to increase the wall thickness so this is not done unless it is considered necessary.

As discussed in chapter three one has that on microstructural level generally smaller grains give longer fatigue lives. Coiled tubing is made of low-alloy carbon steel sheets that are cut, bent and welded to pipes. Then the coil is heat treated to get extremely fine grinds to handle the large cyclic deformations as best as possible. Cyclic bending strains can be up in the range 2-3% (The University of Tulsa, 2012). The presence of surface defects has a greater influence on a small grinded alloy than in a coarse grained alloy, surface damages, even minor ones, are therefore very serious. Defects are hard to control and predict. Full scale fatigue testing of coiled tubing has concluded that crack initiation began on the inside of the coil (Newman and Dowell, 1991). Hence outer inspection of the coil after use is not sufficient.

A welded pipe will never have the shape of a perfect circle. After being coiled on to the reel, bent over the gooseneck and set under pressure the pipe will deform even more and a degree of ovality can be measured or assumed. In addition to the stress the concentrations the ovality alone induces the pipe deformation cause thinning of parts of the pipe wall. Both factors will influence the fatigue life in a negative way.

4.3 Internal Pressure

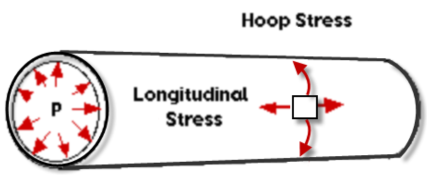


Fig 4.3 Hoop and longitudinal stress directions

Internal pressure in the coil is a force acting circumferentially inducing hoop stress (fig 4.3). This increases the total stress in the coil. In an experiment referred to by Yang et al. (1998) three different coil diameters with 0.102” wall thickness were bent with increasing inner pressure. Fig 4.4 illustrates the influence the pressure increase had on tubing life in this experiment. In a similar experiment referred to by Newman and Dowell (1991), which results are given in fig 4.5, shows that the pressure has a smaller influence than illustrated in fig 4.4, but the results in this experiment are more unclear because more factors were changed and the presentation of the results were not as clear.

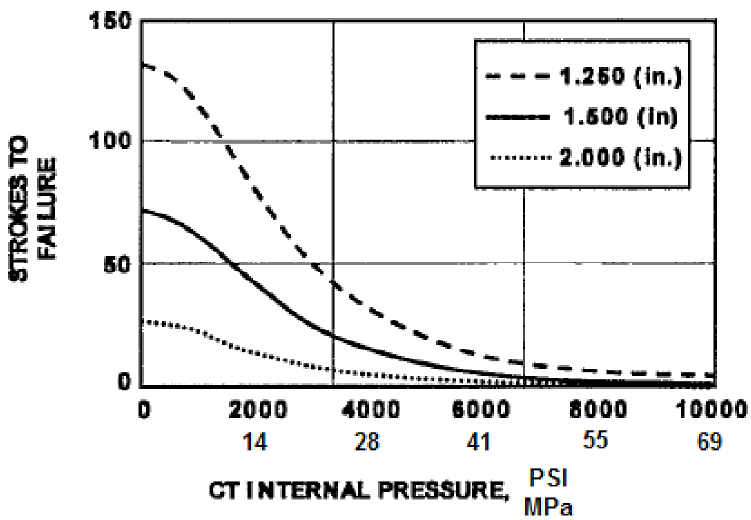


Fig 4.4 Strokes to failure vs. internal pressure for different diameters (Yang et al., 1998)

The conclusion is that as long as the pressure is kept low the hoop stress contribution is small compared to the longitudinal stress, but as the pressure exceeds about 1000 psi (about 7MPa/70bars) there is a steep decrease in coil life. If the running speed cannot be held above the critical velocity, lowering the pressure delay the time it takes before the tubing fails. This is done in the washing operation tracked in fig 4.2. Here the pressure is held on 7MPa (1000 psi) until the washing starts then increased to 31MPa (4500psi).

4.4 Gooseneck radius

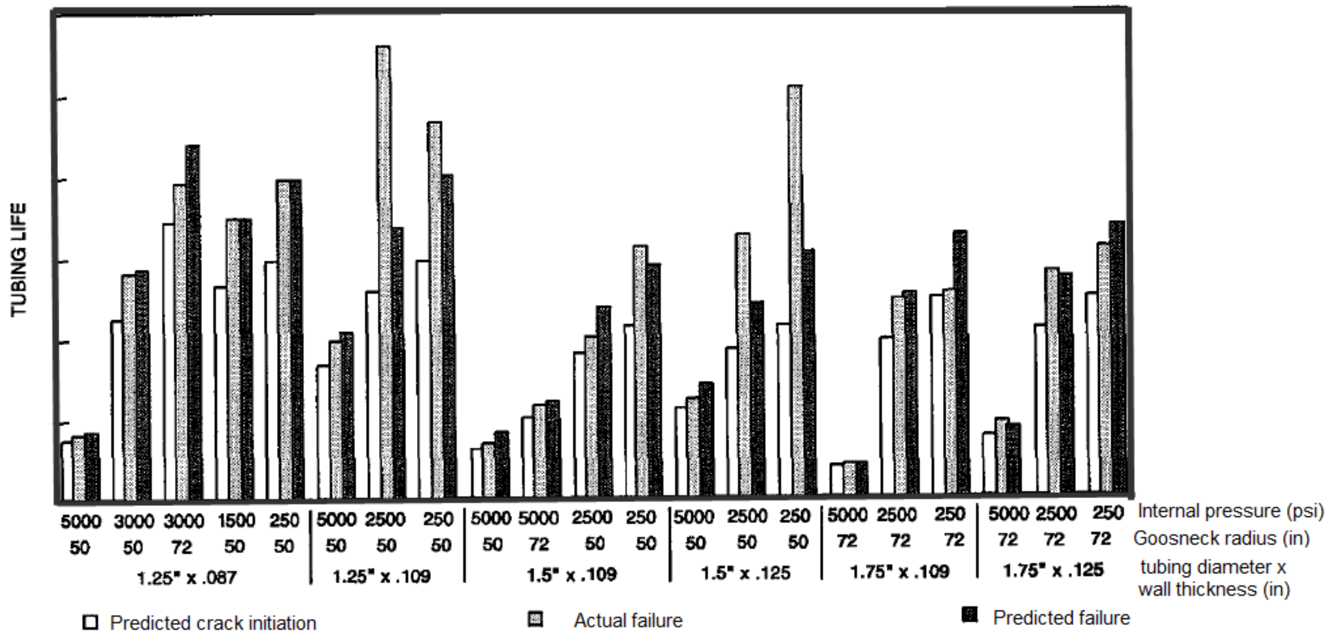


Fig 4.5 Pressure, gooseneck and pipe dimension vs. tubing life (Newman and Dowell, 1991)

The goosneck radius should be as large as practicaly possible to minimize bending strains. Figure 4.5 shows that an increase in goosneck radius from 50 to 72 in (1.27 to 1.83m) increases the life of the tubing. But the practical part limits the goosneck size. It must be possible to transport, rig up, operate and maintain the goosneck. Transporting the goosneck in parts extends rigging time and risk of missing parts/wrongfull assembly. A large goosneck also increases the hight of the equipment stack. If a closed tower structure as in fig 1.3 is used, the stack hight is limited by the V-door opening in the tower structure.

4.5 Physical Environment

The marine environment offshore is not optimal. Particles of sea mist containing salt crystals might settle on the coil, a corrosive environment like this accelerate the fatigue process.

4.6 Vessel Motions

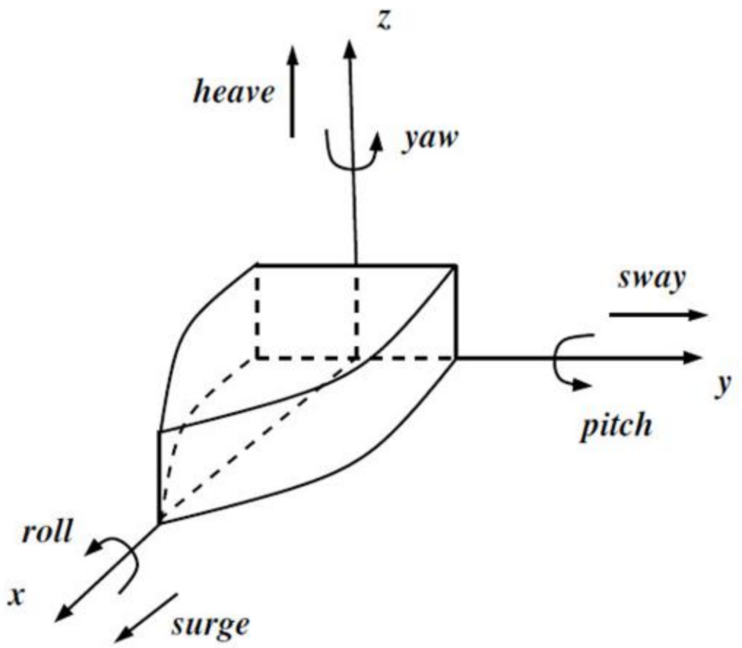


Fig 4.6 Six degrees of freedom (Ardakani and Bridges, 2009)

When the vessel moves with the waves the vessel has movements in 6 degrees of freedom, i.e. in all directions (see fig 4.6).

4.6.1 Wave Height

When a wave height is quoted is it the significant wave height (H_s) if nothing else is said. The significant wave height is the mean of the highest one third of the waves. Now 1.5-2 m heave during rigging and 2-3m during operations are normal limits used for CT from floaters. The lower value for is for upcoming weather and increasing heave and the higher value for weather coming down and decreasing heave. (Furberg et al., 2002)

The main focus in Hovland´s doctorate thesis (2007) is ships. One of his conclusions is that it would be very beneficial to increase the weather window from 3m to 5m H_s. The limiting factor he refers to is being able to launch and receive the ROVs. They are needed for most subsea operations, including CT operations on subsea wells.

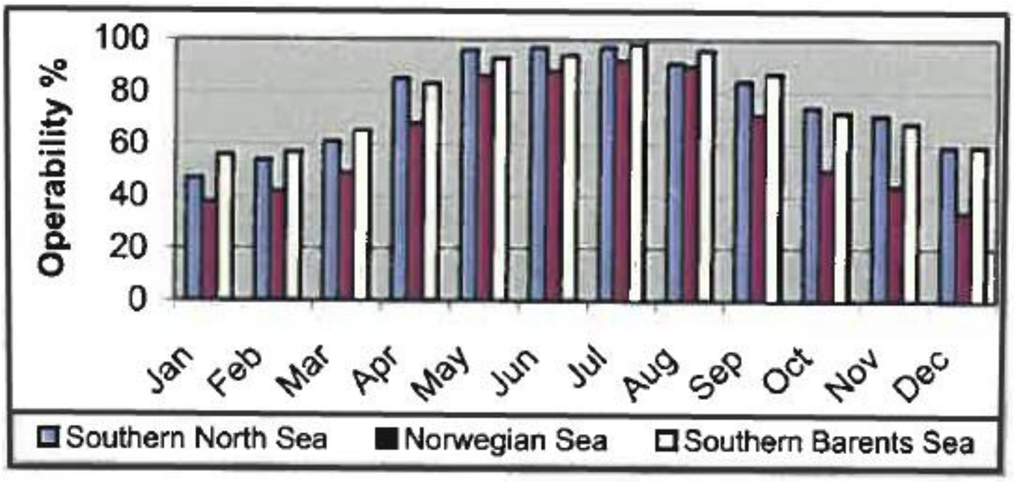


Fig 4.7 Available operability time (in % of 100 total) for a 24h operation with a limiting sea state of 3m H_S. (Hovland, 2007)

Fig 4.7 shows the operability (in % of time) in the Southern North Sea, Norwegian Sea and the Southern Barents Sea when the limiting sea state is 3m. Table 4.1 and figure 4.9 indicate that being able to perform operations when H_s is up to 5m will give a significant increase in operability time. This can be transferred to CT operations. Table 4.1 also shows that in more northern areas the conditions are more severe than in the south where most of the Norwegian oil developments traditionally have been located.

Table 4.1 Approx. fraction of time pr. year when H_s is less than 5m and 3m respectively (Hovland, 2007)

	5m Hs	3m Hs
Southern North Sea	0.98	0.83
Northern North Sea	0.91	0.64
Norwegian Sea	0.91	0.67
Grand Banks	0.93	0.65
Southers Barents Sea	0.95	0.75
Eastern Barents Sea	0.96	0.80

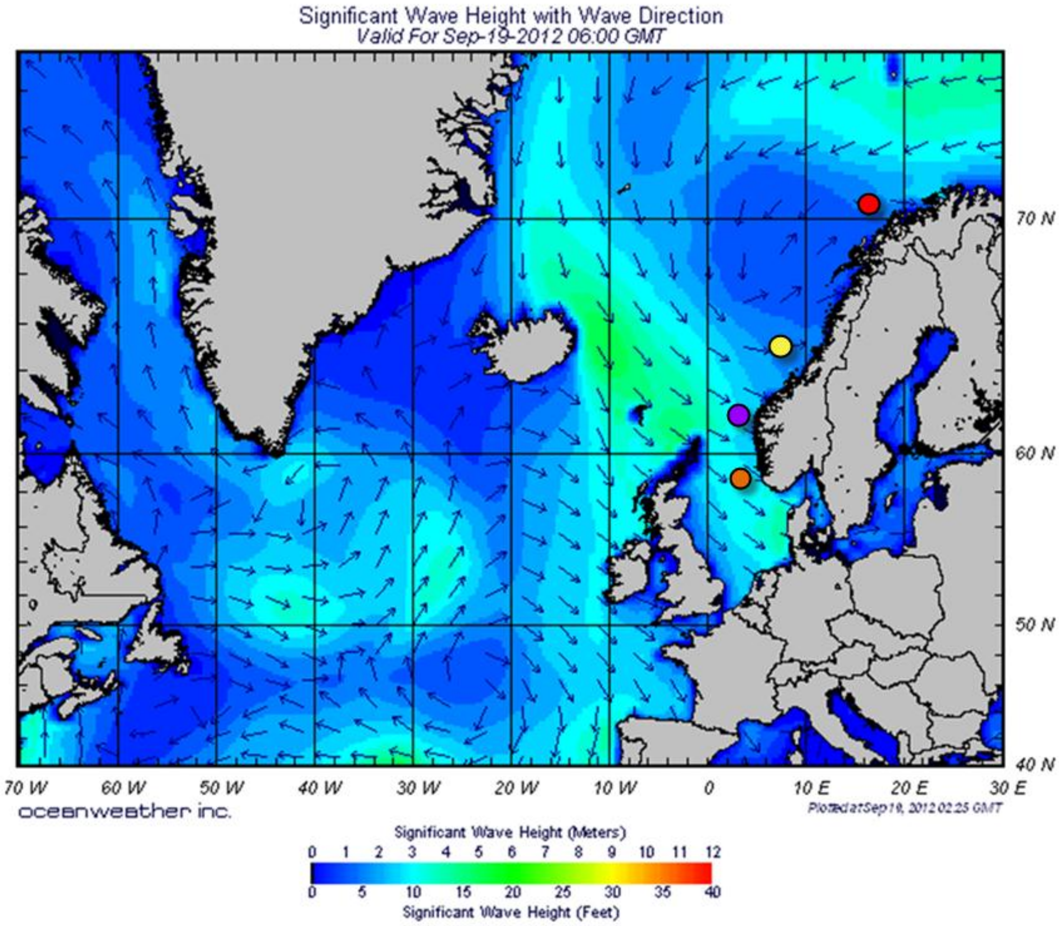


Fig 4.8 Wave situation an arbitrary day in September (Oceanweather, 2012)

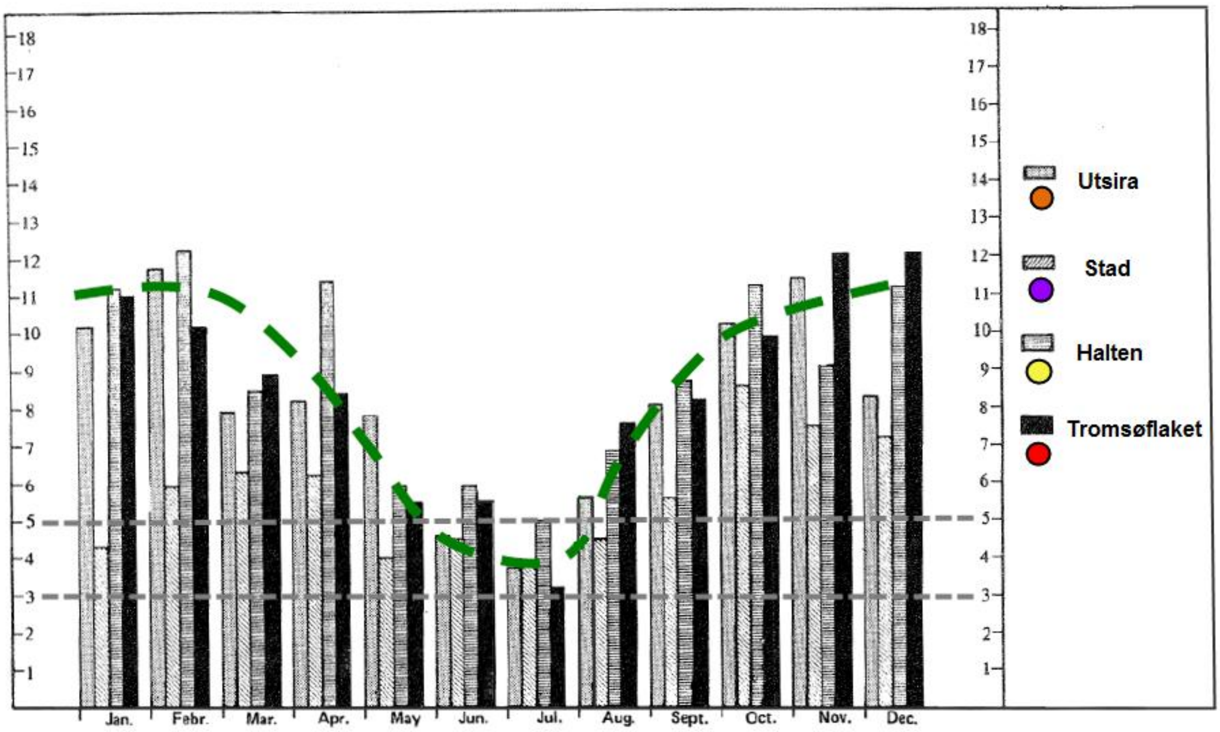


Fig 4.9 Significant wave height variation for areas marked on fig 3.8 (RRMOP)

Fig 4.8 shows how the wave conditions are on an arbitrary day in September. The color codes in fig 4.8 pinpoint where the significant wave heights in fig 4.9 are measured. Fig 4.9 also illustrates how the expected values of H_s vary with season for these areas.

Only the expected values for H_s for different areas at different times a year are known when operations are planned. Generally the expected wave heights increase in the autumn and winter months and decrease in the spring and summer months (as figs 4.7 and 4.9 illustrate). There are also statistics for expected variation of the expected H_s, but how H_s will vary is impossible to predict a long time in advance. Reliable weather forecasts are essential for timing when to start operations. DNV 2009 states that the uncertainty in the weather forecasts always shall be considered when planning weather restricted operations.

4.6.2 Wave Period

It is not just the wave height that is limiting offshore operations, the period of the waves are also important. By comparing the Eigen period (T_e) of a barge/boat and a semisubmersible with the typical wave periods it can be indicated in which wave conditions these two options are suitable. An overlap between Eigen period and dominant wave period will give resonance; the waves will then amplify the vessel movements.

The stiffness (k) in heave is the resistance against vertical motion of the vessel. The stiffness depends on the area in the water line (A_w). The Eigen frequency depends on the stiffness and the total mass. The total mass (M_t) consists of the vessel mass (M_v) and the added mas (M_a). The added mass depends on the way the water around the vessel behaves when the vessel moves. Intuitively one can imagine that a disk lying with the flat face in the horizontal plane moving up and down under the water surface will have larger added mas than the same disk standing in the water. Added mass is determined by model tests, field measurements or calculations using experience data taking the hull shape into consideration. ∇ is the volume of displaced water. (Faltinsen, 1990 and DNV, 2009)

Stiffness: $k = A_W * \rho * g \ \frac{N}{m}$

Eigen frequency: $\omega_e = \sqrt{\frac{A_W*\rho*g}{M_a+\rho*\nabla}} = \surd(\frac{k}{M_t})$

Eigen period: $T_e = 2\pi * \sqrt{\frac{M_a+\rho*\nabla}{A_W*\rho*g}} = \frac{2\pi}{\omega_e}$

A semisubmersible has three or more columns in the water line; this gives a small A_w, and immersed pontoons that increase the added mass. Whereas a ship or barge with a monohull that has its complete outer surface and monohull in the waterline and a smooth regular surface which gives relatively small added mass. The general case is:

$$A_W, semi < A_W, ship$$

$$M_t, semi > M_t, ship$$

If we insert typical numbers the result is that the semisubmersible has a much longer Eigen period than a ship/barge. The typical Eigen periods are between 4-16s for a monohull ship and more than 20s for semisubmersible (Faltinsen, 1990).

A fully developed sea is defined as a sea state where the waves are in equilibrium with the wind. To achieve this, wind has to blow steadily over a large area over a longer time period. The Pierson-Moskowitz (PM) spectra give a connection between the energy in the waves (Spm(ω)), wave frequency (ω) and wind speed (u) in a fully developed sea (Codecogs, 2012):

$$Spm(\omega) = \frac{\alpha * g^2}{\omega^5} * e^{\left(-\beta\left(\frac{g}{\omega * u}\right)^4\right)}$$

Where α and β are numerical constants determined experimentally, g is the gravitational constant and u is the wind speed 19.4 m above sea level.

The Beaufort scale divides the possible wind speeds in 13 categories. The scale starts with completely calm sea in category zero and goes in suitable intervals up to wind with hurricane force in category 12. The dominating wave height interval in each category is also listed. (Met Office, 2012)

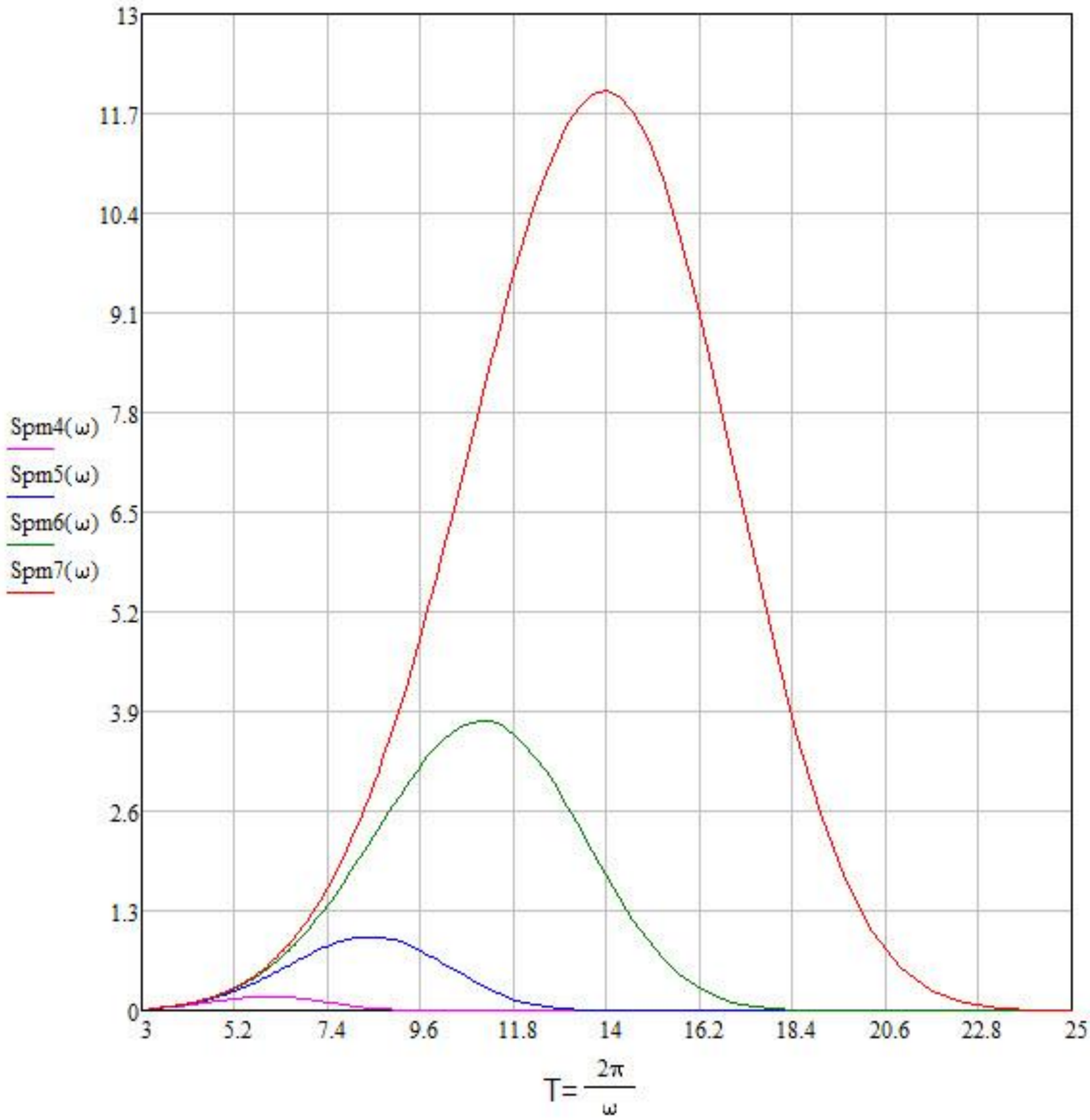


Fig 4.10 Relative wave energy (m^2s, y-axis) versus wave period (s, x-axis)

Fig 4.10 shows how the wave periods and wave energy vary with wind the wind speeds defined for the Beaufort scales 4 to 7 (Spm4(ω) to Spm7(ω), i.e. wind speeds from 6 to 17m/s and H_s ~2-10m). Mean value wind speeds taken from the different Beaufort classes are multiplied with a terrain factor (as described in NS 3491-4) to compensate for height (19.4m) and terrain (above sea) (calculations and justifications are given in the appendix chapter 11.1.1).

The typical wave period under acceptable working conditions for many vessels (Beaufort class 4, 1-2m waves, H_s of about 2m) is approximately 4-8s. If we operate also in class 5 (2-3m waves, H_s of about 2.5m) the dominating return period interval is 6-10s, which is close to an overlap with the typical Eigen periods of monohull vessels (4-16s) and well below the Eigen period of semisubmersibles (20s<).

Class 6 and 7 are included to show how much a relative energy increase an increase in wind speed/wave height gives. But as chapter 11.1.1 in the appendix indicate the relation between H_s, Beaufort scale and PM spectra gets less consistent as the wind speeds increases and the assumption that the sea is fully developed is only an approximation so the curves in figure 4.10 are only considered to be tendency indicators.

From this we can see why the semisubmersible is a better qualified vessel if the weather conditions are not optimal. Semisubmersibles are, however, large and expensive to rent, and it takes days to get them positioned and anchored. Most coiled tubing operations do not require more equipment than what can be placed on a barge or a boat. If a monohull vessel could be used instead of a semisubmersible these vessels can be rented to lower a day rate than a semisubmersible. But the day rates must be paid even if the crew is only waiting on the weather to be able to carry out the operation. So if an operation must be postponed long enough the monohull vessel might not be the cheapest alternative after all.

5 Arctic Environments

5.1 General About the Arctic Environment

The arctic is considered to be the area with the greatest potential of finding undiscovered hydrocarbons today (Ree, TU 26, 2012). On the downside there are many challenges to overcome before these resources can be extracted and transported, or even found.

The cold arctic climate gives problems with icing on the equipment. When the temperature drops below minus 20 degrades, material selection becomes a challenge because of the lack of testing, experience and standards to use when designing equipment for use in such low temperatures. The weather forecasts are less reliable and the periods with daylight during the winter/autumn months are limited and even none-existing in some areas.

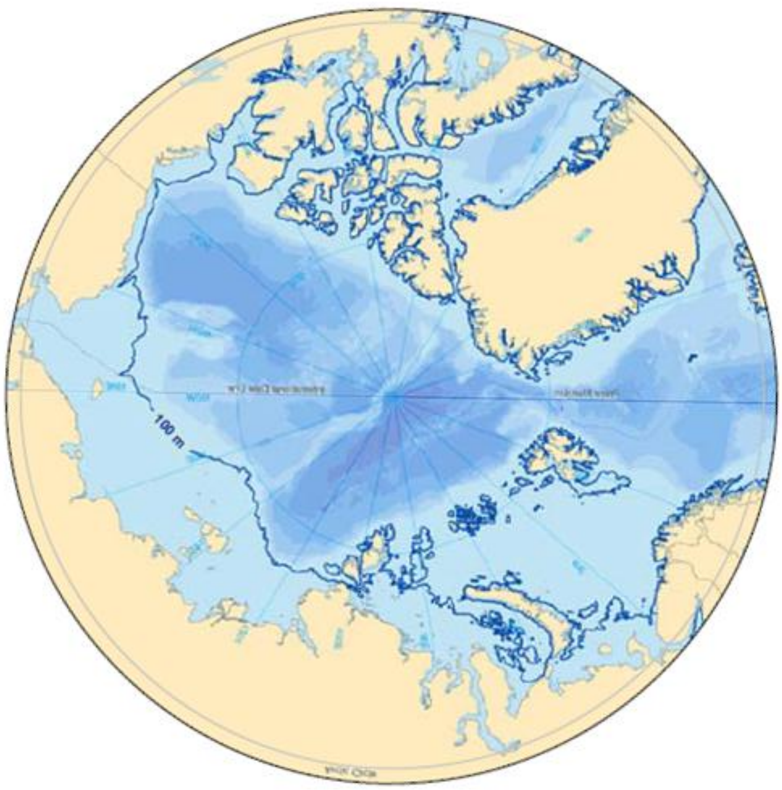


Fig 5.1 Deep water in the Arctic (Hamilton, 2011)

In arctic environments where ice loading must be considered, about 80-100m is considered the maximum water depth for permanent fixed installations. This is because the increased impact strength a bottom founded structure must have when exposed to moving ice is difficult to achieve when the depth increases beyond 80-100m. Above 80-100m is therefore considered deep water in arctic environments. The 100m contour line is shown in fig 5.1.

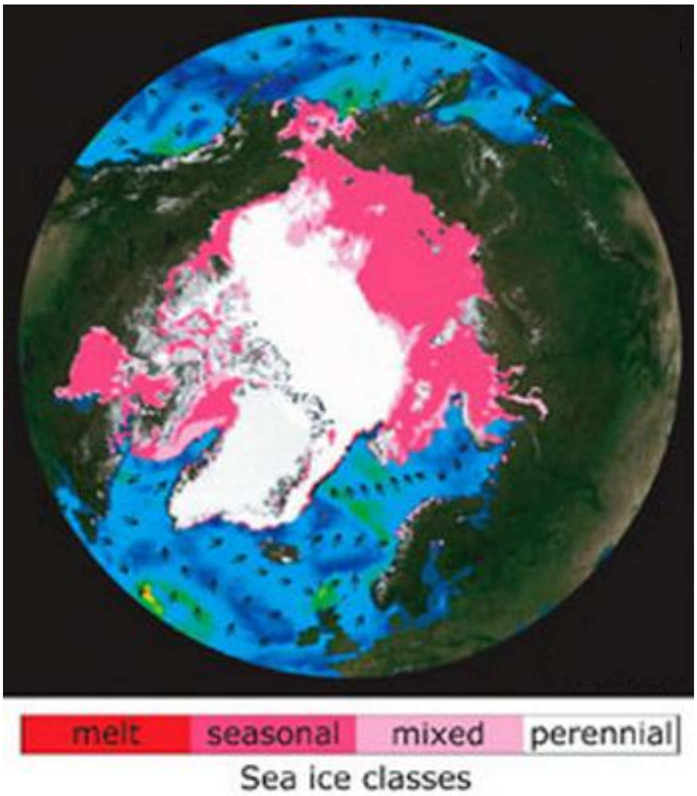
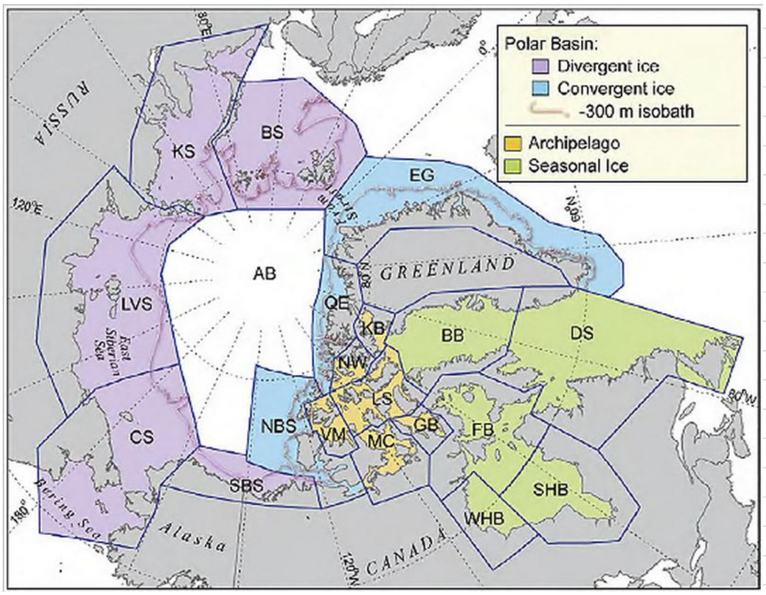


Fig 5.2 Seasonal variation of ice (National Geographic News)



AB	Arctic Basin
SBS	**Southern Beaufort Sea (U.S. and Canada)**
CS	Chukchi Sea (U.S. and Russia)
LVS	Laptev Sea (Russia)
KS	Kara Sea (Russia)
BS	**Barents Sea (Russia and Norway)**
EG	**East Greenland (Denmark)**
QE	Queen Elizabeth (Canada and Denmark)
NBS	**Northern Beaufort Sea (Canada)**
SHB	Southern Hudson Bay (Canada)
WHB	Western Hudson Bay (Canada)
FB	Foxe Basin (Canada)
DS	Davis Strait (Canada and Denmark)
BB	Baffin Bay (Canada and Denmark)
GB	Gulf of Boothia (Canada)
MC	M'Clintock Channel (Canada)
LS	Lancaster Sound (Canada)
VM	Viscount-Melville Sound (Canada)
NW	Norwegian Bay (Canada)
KB	Kane Basin (Canada and Denmark)

Fig 5.3 Seasonal variation of ice (Wikipedia)

Depending on the area icebergs can be a threat, and in some areas one might get stuck in masses of traveling ice that accumulates around the vessel. According to Hamilton (2011) most of the deep water Arctic oil potential lies in areas with ice conditions that make the working conditions difficult. Figs 5.2 and 5.3 give an overview of the ice situation in the Arctic.

West Greenland, East Canada and East Barents Sea have the most predictable ice conditions in the Arctic and an expected open sea interval of over 120 days (Hamilton, 2011). But it must be possible to disconnect from the well on a fairly short notice if an iceberg should be considered a treat.

The Beaufort Sea has an open water window of between 0 and 120 days, with an average of 60 (Hamilton, 2011). Even in the "open water season" it is common that arctic pack ice invades the open area. An ice management fleet that reduces the size of incoming ice flakes might be needed to make sure that the vessel can keep operating.

The remoteness is challenging because manpower replacement, supplies and spare equipment takes longer time to get to location, and the cost getting there is much higher. The remoteness and weather phenomena are also a challenge when the hydrocarbons shall be transported to the market. The distance itself induces high cost. In addition to this, moving ice ridge keels and icebergs can plough the sea floor leaving as much as 5m deep trenches. Hence pipelines must be buried at least 7m deep in areas where this is a threat (Lange et al., 2011). Transporting hydrocarbons by tankers requires special build ice-breaking vessels in areas/seasons where ice is a threat.

The most discussed and disputed challenge, at least in the public, is the threat petroleum activity will induce to the sensitive arctic environment. That the environment indeed is vulnerable is mostly agreed upon. The cold climate slows the decomposing process; hence the discharge of toxic substances will influence the environment over a longer time period than in warmer waters. The process of removing discharge and evacuation is also much more complicated due to the same challenges as discussed earlier when considering petroleum activities. Even the "harmless" activity of releasing sound waves in the ocean during seismic activity is disputed. A rapport from the Institute of Marine Research (Løkkeborg et al., 2010) concluded that the fish to some extent reacted to the sound of the air guns with stress and/or confusion, but not to an extent that justified a stop in seismic activity. Experienced fishermen, on the other hand, have claimed that the Oil Directorate has sabotaged the research and that coexistence between fishing and petroleum industry is impossibility (Høyem and Johansen, 2010).

In spite of the challenges of the Arctic Statoil announced at ONS 2012 that they will more than triple their arctic research investments from 80 to 250 million NOK and be drilling nine wells in the Barents Sea during the next year in addition to the 89 that Statoil already has been anticipating drilling. This in in line with the Norwegian governments' suggestion to use 130million NOK on continued chart map surveys in areas in the Barents Sea and around Jan Mayen in 2013. (Ree, TU 34, 2012)

5.2 CT Challenges and Possible Solutions

This thesis alone will not solve the challenges met in the Arctic. But the coil in coil solution might solve some of the problems that will be present when the time comes to do well intervention on a subsea well in the Arctic.

When using the CiC procedure the coil is not directly exposed to the environment from it leaves the reel. It should be possible to adapt this way of performing CT operations to an arctic climate without too many adjustments. If the guide pipe is isolated and the reel and tower structure is built in to an as great extent as possible, this should be enough to improve the coil conditions considerably, especially if heated fluid or gas is pumped inside the coil.

6 Material Selection for Coil in Coil

How materials wear when put against each other depends on several factors, some are interconnected. The main factors are: friction, contact pressure, sliding distance, surface hardness, ductility, surface finish and lubrication type (if any). We look for a combination of coil material, guide pipe material and lubrication (if necessary) that makes it possible to perform the operation safely without intolerable surface damage to the coil or guide pipe. Some damage to the guide pipe can be tolerated as long as this does not increase the operational risk or the need for exchanging the guide pipe regularly makes the concept uneconomical.

Which coil to use depends on the operation that shall be performed and the geometry and depth of the well. It is preferable to use “standard coil”. That is to use the coil that would be used if this was a traditional coil tubing operation. If it would be necessary to use a material or coil dimension that would not normally be used this would probably increase the cost and the risk of using wrong coil material.

Normal guide pipe length is estimated to be between 30 and 40m, but it is possible that shorter or longer lengths will be needed. The assumption is, furthermore, that one orders the guide pipe in a specific length, diameter, thickness and material composition suitable for the actual operation that is then provided on a reel in a similar manner as coil is provided today.

The alternative is to use guide pipe lengths that must be transported in baskets and rigged up offshore. This alternative is, even without a thorough analysis, considered to be the less favorable option because of the amount and type of work that in that case must be performed offshore. In addition the connection points are assumed to make the guide pipe less robust/dependable because of the extensive movements the guide pipe must be capable of handling.

The intention is therefore to find a material alternatives where option one, guide pipe coiled up, is possible.

6.1 Friction and Rougness

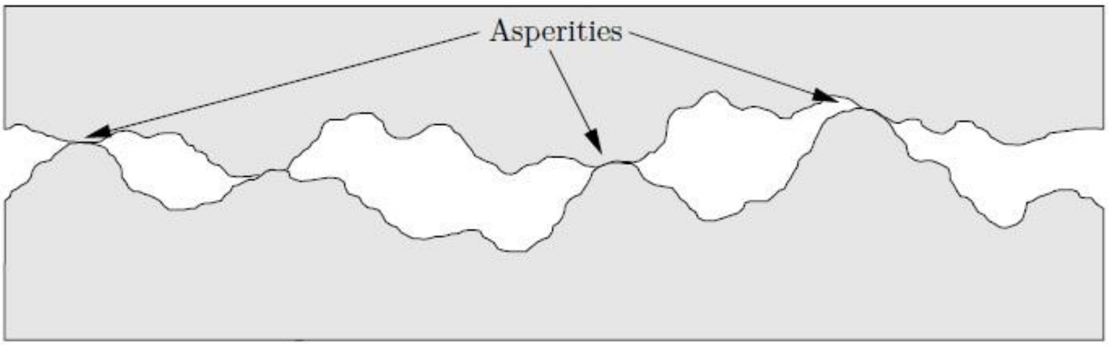


Fig 6.1 Surface roughness (Amundsen, 2011)

Fig 6.1 illustrates two surfaces in contact. Surfaces that feels and looks smooth to the human eye look rough when magnified enough times. When these surfaces move relative to another the unevenness (also called asperities) will interact. The degree of surface roughness and orientation of the asperities on the respective surfaces will influence how munch force is needed to get movement and how the surfaces wear. In a paper by Bayer and Sirico (1975) it is claimed (after experiments) that wear is more sensitive to degree of surface roughness for finer surfaces and more sensitive to the orientation of the surface roughness for coarser surfaces.

The frictional force is the sum of electromagnetic forces between charged particles in contact. We have to use an empirical method for analyzing these forces because calculations from first principle would be to complex. In our case we evaluate motion of two solid surfaces in contact. Then the friction force is found by:

$F=\mu*N$

The coefficient of friction μ (COF) is an empirical property of the masses in contact that is determined by experiments. N is the normal force between the surfaces. The force is converted to kinetic energy (heat) and will cause some extent of wear. An high COF will also increase the needed force to pull the coil through the guide pipe.

Extensive tables of friction combinations are given in “The Engineering Toolbox” (2012) and “Engineers Handbook” (2012). The material combinations that might be relevant from these tables are summed up in table 6.1. At least one of the parts is assumed to be steel as the hypothesis is to use a steel coil as done at present and consider other options for the guide pipe. Combining steel and another material for the guide pipe is also an option to be considered. There will be some variation of given friction values from source to source as the surface roughness, contact force, test method etc. will vary, the values are not to be considered absolute and will only be used as an indicator of which material combinations that could be preferable above others when considering friction as acceptance criteria.

Table 6.1 Frictional coefficients (The Engineering Toolbox and Engineers Handbook, 2012)

Material 1	Material 2	Coefficient Of Friction			
		DRY		LUBRICATED	
		Static	Sliding	Static	Sliding
Aluminum-bronze	Steel	0.45			
Aluminum	Mild Steel	0.61	0.47		
Bronze	Steel			0.16	
Cadmium	Mild Steel		0.46		
Copper	Mild Steel	0.53	0.36		0.18
Copper	Steel		0.8		
Copper	Steel (304 stainless)	0.23	0.21		
Graphite	Steel	0.1		0.1	
Hard Carbon	Steel	0.14		0.11 - 0.14	
Nickel	Mild Steel		0.64		0.178
Plexiglas	Steel	0.4 - 0.5		0.4 - 0.5	
Polystyrene	Steel	0.3-0.35		0.3-0.35	
Polythene	Steel	0.2		0.2	
Sintered Bronze	Steel	-		0.13	
Steel	Brass	0.35		0.19	
Steel(Mild)	Brass	0.51	0.44		
Steel	Copper Lead Alloy	0.22		0.16	0.145
Steel (Hard)	Graphite	0.21		0.09	
Steel (Mild)	Phos. Bros		0.34		0.173
Steel	Phos Bros	0.35			
Steel(Hard)	Polythene	0,2		0.2	
Steel(Hard)	Polystyrene	0.3-0.35		0.3-0.35	
Steel (Mild)	Steel (Mild)	0.74	0.57		0.09-0.19
Steel (Mild)	Steel (Mild)	-	0.62		
Steel(Hard)	Steel (Hard)	0.78	0.42	0.05 -0.11	0.029-0.12
Steel	Zinc (Plated on steel)	0.5	0.45	-	-
Teflon	Steel	0.04-0.2		0.04	0.04
Tungsten Carbide	Steel	0.4 - 0.6		0.08 - 0.2	

6.2 Hardness

Hardness is a property of the material that says something about the ability to resist permanent deformation as scratching, abrasion or cutting. The hardness is relevant when estimating at what proportion and ratio two materials that run against each other will wear. Equal force act normal to both surfaces illustrated in fig 6.1, but if one surface is harder than the other the asperities on this surface will to a greater extent scratch the softer surface than itself will be worn.

As the coil material is assumed to be the steel type normally used, it is interesting to know how other materials will wear when put up against steel. The hypothesis is that it is better that the guide pipe is worn than the coil because the purpose of the coil in coil concept is to reduce the coil fatigue problem and this will probably not happen if the coil is damaged by the guide pipe.

There are different ways to estimate and present the hardness of a material. Which method is chosen depends on the material, available equipment and common practice at the institution performing or requiring the test. A short description of the most common methods in use is included here to provide some background knowledge for comparing the hardness of different materials to be able to evaluate how they would behave if combined.

6.2.1 Brinell Hardness

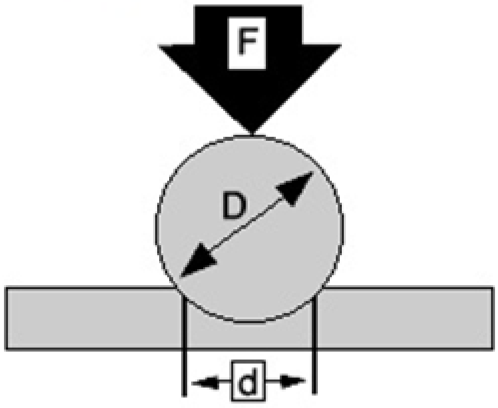


Fig 6.2 Brinell hardness (Instron, 2012)

A carbide ball indenter is used; fig 6.2 illustrates the test principle. The method has a wide range of use since the ball size (D) and test force (F) can be varied to get results that cover the entire hardness range. But for the results to be comparable, the same ball size and test force relation must be used so comparison of results cannot be accurately done. The method is often used when the grain structure is to coarse for Rockwell or Vickers. The Brinell hardness, HB, is given by:

$$HB = \frac{2F}{\pi D(D - \sqrt{D^2 - d^2})}$$

6.2.2 Vickers Hardness

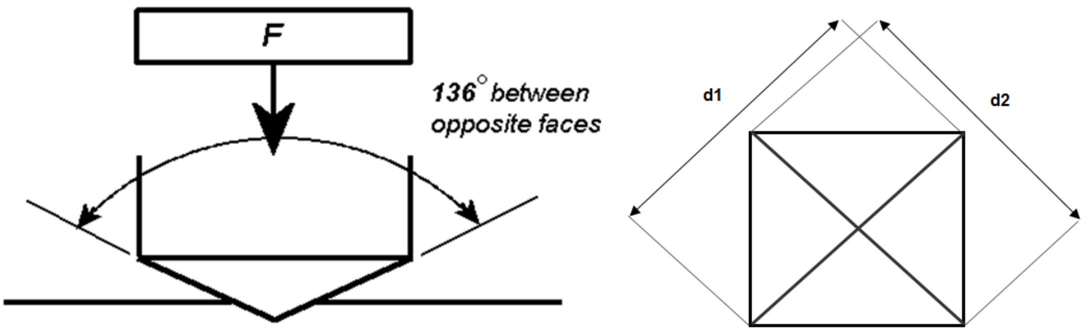


Fig 6.3 Vickers Hardness (England, 2012)

The Vickers hardness test is performed with a diamond indenter, as illustrated in fig 6.3. The hardness number varies little with changed load settings and it is easy to make accurate readings. The Vickers hardness, HV, is defined by:

$$HV = \frac{2Fsin(\frac{136°}{2})}{d^2}$$

Where F is the test load and d is the mean value of d1 and d2.

6.2.3 Rockwell Hardness

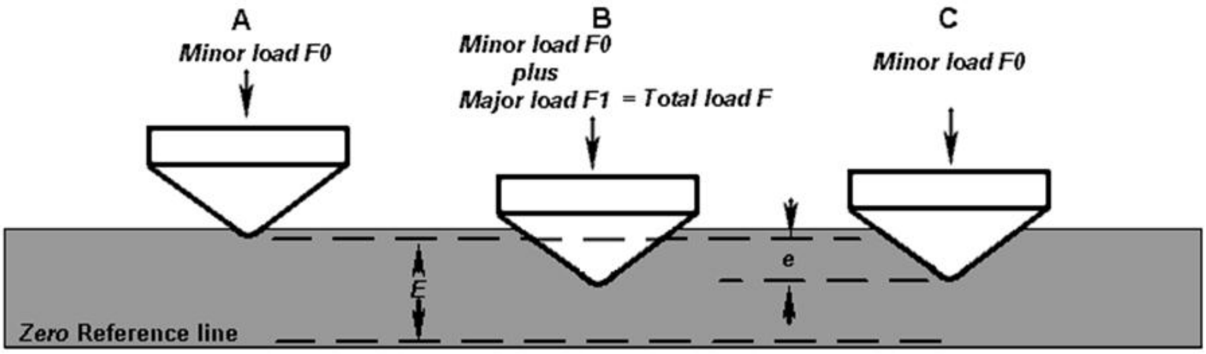


Fig 6.4 Rockwell Hardness (England, 2012)

The Rockwell hardness test principle is illustrated in fig 6.4. A diamond cone or hardened steel ball indenter is used, depending on the suitable scale, see table 6.2 and 6.3. The Rockwell hardness, HR, is given by:

$$HR = E - e$$

Table 6.2 Rockwell scales (England, 2012)

Scale	Indenter	Minor Load *F0* kgf	Major Load *F1* kgf	Total Load *F* kgf	Value of *E*
A	Diamond cone	10	50	60	100
B	1/16" steel ball	10	90	100	130
C	Diamond cone	10	140	150	100
D	Diamond cone	10	90	100	100
E	1/8" steel ball	10	90	100	130
F	1/16" steel ball	10	50	60	130
G	1/16" steel ball	10	140	150	130
H	1/8" steel ball	10	50	60	130
K	1/8" steel ball	10	140	150	130
L	1/4" steel ball	10	50	60	130
M	1/4" steel ball	10	90	100	130
P	1/4" steel ball	10	140	150	130
R	1/2" steel ball	10	50	60	130
S	1/2" steel ball	10	90	100	130
V	1/2" steel ball	10	140	150	130

Table 6.3 Use of Rockwell scales (England, 2012)

HRA	Cemented carbides, thin steel and shallow case hardened steel
HRB	Copper alloys, soft steels, aluminium alloys, malleable irons, etc.
HRC	Steel, hard cast irons, case hardened steel and other materials harder than 100 HRB
HRD	Thin steel and medium case hardened steel and pearlitic malleable iron
HRE	Cast iron, aluminium and magnesium alloys, bearing metals
HRF	Annealed copper alloys, thin soft sheet metals
HRG	Phosphor bronze, beryllium copper, malleable irons HRH . . . . Aluminium, zinc, lead
HRK	Soft bearing metals, plastics and other very soft materials
HRL	Soft bearing metals, plastics and other very soft materials
HRM	Soft bearing metals, plastics and other very soft materials
HRP	Soft bearing metals, plastics and other very soft materials
HRR	Soft bearing metals, plastics and other very soft materials
HRS	Soft bearing metals, plastics and other very soft materials
HRV	Soft bearing metals, plastics and other very soft materials

The method is quick and easy, but the many scales that are not linearly related, makes it hard to compare values from the different hardness scales accurately.

6.2.4 Mohrs Scale

The Mohr's scale is a qualitative hardness index ranging from one to ten; one being the softest and ten the hardest. It was made for minerals; each mineral had to be able to scratch the ones in the scales below it. The hardness does not increase linearly and the hardness value does not pinpoint the hardness accurately compared to the other hardness scales. For instance, diamond which has Mohr hardness of 10 is 140 times harder than corundum that has an hardness of 9, whereas fluorspar with an hardness of 4 is only about 10% harder than calcite with an hardness of 3 (Efunda, 2012). Advantages are; it covers the entire hardness range, something that makes coarse comparison of a wide range of materials on the same scale possible and it is a very simple test to perform. If one have files with known hardness available it can be done almost anywhere and on anything.

6.2.5 Correlation Between Hardness Scales

Fig 6.5 gives an overview of how some of the hardness scales correlate. Conversion tables that compare/convert numerical hardness values between different scales for a given material are widely available. Comparing hardness of different materials using different scales is not that straight forward.

After some research of hardness values and conversion tables, the Mohr's scale is suggested to be most consistent and practical to use at this point. It gives a very coarse first impression of the hardness of the material candidates, which is considered to be sufficient at this stage. During the material discussion the other listed hardness values are therefore only noted and not discussed much further in this first evaluation round (this thesis). When the material candidate list is shortened it might be beneficial to look again at the other hardness scales using more time making sure that test load, scale and procedures are comparable.

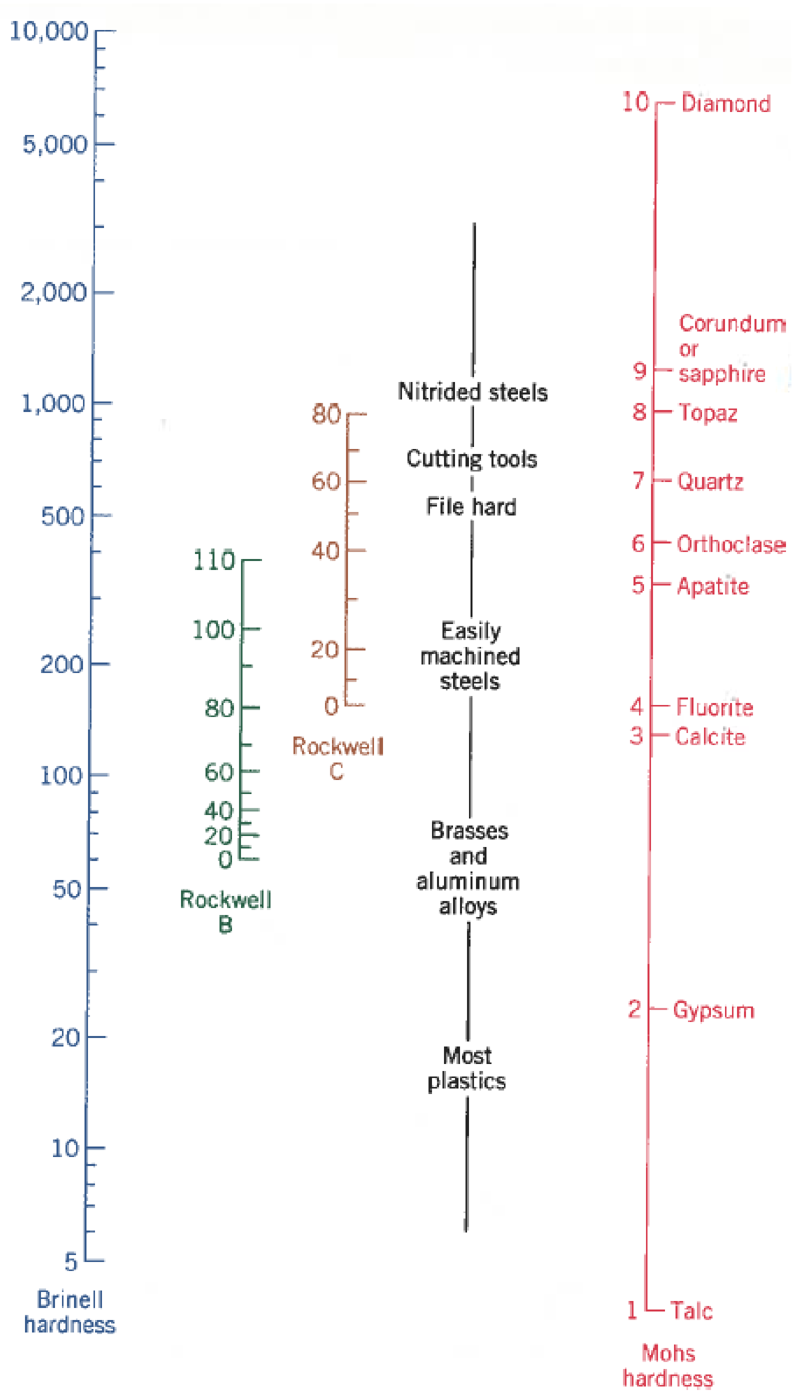


Fig 6.5 Correlation between Brinell, Rockwell and Mohr hardness (Callister, 2007)

6.3 Material Discussion

The focus is on the properties considered to be of most importance. That is how the wear rate is against steel, if the material can handle the expected cyclic loading, how easy the coil will slide against the guide pipe material and if coil damage can be expected. Other properties such as corrosion resistance, chemical resistance and acceptable temperature range are seen as less important at this point.

The materials found to have a low friction factor are seen as potential candidates for guide pipe material and some of their other properties will in this subchapter be evaluated to exclude materials that are bad candidates' even if the friction factor is low.

As quoted by Elliott et al. (1998) the wear rate is not an intrinsic material property. Hence the wear rate of a material in any situation cannot be predicted after a set of wear tests as the wear rate depends on many varying factors besides friction coefficient and material properties. Factors such as contact pressure, temperature, running sped and orientation of grinds or fibers (some factors are interconnected) will also influence the wear rate, and not necessarily in a predictable way. But experiments performed by others reveal tendencies that can be used in the search for material candidates.

Steel had a relatively high dry friction coefficient, but is discussed with lubricant or "inner glide pipe" as an option because the availability of steel pipes with different properties on a reel is known to be high; an asset that is valued higher than the possible disadvantage a lubricant/double pipe system will induce.

The polymers and alloys in table 6.1 are discussed together with their "mother material" even if they are differentiated in table 6.1. The candidate list it therefore cut down to: aluminum, carbon, copper, polymers, steel and tungsten.

Tables with material properties are made for most of the main candidates to give a systematic representation of the property range as base for the discussion. There is a wide variation of alloys with different properties; all possible alloys could not be considered. There will probably be alloys with some of its properties outside the range in the tables, but the property tables reflect a range found to be representative. As the material theory in chapter three accounts for, the properties a material possess is a compromise, all properties cannot coexist on an optimal level. This is mentioned again to make clear that the value range in the property tables is not a possible range of one single material.

The values in these tables are gathered from a large amount of public sources. As the properties vary greatly from alloy to alloy no source alone was found to have all the needed information. Specific values are needed for further evaluation of the material candidates found to be potential candidates.

6.3.1 Aluminium

Some aluminum properties are shown in table 6.4.

Table 6.4 Aluminum properties

Aluminium	
Friction coefficient against steel	0.47-0.61 dry
	lubricated
Yong`s Modulus (E)	70-79GPa
Shear Modulus (G)	26GPa
Yield Stress	47-320 MPa
Ultimate Tensile Strenght	200-350 Mpa
Density	2700 kg/m3
Elongation	10 -30
Poisson`s Ratio	0.33-0.35
Hardness	
Vickers	100HV
Rockwell	60HRB
Brinell	95HB
Mohr	2.5-3

Aluminum is light in weight compared to its strength and is therefore often used to save weight in constructions. It is relatively easily welded (with the right procedures) and can therefore be provided in pipes with needed size.

The low E modulus and softness indicate that it is easily deformed, probably too easy for the purpose of serving as a guide pipe, as quite some stiffness is needed to keep an even radius on both sides of the saddle support. In addition the softness of the material combined with a not especially low friction coefficient would probably cause excessive guide pipe wear and a high needed force to pull the coil through the guide pipe. As aluminum is an initially soft material the hypothesis is that it will harden under plastic loading. This is not necessarily a positive property as brittle uniformities might form.

6.3.2 Carbon

Pure carbon in solid form exists as diamond and graphite. On a molecular level two completely different structures with different properties.

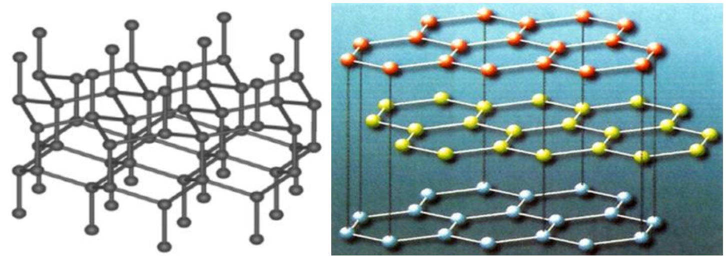


Fig 6.6 Left; diamond and right; graphite

Fig 6.6 shows the diamond and graphite structure. In the diamond structure each carbon atom is bound to the maximum number of atoms (four in the case of carbon), this bounding is very strong and the resulting material is the hardest of all natural elements (10 on Mohrs scale). Graphite is bound to two other carbon atoms forming pentagons lying in the same plane, each plane is held togheter with the plane below and above with weaker van der Waal bounds as illustrated right in the figure. The result is a very soft material (1-2 on mohrs scale) with little ability to deform without breaking.

Even if the friction against steel is low neither of the alternatives is an potential candidate for guide pipe material. Diamond is both financially and practically impossible to considder (expencive and brittle). Graphite properties are known from pencils, a pipe from this material would break instantly and wear fast if used as an inner guide pipe.

6.3.3 Copper Alloys

Copper is the main element in some of the materials in table 6.1. This subchapter focuses on pure copper, brass and bronze.

Properties of pure copper are shown in table 6.5.

Table 6.5 Properties of copper

Copper	
Friction coefficient against steel	0.22 dry
	0.2 lubricated
Yong`s Modulus (E)	110-128GPa
Shear Modulus (G)	46-48GPa
Yield Stress	47-320 MPa
Ultimate Tensile Strenght	200-350 Mpa
Elongation	10 -55
Density	8940kg/m3
Poisson`s Ratio	0.36
Hardness	
Vickers	40HV
Rockwell	40HRF
Brinell	40-100 HB
Mohr	2.5-3

Pure copper is a soft and ductile material, copper pipes was (and is still to some extent) used in house pluming, as they are corrosion resistant and easy to form. Depending on the way of production σ_y and σ_u varies, but the σ_u/σ_y relation seems to land in the range above 1.2 which indicates that the material will harden with plastic loading. The result is a brittle pipe that might buckle on the inside.

It is not common to weld copper, copper pipes are normally made by extrusion which only works well up to about 3”. Large pipe dimensions as needed for a guide pipe are not stock items, if obtainable at all in a homogenous quality.

Brass is an alloy of mainly copper (typically 50-75%) and zink (25-50%), but other additives as nickel, tin and aluminum can be added to get a brass version customized to certain types of usage. Brass properties are shown in table 6.6.

Table 6.6 Properties of brass

Brass	
Friction coefficient against steel	0.35-0.51 dry
	0.19 lubricated
Yong`s Modulus (E)	97GPa
Shear Modulus (G)	37-46GPa
Yield Strenght	124-310 MPa
Ultimate Tensile Strenght	340-470 Mpa
Elongation	5 -40
Density	8400 - 8700kg/m3
Poisson`s Ratio	0.31
Hardness	
Vickers	
Rockwell	30-80HRB
Brinell	60-100HB
Mohr	3 -4

Brass is harder than pure copper, a hardness value a bit below steel, as wanted, seems achievable. There exists such a variety of brasses that it is likely that there are types with the other needed properties. As an example tungum is an aluminum-nickel-silicon-brass alloy that is said to have an unusually high strength to weight ratio, good ductility, excellent corrosion resistance and first class fatigue properties (Tungum Limited, 2012).

A relatively large pipe is needed (estimated range 3”-7” inner diameter), as such large pipes cannot be made by extrusion the chosen brass type must be weldable. According to the Copper Development Association (2012) there exist some welding procedures relevant for welding of brass, but evolution of zinc oxide fumes due to zinc boiling off in the weld pool is a common problem. If special care is taken the problems can be minimized, but if the welds can cope with the loads that a guide pipe will be exposed to must be confirmed. The pipes sizes found to be available among several venders where maximum 4”, mostly below 2”, this indicates that larger pipes are not commonly made.

Bronze is an alloy of typically 95-85% copper. Tin is usually the main additive, typically 5-15%. Some alloys also contain varying amounts of other components as aluminum, manganese, phosphorus, silicon and beryllium. Form table 6.7 one can see that the properties can wary widely depending on composition, cold working and heat treatment.

Cold worked bronze is known to be hard and brittle, but with an annealing process the material is softened. This is documented by the great variation on the Mohr's scale (3-6).

Table 6.7 Properties of bronze

Bronze	
Friction coefficient against steel	dry
	0.16 lubricated
Yong`s Modulus (E)	117.2GPa
Shear Modulus (G)	46GPa
Yield Stress	47-320 MPa
Ultimate Tensile Strenght	200-350 Mpa
Elongation	10 -30
Density	7400-8900 kg/m3
Poisson`s Ratio	0.34
Hardness	
Vickers	60-260HV
Rockwell	78HRB
Brinell	60-225HB
Mohr	3 -6

Aluminum, manganese and tin bronzes are used in gears because one can achieve low friction against steel and hence little wear of the bronze and even less of the steel, the same situation as is wanted from the coil-guide pipe interaction. But the material types used in gears are probably not suitable in a guide pipe material because it has to be cast and only continuous casting of small diameter pipes is possible. (Anchor Bronze and Metalls Inc, 2012)

As with brass, small diameter pipes are most common on the market, but some larger diameters are found as standard up to 6" (Farmers Copper, 2012), this indicate that also larger pipes can be made. But since only certain types of brasses can be welded it is not certain that the wanted pipe size is achievable with the needed properties (eHow, 2012). Braze welding is a common way of "welding" bronze (it is even called bronze welding) (Integrated, 2012). It is a weld procedure where the base metal is not melted, and this has many advantages (joining dissimilar metals, minimize heat distortion, reduced need for pre-heating, eliminate stored-up stress), but the ability to withstand stress is not high so it is doubtful that this procedure is fitted for making guide pipes.

6.3.4 Polymers

As table 6.8 shows the range of polymer properties is wide. But since the range is so different from that of metals some general conclusions can be made. The elastic modulus for polymeric materials normally range from 7MPa to 5GPa, which is very low compared to metals which normal range is 48-410GPa. The maximum tensile strength for polymers is about 100MPa, for metals one might get up to 4100MPa. The low E module of polymers indicate that they deform easily and the low tensile strength that the plastic behavior set in after a low applied load, but this does not mean that a polymeric pipe will break during loading because of the ability polymers can have to deform. The found elongation range is 3-700%, with few alternatives in the lower range. A metal is considered to have a high elongation if it can elongate 50%.

Even though metals are superior in many areas some polymeric materials are evaluated to see if they could be possible candidates because of the benefits they possess that would be beneficial in a guide pipe. (Callister, 2007)

Possible benefits in a polymer material:
-low friction coefficient
-high fatigue resistance
-low weight
-low cost

The challenge is to find a material that has the most optimal combination of properties with respect to serving as a guide pipe material as all the wanted properties cannot coexist at an optimal level.

Table 6.8 Polymer properties.

Polymers	
Friction coefficient against steel	0.05-0.4 dry
	lubricated
Yong`s Modulus (E.)	7MPa-5GPa
Shear Modulus (G)	GPa
Yield Stress	MPa
Ultimate Tensile Strenght	13-100Mpa
Density	900-1300kg/m3
Elongation	3-700%
Poisson`s Ratio	0.32-0.46
Hardness	
Vickers	
Rockwell	
Brinell	2-72HB
Mohr	1-2

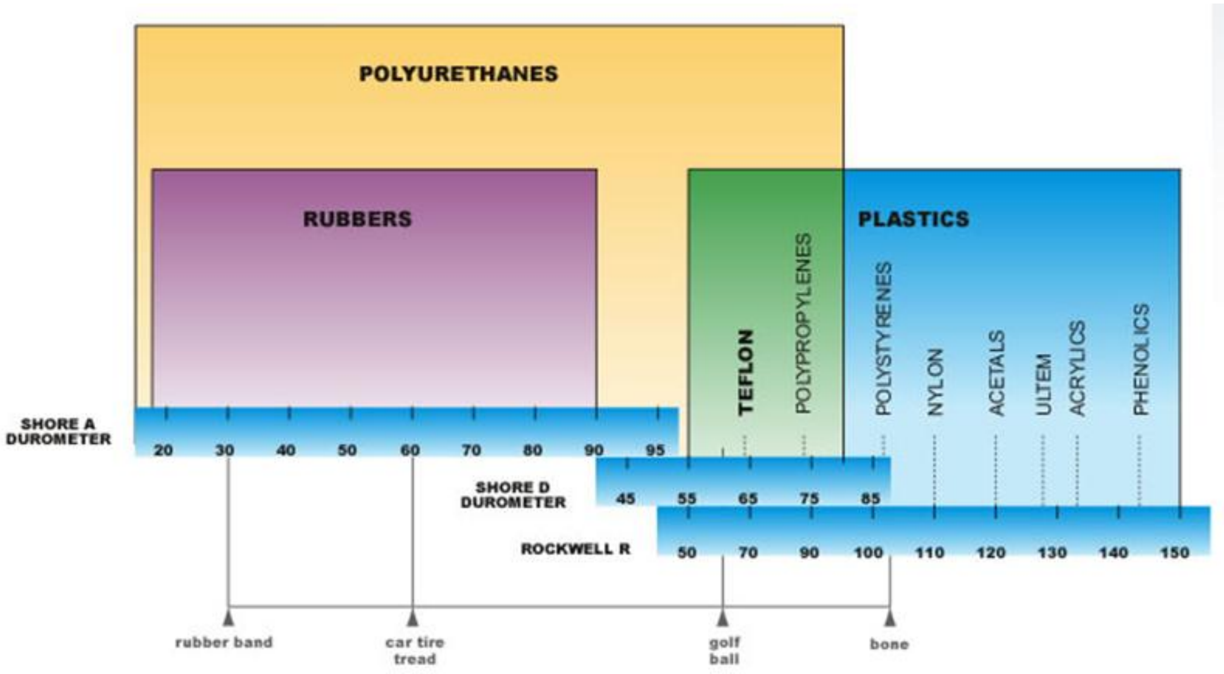


Fig 6.7 Hardness Scale (Plastics International, 2012)

Fig 6.7 shows the hardness spectra of some polymers. As the scales are not linearly correlated it is difficult to compare accurately, especially against metals which hardness scales correlate even less. But we know that polymers in general are much softer than most metals, the challenge is therefore to find a material that despite of this do not wear to fast. This could be achieved by a relatively hard material (in the polymeric "world") with a low friction factor, properties that often coexist. In addition to this the material must be able to deform plastically without risk of fatigue failure, but hardness and ability to deform without breaking are not necessarily compatible properties.

In a paper by Benabdallah (2006) the wear rate and friction of some common plastics where tested against SAE 52100 steel and silicon nitride a ceramic (Si_3N_4). The reason for this experiment was that debris of plastics is a cause of failure in machine components. In our case debris is not likely to be a cause of failure as long as the amount of debris can be predicted and kept under an acceptable limit; eventually drainage system must be designed in if necessary. What is important is that the wear does not influence the mechanical properties in such a way that there is risk of guide pipe failure or coil damage.

Some material properties of the materials in the experiment by Benabdallah (2006) are shown in table 6.9. It is claimed that plastics behave the same way when rubbed against ceramics as against metals; this does not mean that all ceramics and metals will give the same results, but that the results using a ceramic should be compatible to using a metal with the same surface finish. Here Si_3N_4 had a maximum surface roughness of 0.06µm and the steel is said to have a similar roughness.

Table 6.9 Plastic properties (Benabdallah, 2006)

Material and grade	Designation	Tensile modulus E (MPa)	Poisson's ratio	Thermal conductivity K (cal/s/°C/m)	Specific heat c_p (cal/g/°C)	Density ρ (g/cm^3)
						Plastics
Polyoxymethylene Delrin 500P	POM	3250	0.35	7.94×10^{-2}	0.35	1.42
Polyamide Zytel 101L C010	PA 66	2700	0.32	5.795×10^{-2}	0.42	1.14
Poly(amide-imide) Torlon-4203L	Torlon	4500	0.41	6.2×10^{-2}	0.42	1.41
Polypropylene Pro-fax 6323	PP	1550	0.43	5.99×10^{-2}	0.23	0.9
Polytetrafluoroethylene Teflon	PTFE	550	0.46	5.86×10^{-2}	0.25	2.21
Polyethylene high density HiD 9012	HDPE	1100	0.45	5.2×10^{-2}	0.55	0.95
Poly(vinyl chloride) PVC-CAW	PVC	2500	0.44	2.8×10^{-2}	0.24	1.42
Ceramic						
Hot pressed silicon nitride containing 8%Y_2O_3, less than 0.5% Al_2O_3	Si_3N_4	310×10^3	0.24	0.35	0.2	3.29

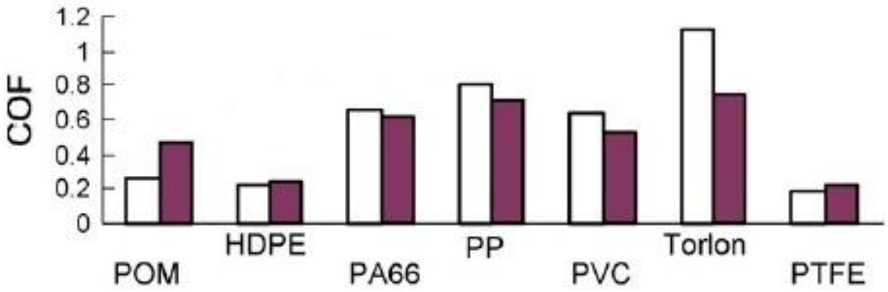


Fig 6.8 Dynamic coefficient of friction (COF) against steel (type SAE 52100, purple columns) and Si_3N_4 (white columns) (Benabdallah, 2006)

Fig 6.8 shows how the dynamic coefficient of friction (COF) wary with material type table 6.10 shows how the wear rate wary for the same materials. The wear rate is calculated with the equation W=K∗F∗V∗T (W =wear volume (mm^3), K_w = wear factor (mm^3/Nm), F = force (N), V =velocity (m/sec), and T = time (s)). A lower wear factor indicates a greater resistance to wear.

Table 6.10 Wear rate for: 10N≤F≤37N, 0.1 m/s≤V≤1.5 m/s, distance s = 500m (Benabdallah, 2006)

Plastic	K_w (mm^3/Nm) Against Si_3N_4	K_w (mm^3/Nm) Against SAE 52100 steel
POM	8×10^{-8}	4.5×10^{-7}
HDPE	1.2×10^{-6}	1.1×10^{-6}
PA66	10^{-6}	4×10^{-6}
PP	3.5×10^{-6}	6.6×10^{-5}
PVC	2.5×10^{-6}	4.8×10^{-5}
Torlon	7.6×10^{-8}	3.3×10^{-7}
PTFE	10^{-4}	2.5×10^{-4}

Fig 6.8 and tables 6.9 and 6.10 exemplify that the material with the lowest COF does not necessarily have the lowest wear. In fact polytetrafluorethylene (PFTE/Teflon) which has the lowest COF had the highest wear and Torlon who has the highest COF had the lowest wear. This is explained by the tensile modulus that is only 550MPa for PTFE and 4500 for Torlon. The same tendency can be seen for the rest of the polymers. Hence a low friction coefficient is wanted to minimize the force needed to pull the coil through the guide pipe, but it might not be possible to get a combination of optimal COF, low wear and no damage to the coil.

The maximum surface roughness of the ceramic disc was 0.06µm and the plastics had a roughness of 0.08 µm. The roughness of the coil will be much higher than this; in addition there might be impurities present, hence if the guide pipe material is too soft the coil will dig in the material.

Some fluorocarbon polymers and belonging properties are included in table 6.11.

Table 6.11 Fluorocarbon properties (DUPOINT, 2012)

Property	ASTM Standard	Unit	Teflon® PTFE	Teflon® FEP	Teflon® PFA	Teflon® ETFE
Specific Gravity	D792	--	2.15	2.15	2.15	1.76
Tensile Strength	D1457 D1708 D638	MPa (psi)	21-34 (3,000-5,000)	23 (3,400)	25 (3,600)	40-46 (5,800-6,700)
Elongation	D1457 D1708 D638	%	300-500	325	300	150-300
Flexural Modulus	D790	MPa (psi)	496 (72,000)	586 (85,000)	586 (85,000)	1,172 (170,000)
Folding Endurance	D2176	(MIT) cycles	>10^6	5-80 x 10^3	10-500 x 10^3	10-27 x 10^3
Impact Strength	D256	J/m (ft·lb/in)	189 (3.5)	No Break	No Break	No Break
Hardness	D2240	Shore D pencil	50-65 HB	56 HB	60	72
Coefficient of Friction, Dynamic	D1894	--	0.05-0.10	0.08-0.3	--	0.3-0.4

As tables 6.1 and 6.11 indicate, fluorocarbon polymers have superior non-stick properties (hence low friction against other materials). Even if the tensile strength compared to steel is very low this does not mean that there will be a fracture because the elongation is in the range of 150% and above. As long as there is an outer pipe that provides the required stiffness, the low tensile strength does not have to be a problem as the elongation will be restrained by the outer pipe.

On the downside the hardness and E module are very low, the consequences were illustrated in the paper by Benabdallah (2006). But all who have used a metal spatula on a Teflon coated frying pan have experienced the consequence first hand. From figure 6.5 one can tell that HB60 which is average for Teflon is much lower than HRC25 which is normal for the coil. Fillers can be added to enhance wanted properties, for example will glass and carbon enhance mechanical strength and wear resistance.

According to Zeus (2012) polyetheretherketone (PEEK) is widely regarded as the highest performance thermoplastic material, it is claimed that it is comparable to steel in strength, but lighter and with excellent fatigue resistance and low friction coefficient. Some of its properties compared to bronze and steel is summed up in table 6.12.

Table 6.12 PEEK properties compared to bronze and steel (Zeus, 2012)

PEEK Comparison to Metals		
Steel	**Bronze**	**Aluminum**
PEEK has cheaper manufacturing cost	PEEK has better mechanical properties	PEEK has cheaper manufacturing cost
PEEK has fewer leachables	PEEK is harder	PEEK is harder
PEEK has better dry wear properties	PEEK has better wear & friction	PEEK has better wear & friction
PEEK has better chemical resistance	PEEK has better chemical resistance	PEEK has better chemical resistance
PEEK has 83% Lower Density	PEEK has 85% Lower Density	PEEK has 50% Lower Density
PEEK has less "memory" / chemical absorption & release	PEEK has low outgassing	

The wear resistance can be increased and friction coefficient lowered even more by using PEEK in a copolymer or as a composite adding carbon, glass fibers, SiC or other fillers depending on which properties are needed and what is compatible with the area of use (if the PEEK is needed as pipe, plate, coating etc.). There are several papers on this as PEEK based composites and copolymers have been found to eliminate the need for traditional lubrication systems (examples; Davim and Cardoso (2008), Wang, et al. (1995) and Zhang et al. (2005)). This is a great advantage as lubrication fluids create unwanted (often toxic) waste; induce extra cost, maintenance and practical challenges.

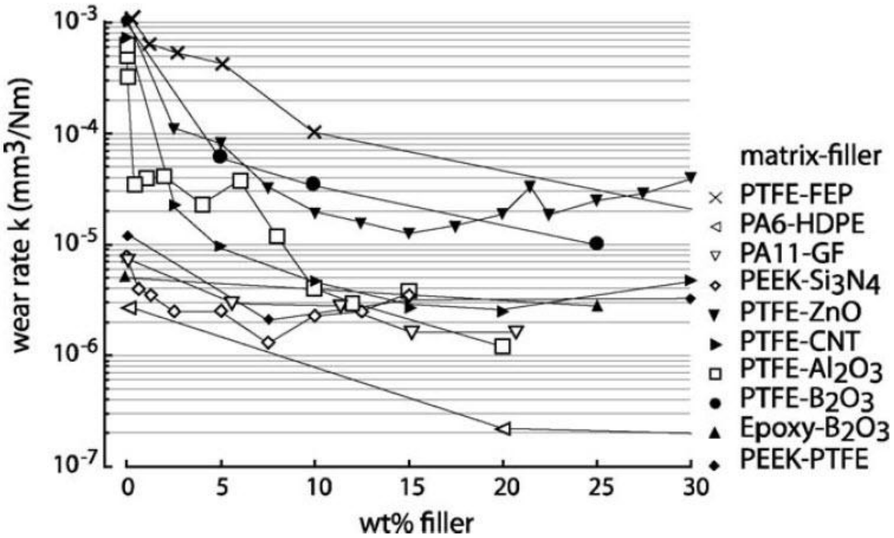


Fig 6.9 Wear rate vs. wt% filler in PEEK copolymer (Burris and Sawyer, 2005)

Figure 6.9 shows some examples on how different polymer compositions increase the wear rate of PEEK. The table can only be used as an indication of wear properties as the wear rate depends on several factors such as temperature, contact force, surface roughness and running speed, factors that are not shown in the figure.

In a paper by Burris and Sawyer (2005) combinations of PEEK and the fluorocarbon PFTE gave promising results. The PEEK-PFTE combinations were tested against AISI 304 stainless steel with a Rockwell B hardness of about 90, a relatively soft steel, and a contact pressure of 6.25MPa, which is found to be a higher contact pressure than expected contact force coil-guide pipe (see appendix chapter 11.2.1 for calculations).

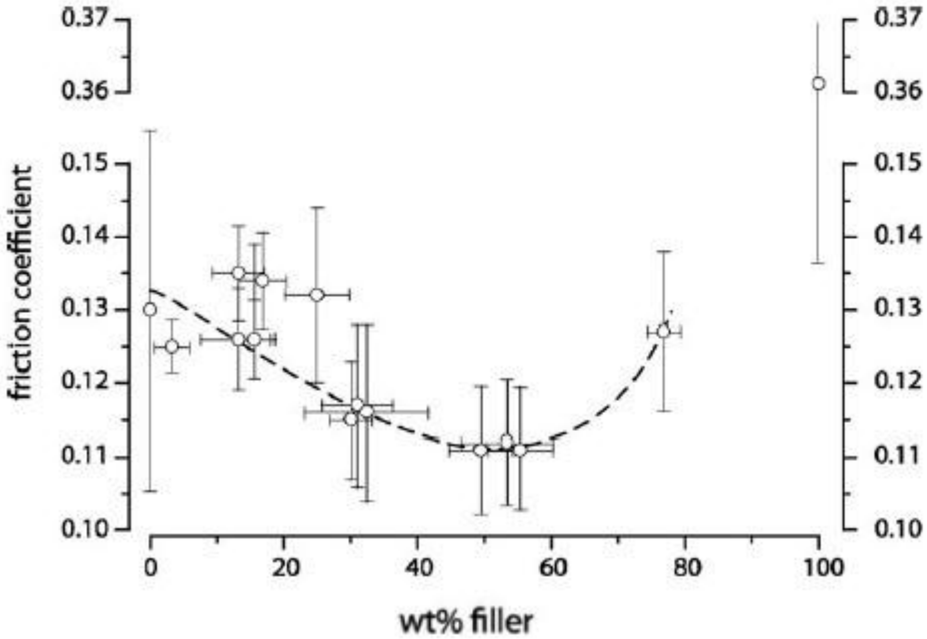


Fig 6.10 Friction coefficient vs. wt% PEEK filler in PTFE (Burris and Sawyer, 2005)

PFTE have a friction coefficient of about 0.13 and PEEK about 0.4. As figure 6.10 indicates adding PEEK to PTFE gave friction coefficients below that of PFTE alone, the COF is lowest in the range of 30 to 70 wt % PEEK.

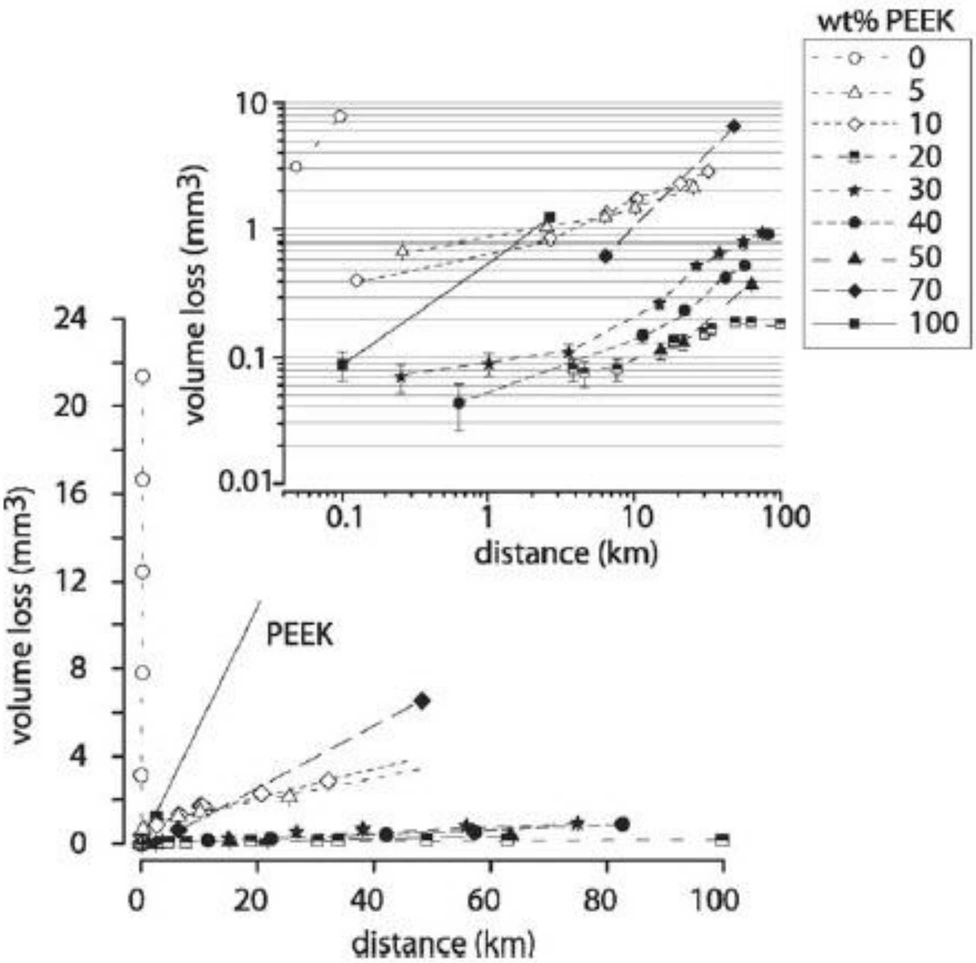


Fig 6.11 Volume loss vs. sliding distance and PEEK content in PFTE (Burris and Sawyer, 2005)

The wear rate (expressed by volume loss in mm^3) was reduced considerably with a PEEK content of between 20 and 50 wt %, 20 % giving the lowest wear rate, as figure 6.11 indicates. As the amount of coil to be guided often is in the range 5 000 to 15 000m (RRM, 2011) these results looks promising even if the surface roughness of the coil is expected to be higher than the average roughness of 0.16μm for the steel used in the experiments by Burris and Sawyer (2005) and impurities from the well can worsen the wear conditions.

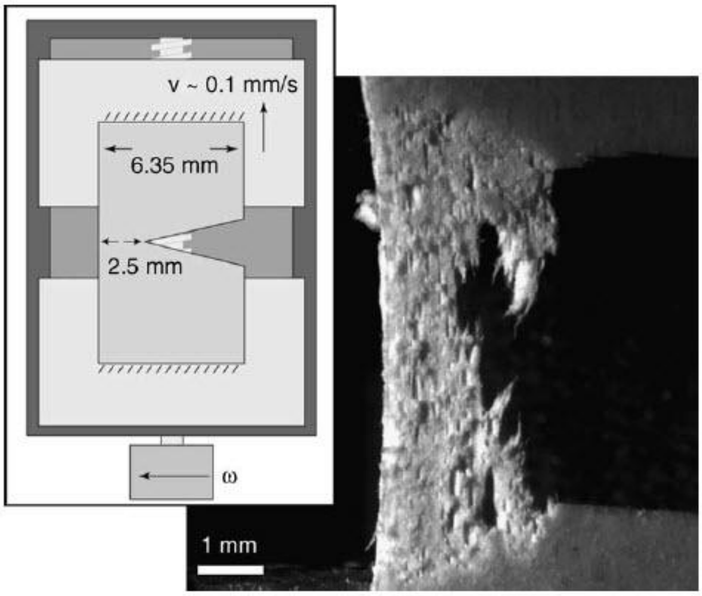


Fig 6.12 Elongation before break PFTE with 30% wt% PEEK (Burris and Sawyer, 2005)

Fig 6.12 shows how a piece of PFTE with 30% PEEK elongates when put under stress. The elongation was too large to be able to capture the breaking point in the microscope, but the elongation before break was estimated to be in the range of 250-500%. This result was quite surprising as neither PEEK nor PFTE alone would elongate to such a great extent under the given circumstances. The behavior is explained by PEEK coalescing around PTFE fibrils under deformation mechanical interlocking the two phases. The exceptional wear properties are probably also a result of the same phenomena.

The results are found to be transferable to some extent, but they cannot be directly used to estimate the wear rate in our case as loading, steel type and surface roughness etc. are not the same. But the results are found to be promising, and illustrate the possibilities polymer composites possess regarding “engineering in” needed properties.

6.3.5 Steel

There exists a wide range of steel types. Chemical composition, heat treatment and warm or cold working is used to affect the mechanical properties to get the steel adapted to the area of use. It is common practice to weld steel pipes and a variety of dimensions with a range of properties are available. Table 6.13 shows the steel property range found to be representative.

Table 6.13 Properties of steel

Steel	
Friction coefficient against steel	0.4-0.8 dry
	0.1-0.2 lubricated
Yong`s Modulus (E)	200-210GPa
Shear Modulus (G)	80GPa
Yield Stress	200-400MPa
Ultimate Tensile Strenght	300-600 Mpa
Elongation	10 -50
Density	7480-8000kg/m3
Poisson`s Ratio	0.26-0.3
Hardness	
Vickers	210HV
Rockwell	90-95HRB
Brinell	130-290HB
Mohr	4 -7

Table 6.14 shows the composition of a typical coil pipe and table 6.15 how the properties can vary within this composition.

Table 6.14 Typical composition of CT material (Global Tubing, 2012)

Element	Max (%)	Min (%)
Iron, Fe	98,650	95,620
Manganese, Mn	1,700	0,700
Chronium, Cr	1,000	0,250
Silicon, Si	0,500	0,100
Copper, Cu	0,400	0,200
Molybdenium, Mo	0,300	0,100
Nickel, Ni	0,250	0,000
Carbon, C	0,150	0,000
Phosphorus, P	0,025	0,000
Aluminium, Al	0,050	0,000
Sulfur, S	0,006	0,000

Table 6.15 Typical coil properties (Global Tubing, 2012)

Properties	Min	Max
Minimum yield strenght	483Mpa	758MPa
Maximum yield strenght	586MPa	793Mpa
Specified Minimum tensile strenght	758Mpa	793MPa
Maximum hardness	22 HRC	30HRC

All exact coil properties are not known and will vary depending on type of coil used. If the coil is previously used the surface and internal properties will vary to some extent from the properties given in datasheets. But as the wear rate is not an intrinsic material property the resulting fault margin when estimating wear against other materials based on knowledge acquired from reading papers, text books and web sites will be large irrespective of the accuracy of the knowledge about the coil. Much information on the subject of the coil is therefore not gathered, as this is assumed to be available at a later stage if material trials will be actual.

Steel against steel has a relatively high friction coefficient without using lubrication (about 0.7). Hence a considerable force would be needed to pull the coil through the long guide pipe. A lubrication or glide pipe system must be evaluated to get the friction coefficient down.

Getting a lubricant to function satisfactory in such a long pipe that is shaped the way it is, is considered a challenge in itself. Transport of lubricant to the most exposed part of the guide pipe is difficult without puncturing the guide pipe and applying the lubricant at the highest point, something that could give a weak point on the guide pipe and increase the risk of failure. The needed amount of lubricant is assumed to be high as the amount of coil length to be guided through is long (5 000-15 000m). As mentioned in chapter 6.3.4 lubrication fluids also create unwanted (often toxic) waste; induce extra cost, maintenance and practical challenges. A glide pipe system is therefore considered to be the best option.

A guide pipe in steel with a replicable pipe in another material with a lower friction coefficient on the inside could give the needed stiffness, strength and low friction to minimize the force needed to pull the coil and possibility to minimize the coil damage.

6.3.6 Tungsten

Tungsten is also called wolfram, it is often added some carbon to form tungsten carbide. The high values in table 6.16 are representing tungsten carbide and the lower values are tungsten alone.

Table 6.16 Properties of tungsten (carbide)

Tungsten	
Friction coefficient against steel	0.4-0.6 dry
	0.1-0.2 lubricated
Yong`s Modulus (E)	350-650GPa
Shear Modulus (G)	160-180GPa
Yield Stress	NA
Ultimate Tensile Strenght	100-400 Mpa
Elongation	2 -10
Density	19600kg/m3
Poisson`s Ratio	0.28-0.3
Hardness	
Vickers	1560HV
Rockwell	92HRA
Brinell	
Mohr	7.5-9

Tungsten is one of the hardest of all melted, cast and forged metals. With a young's modulus of up to 653GPa the resistance to deformation is 2-3 times higher than steel. The weight is 1.5 to 2 times higher than steel.

The hardness is so high that it is obvious that the steel tubing will wear while the guide pipe remains intact. It is also very doubtful that such a hard material will cope well with the dynamic motion that is required from the guide pipe, something that the low elongation also indicates. The high weight is also an unwanted factor.

Even if tungsten had a relatively low friction coefficient against steel it is not considered to be a good alternative for further evaluation because of the other properties that does not correlate well with the intended use.

7 Risk Evaluation

The operator and contractors have strict HSE requirements that they are obliged to follow. Therefore personnel health and safety, together with environmental considerations, are important when deciding on a concept. These factors should be considered already in the design phase in order to meet the HSE requirements at an early stage.

7.1 The Risk Management Process

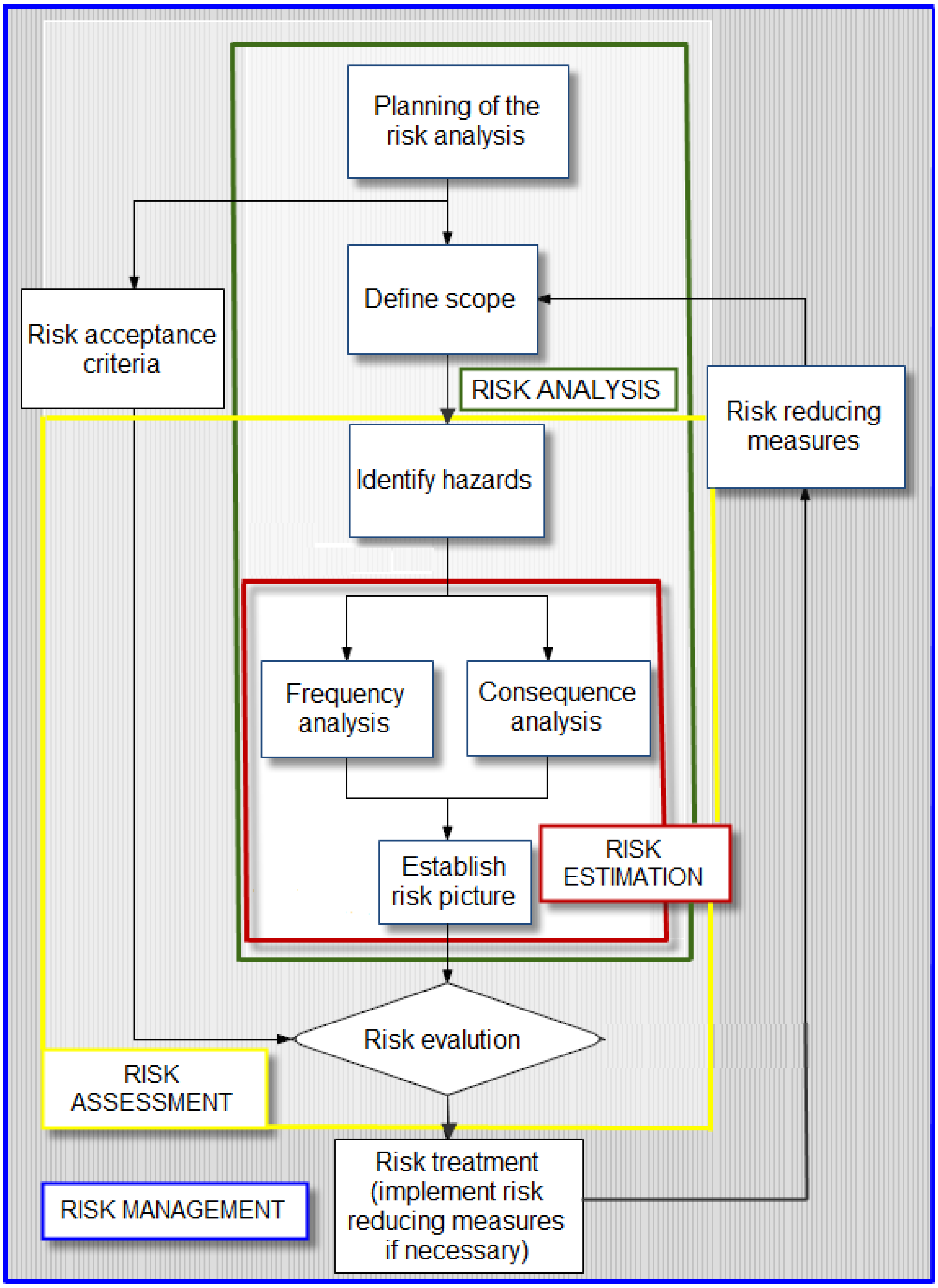


Fig 7.1 Risk management (inspired by NORSOK Z-013N)

Fig 7.1 gives a simplified overview of the risk management process. The aim when performing a risk analysis is to reveal all possible unwanted events, or hazards, and estimate the risk. To do this the scope, including the surrounding factors that might influence the risk picture, must be defined. When all hazards are listed the consequence and probability for each event are evaluated to establish a risk picture. The result is then evaluated against pre-defined acceptance criteria to decide if and which measures must be taken to reduce the risk. If measures are taken to reduce the risk, this is a part of the risk management. After the measures found necessary in the first evaluation round are implemented, the new scope is evaluated again to check that the risk is as low as reasonably possible. If not, more measures must be taken and a third evaluation round must be made.

7.1.1 Risk Evaluation and Reduction

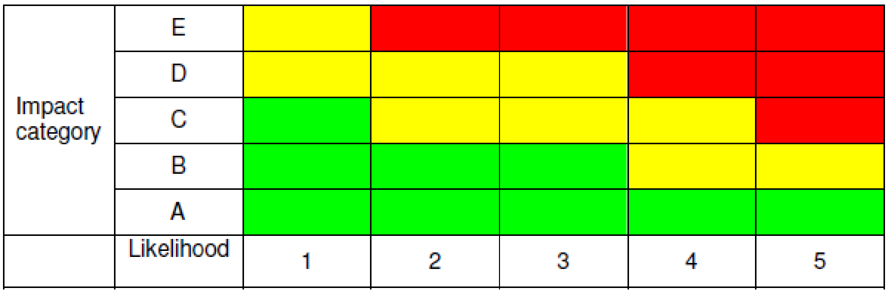


Fig 7.2 Risk matrix (NORSOK Z-013)

To do a thorough evaluation of every single hazard in a large scope is time and resource consuming. A risk matrix is a visual tool that can be used to categorize the hazards and reveal which events need a more thoroughly evaluation. Fig 7.2 shows an example of a risk matrix. This risk matrix has increasing probability along the x-axis and increasingly severity of hazard along the y-axis. The combinations of risk and consequences are evaluated coarsely and categorized in three zones; mostly green is defined as the low risk zone, red as high risk and yellow intermediate. The acceptance criteria shall be defined before the evaluation/categorization of hazards starts.

Lowering the risk is done by reducing the probability for the event to happen; implementing probability reducing measure(s) and/or reduce the consequence if the event should happen; consequence reducing measure(s). If there are events in the high risk zone, risk and/or consequence reducing measures must be implemented to get the risk down to an acceptable level. The hazards in the low risk zone are considered harmless and/or with an associated probability to happen that is considered sufficiently low for the event not to be considered as a threat. Events in the yellow zone need further analysis before a conclusion can be made. When this is done the as low as reasonably possible (ALARP) principle is followed.

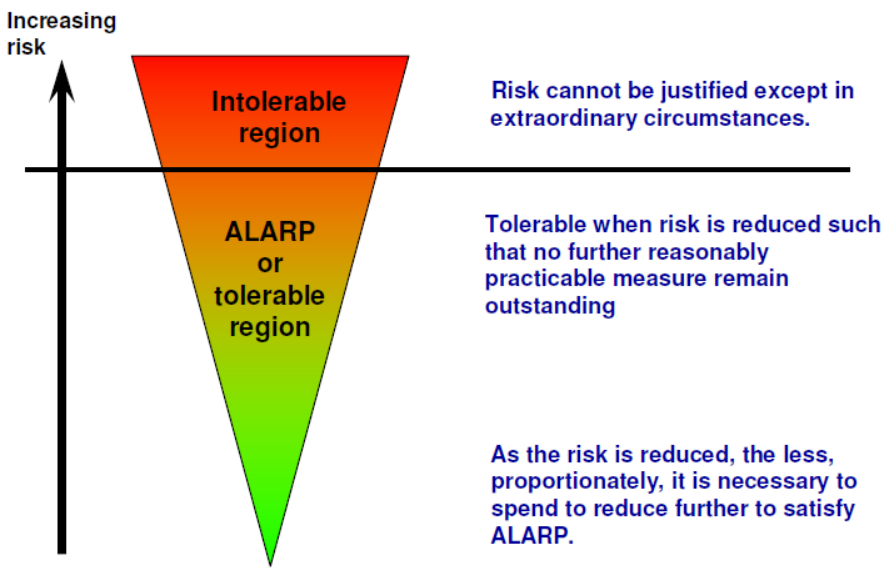


Fig 7.3 The ALARP principle (NORSOK Z-013)

The risk shall always be as low as reasonably possible. Sometimes a higher risk is accepted if the possible gain is considered worth the risk, see fig 7.3. Risk management is a tool used to find the optimal balance between exploring possibilities and avoiding unwanted events (Aven, 2007).

7.1.2 Methods of Revealing Hazards

To identify as many of the existing hazards as possible the analysis must be well planned and the scope clearly defined and known for all people involved. All relevant disciplines shall be represented in the work and a method suitable to the scope must be chosen.

In a Hazard and Operability Analysis (HAZOP) leading words related to time, place, material and activity are used to reveal combinations of events that alone might be harmless can represent a risk when acting together. This method is mostly used for process facilities.

A Failure Modes, Effects and Criticality Analysis (FMECA) considers the consequences of failures of each component separately in a systematic way. This is to find the most critical components and take action to reduce the risk of single component failure if necessary. The focus is on technical errors. This method is not optimal for revealing risk induced by failure caused by overlapping functions and human errors. (Aven, Røed and Wiencke, 2008)

A Structured What-If Technique (SWIFT) might reveal risks caused by combinations of events and can be adapter to several industries. Here one uses a checklist adapted to the scope and industry and asks "What-If?" to reveal potential hazards.

Event Tree Analysis (ETA) and Fault Tree Analysis (FTA) are good tools for evaluating hazards in a system where there are causal connections.

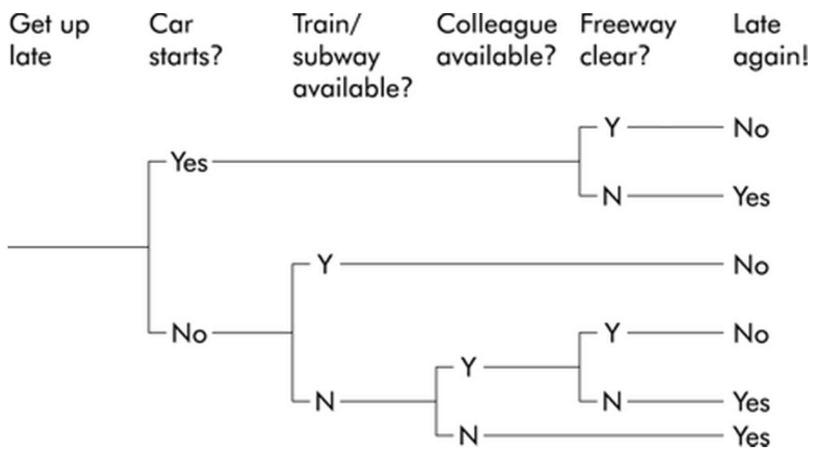


Fig 7.4 Event tree (Wrethall and Nemeth (2003))

An Event Tree (fig 7.4) is used to map and rate potential scenarios arising from one hazardous event. A probability can be assigned for each yes/no to rate the probability for each end scenario. An event tree makes it clearer where to implement consequence reducing measures.

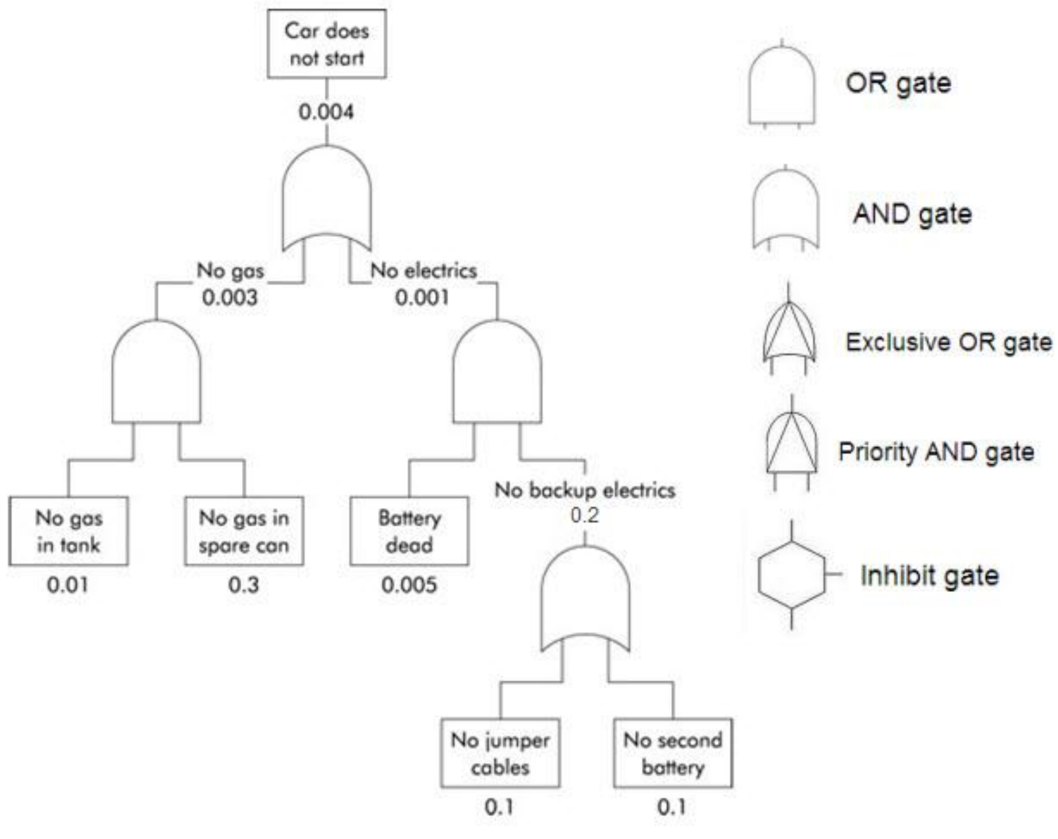


Fig 7.5 Fault tree (Wrethall and Nemeth (2003))

The Fault Tree maps what different incidents a component or human failure can lead to. In the fault tree different logical gates are used to get an overview of which connections that must be present for a scenario to occur (see fig 7.5). A fault tree makes it clearer where the effect of implementing risk reducing measures is most effective.

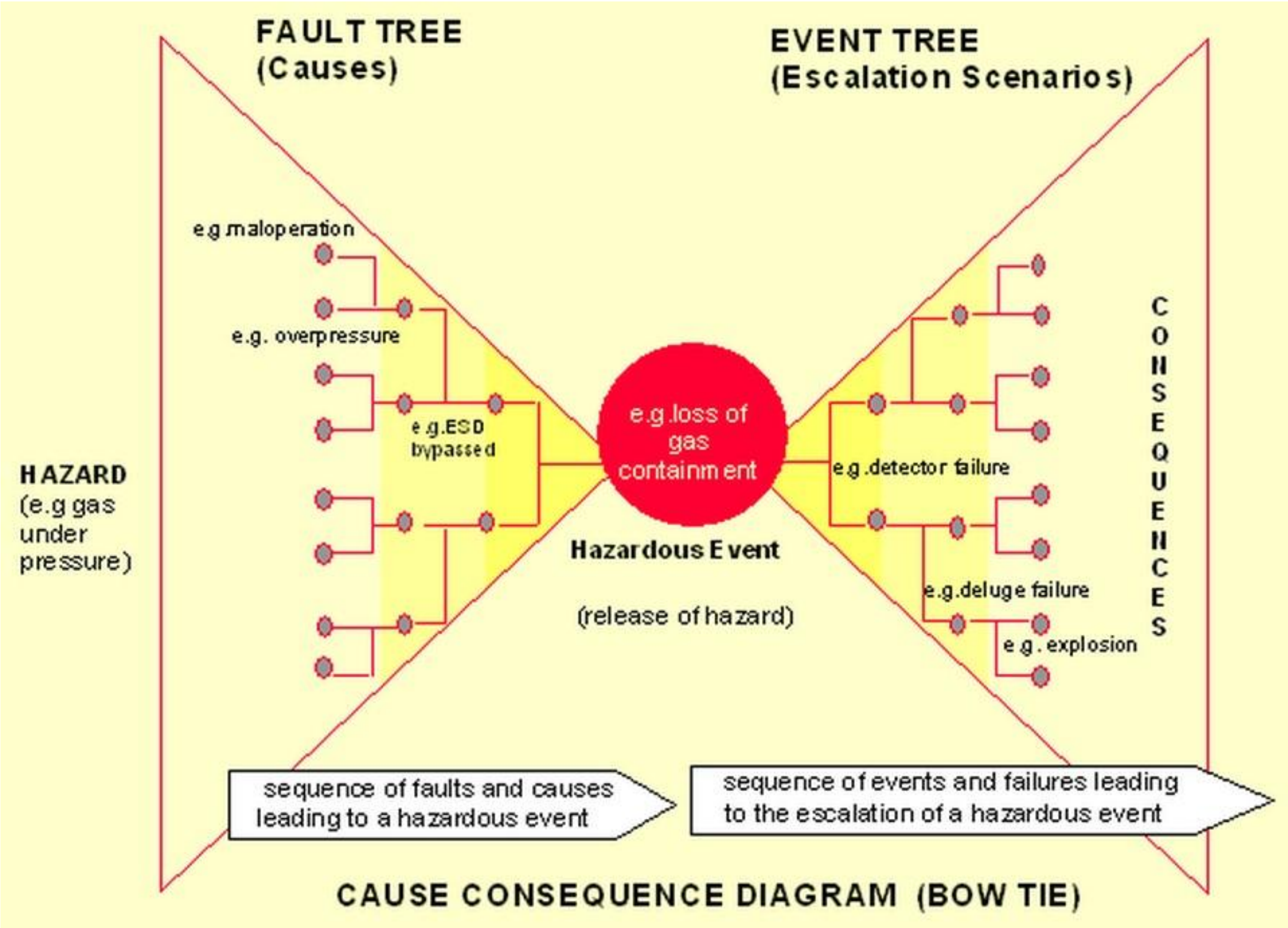


Fig 7.6 Bow tie diagram (OGP, 2012)

To be able to identify the most effective combination of barriers and consequence reducing measures to get the risk down to an acceptable level the fault and event tree diagrams can be combined into a bow tie diagram to map the big picture around an unwanted event as fig 7.6 illustrates.

The risk analysis should be updated regularly as the components age, considering the maintenance history, as well as changes in environment, technology, procedures and suppliers. To be able to do this, there must be a reliable system for keeping track of the history of each part. The complexity of most systems today demands good routines for logging relevant information regarding the different parts. To do this a tagging systems and dedicated computer programs are used. (Markeset, 2010)

The plan for the installation work should be prepared already in the design phase to reveal as many undesirable scenarios as possible and designing out the probability for them to happen, if possible. This installation plan should be kept as closely as possible to avoid unexpected incidents. The Safe Job Analysis (SJA) shall also cover the rig up part of the operation and be adapted to the operation that shall be done.

Early in the design phase a qualitative risk analysis is often the most suitable method to get an overview of the potential hazards and suggesting possible risk and consequence reducing measures. A qualitative analysis does not contain numerical values, but descriptive data.

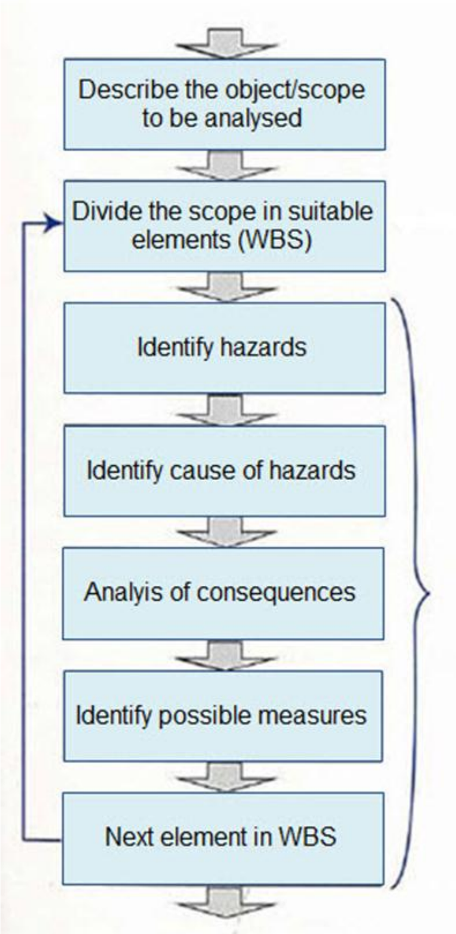


Fig 7.7 Workflow Qualitative Risk Analysis (Aven, Røed and Wiencke, 2008)

Fig 7.7 illustrates the workflow in a qualitative risk analysis. First the scope (equipment/operation/working environment) is defined. Then one divides the scope in suitable work frequencies (Work Breakdown Structure, WBS) that are evaluated separately to keep the focus on one limited part of the scope at the time. Each WBS element should then be evaluated with full focus to reveal the initiating events, causes and consequences of each hazard.

Mostly risk is represented as a combination of an event; as winning the lottery or getting into a plane accident, and the probability for this event to happen; both very low. But to an assigned probability there will always be an uncertainty and this belonging uncertainty should also be considered. That is what people buying lottery tickets or avoiding plane rides do. (Aven, Røed and Wiencke, 2008)

7.2 Evaluation of Traditional CT and Coil in Coil

To estimate the risk and reliability, availability, maintainability and servability (RAMS) of the coil in coil solution against the traditional CT procedure, a thorough analysis is needed.

7.2.1 Defining the Scope

The focus in this analysis is on the steps that are different when comparing use of coil in coil (CiC) and traditional rig up (TR). Some intermediate steps that are the same for both solutions are summed up to keep clear what happens throughout the operation, but these steps are not evaluated with respect to hazards.

It is assumed that the intervention vessel used is the same. The marine riser and safety head installation, or the installation of the equipment stack needed when performing riserless CT, is therefore assumed to be the same for both solutions and should not influence the difference in risk. To keep focus on one new factor at the time this analysis assumes use of marine risers as is normally used.

The design is in the early concept stage. Solution suggestions on how to solve the rig up and operations are not in place and weight and sizes can just be coarsely estimated. On this stage a qualitative risk analysis is considered the most suitable analysis method. The intention of this first analysis is to find the potential hazards in some rig up suggestions and during operation, then suggest possible risk and consequence reducing measures to find more detailed solutions with a low as practically possible risk. Hopefully one is also able to evaluate if the CiC technology means an increased or lowered risk during rig up, operation and rig down compared to TR. In case of an increased risk, it must be evaluated if this is acceptable in order to achieve the benefits the CiC gives.

Consequence						
Extreme(5)	5-NL	5-L	5-M	5-H	5-E	
High (4)	4-NL	4-L	4-M	4-H	4-E	
Moderate (3)	3-NL	3-L	3-M	3-H	3-E	
Low (2)	2-NL	2-L	2-M	2-H	2-E	
Neglible (1)	1-NL	1-L	1-M	1-H	1-E	
	Not Likely (NL)	Low (L)	Medium (M)	High (H)	Expexted (E)	Probability

Fig 7.8 Defined acceptance criteria

Fig 7.8 shows the defined acceptance criteria, they are inspired by Robertson and Shaw (2012). The explanations for the likelihood and consequences are included in the appendix, chapter 11.4.1. As mentioned earlier, and by Robertson and Shaw, the uncertainty in the assigned consequences and probabilities must be considered. In such an early phase it is considered best to be conservative not to underestimate the risk.

In the first evaluation round all relevant steps found in chapter 7.2.2 was evaluated except step 2d. Step 2d is a result of the risk evaluation in chapter 8.3 and is added to chapter 7.2.2 after the evaluation in chapter 8.3.

7.2.2 Traditional Rigup (TR) vs Coil in Coil (CiC)

Step 1-Place equipment in the tower and needed equipment on deck (both TR and CiC)

It is assumed that an advanced coiled tubing tension frame (ACTF) is used. This is a frame which is connected to the marine riser stack at the lower end and the topdrive at the top end. Hence the frame is heave compensated and does not move relative to the well. Winches installed in the ACTF lifts the equipment that shall be installed in the frame in place and there is therefore no movement between the ACTF and the equipment to be installed.

The BOP is installed in the bottom of the frame and an injector with strippers attached is installed on a level above the BOP. It is possible to skid the injector/stripper assembly forward, some vertical movement is also possible. Mostly the equipment in the ACTF is connected to the riser stack after the coil is in place to avoid relative movement between tower and ACTF during the coil installation. When CT is performed on a subsea well a surface flow tree is used as an upper barrier in addition to the BOB and strippers, this is placed on top of the rises stack. Reel, control cabin and power pack are placed on deck.

The total height of the injector used during an operation where one uses CiC is probably a bit lower than a traditional injector because the bend restrictor is probably smaller than the traditional gooseneck, but the design is too unclear to conclude that this will influence the risk a significant amount.

The operation is divided in steps found to be suitable at this stage of the design. Each work breakdown element has gotten a code on the format WBS (work breakdown structure).step in rig up (for example 2a).number of sup step. The codes defined in this subchapter are used to refer to the steps in the discussion in chapter 8.3. The complete results from the risk analysis are given in the appendix chapter 11.5.3.

Step 2a-Guide pipe and coil installation suggestion 2a *(CiC)*

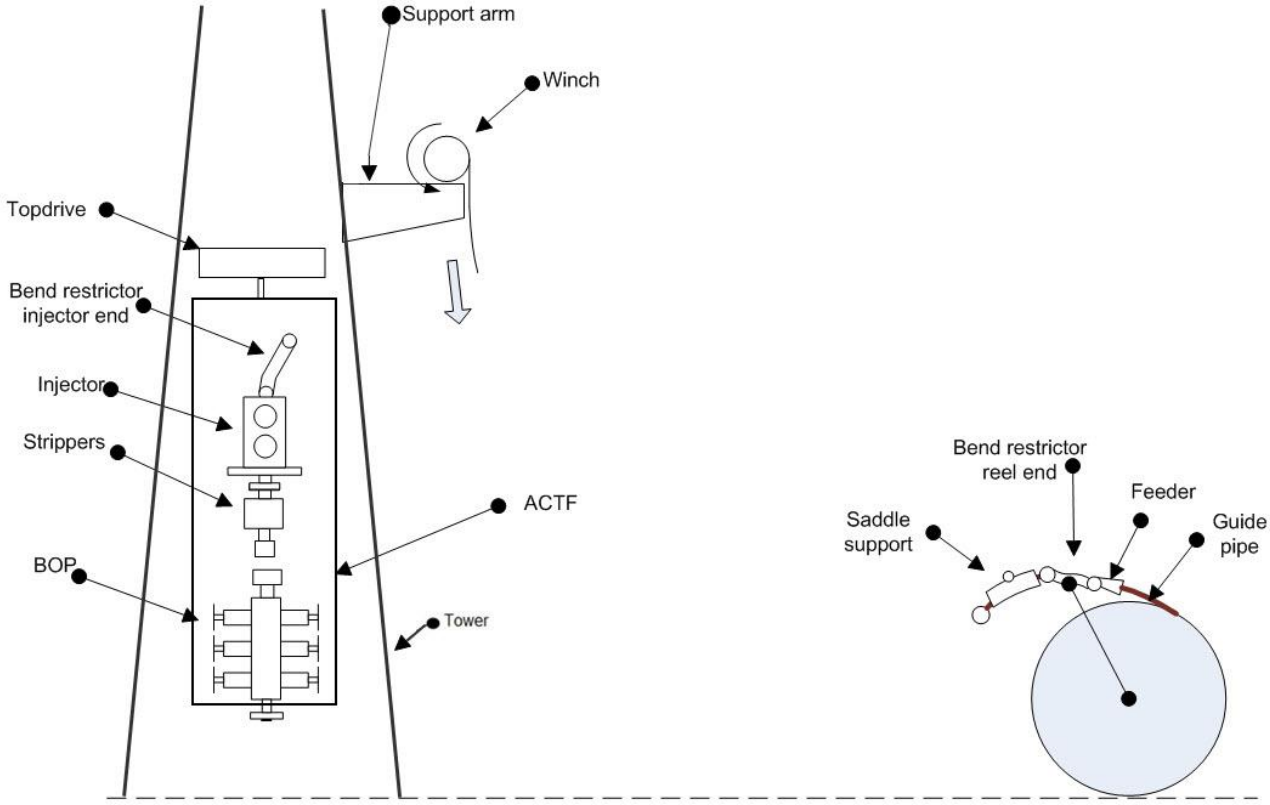


Fig 7.9 Start of guide pipe installation

The tower structure must contain a support arm that holds the guide pipe in a suitable loop. This part of the tower structure is assumed to serve a function also during rig up. The tower, ACTF and topdrive are illustrated in fig 7.9 to give an overview of the situation, but these elements are not shown in the following figures illustrating step 2a. The coil is assumed to be pre-installed inside the guide pipe and the guide pipe pre-installed through the feeder and bend restrictor onshore. The saddle support is assumed to be pre-installed and locked to the guide pipe as fig 7.9 illustrates.

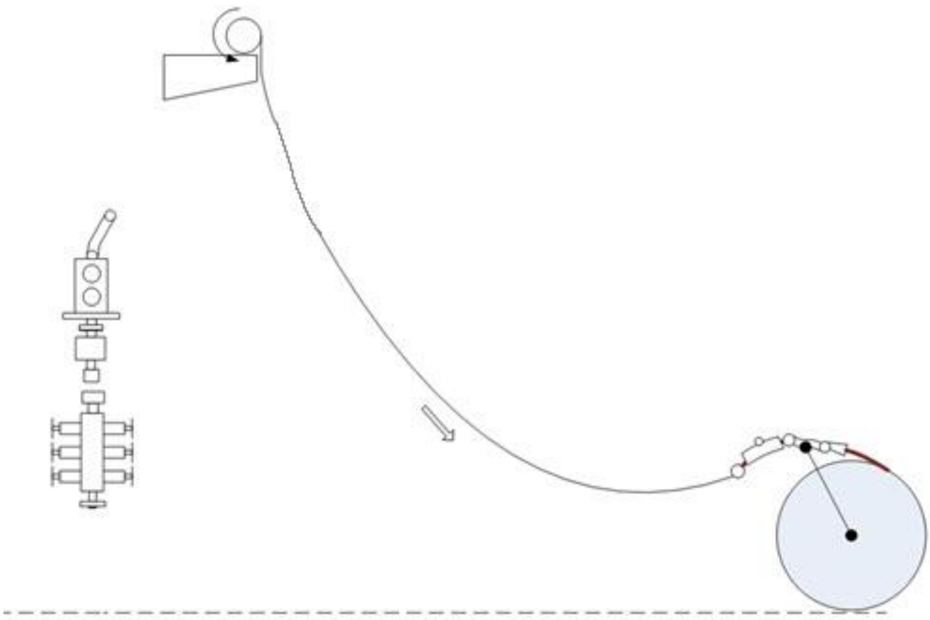


Fig 7.10 Lower wire and connect to guide pipe

WBS 2a.1: A wire is spooled from the support arm down towards the deck.
WBS 2a.2: As the wire reaches the deck it must be pulled towards the reel and attached to the guide pipe as shown in fig 7.10. To attach the wire, personnel probably have to work on a working platform more than 1m above solid ground (the working platform is not shown in the figure).

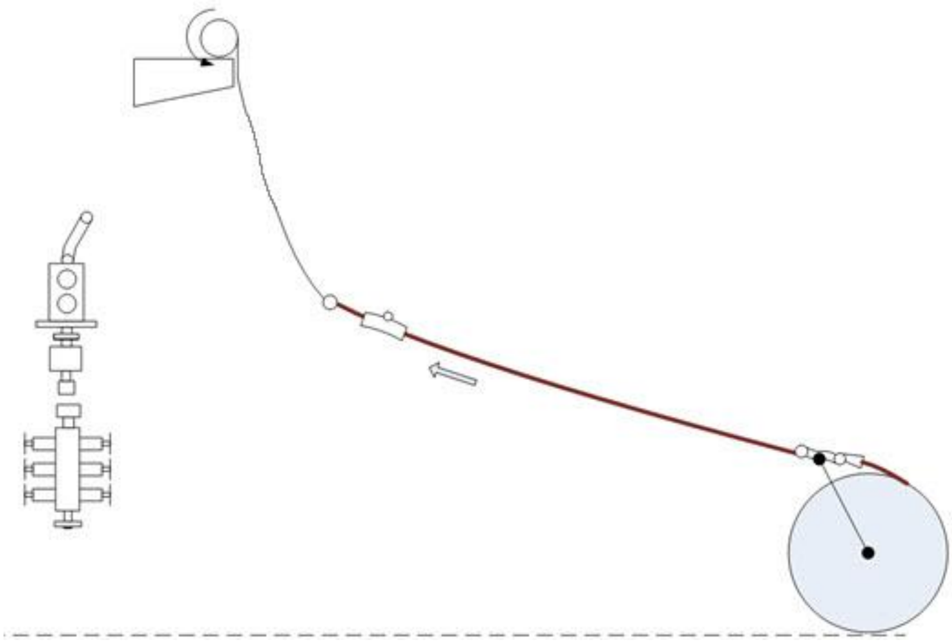


Fig 7.11 Pull the guide pipe upwards

WBS 2a.3: The wire then pulls the guide pipe upwards as fig 7.11 illustrates. The coil is located inside the guide pipe. A feeder could assist if necessary.

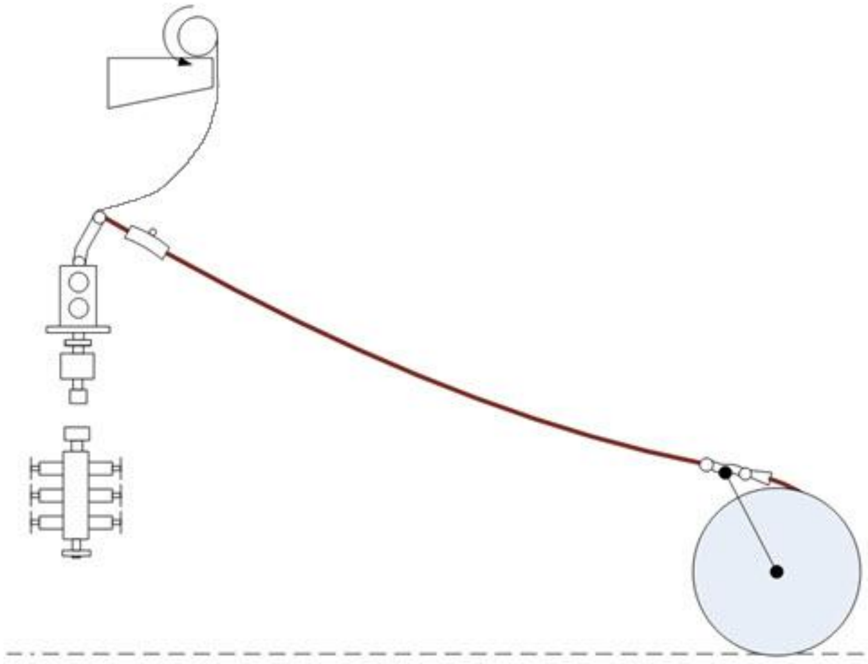


Fig 7.12 Connecting guide pipe

WBS 2a.4: The guide pipe is then connected to the upper bend restrictor as fig 7.12 illustrate. This operation will demand some manual interaction (hence access and working platform is needed (not shown in the figure)).

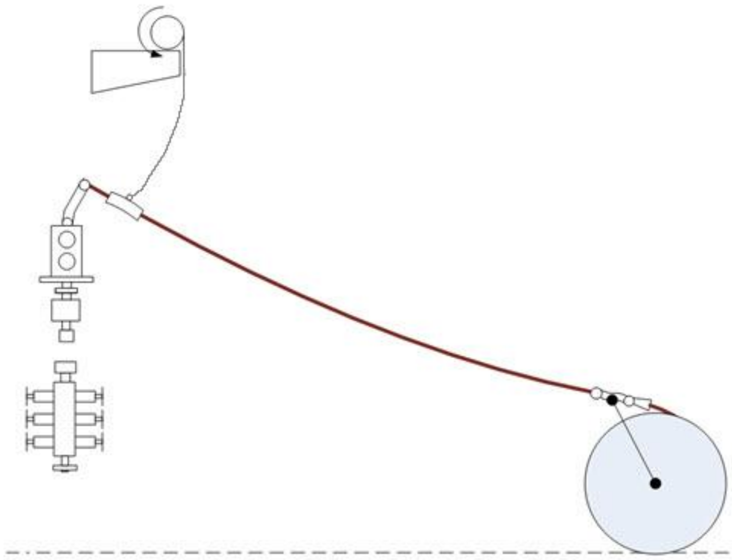


Fig 7.13 Connect saddle support to structure

WBS 2a.5: The saddle support has to be connected to the tower structure. Some heave compensation might be needed in this connection to let the saddle support move to some extent with the vessel motions. In fig 7.13 (and figures to come) the winch is used directly; if there is need for some heave compensating link between the saddle support and tower structure the installation of this element has to be considered. This operation will demand some manual interaction (hence access and working platform is needed).

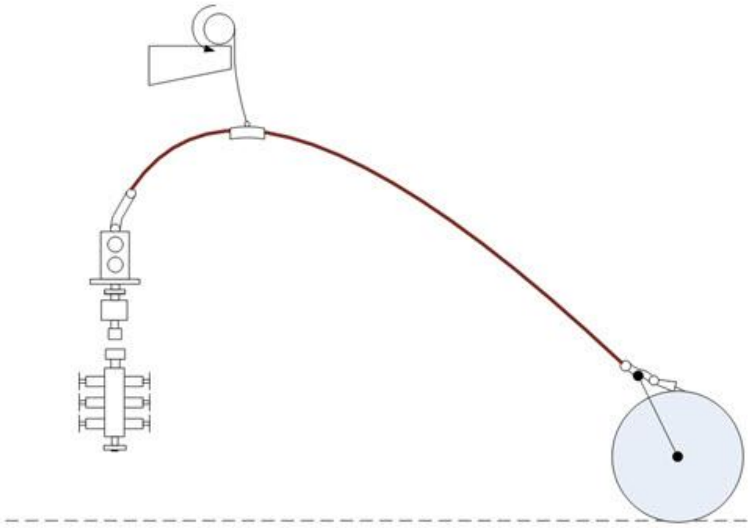


Fig 7.14 Release saddle support, raise guide pipe and lock bend restrictors

WBS 2a.6: The saddle support locking mechanism must be released.
WBS 2a.7: The winch pulls the guide pipe in position as fig 7.14 illustrates.
WBS 2a.8: When the guide pipe reaches the correct position the bend restrictors probably need to be “locked”. There is need for some flexibility from the bend restrictors also in the “locked” position, but probably less than during rig up.

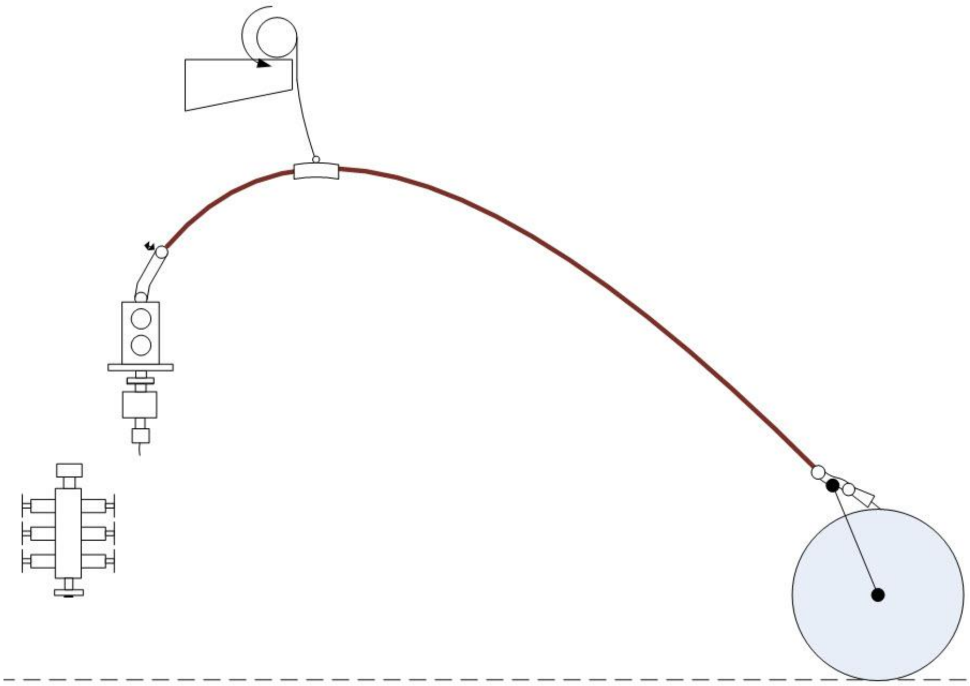


Fig 7.15 Feeding coil

WBS 2a.9: The coil has been inside the guide pipe through the entire guide pipe installation. It must be fed the last distance through the injector and strippers as shown in fig 7.15. As the coil enters the injector the injector could assist in pulling the coil. The coil is then locked with the injector.

Step 2b- Guide pipe and coil installation suggestion 2b (CiC)

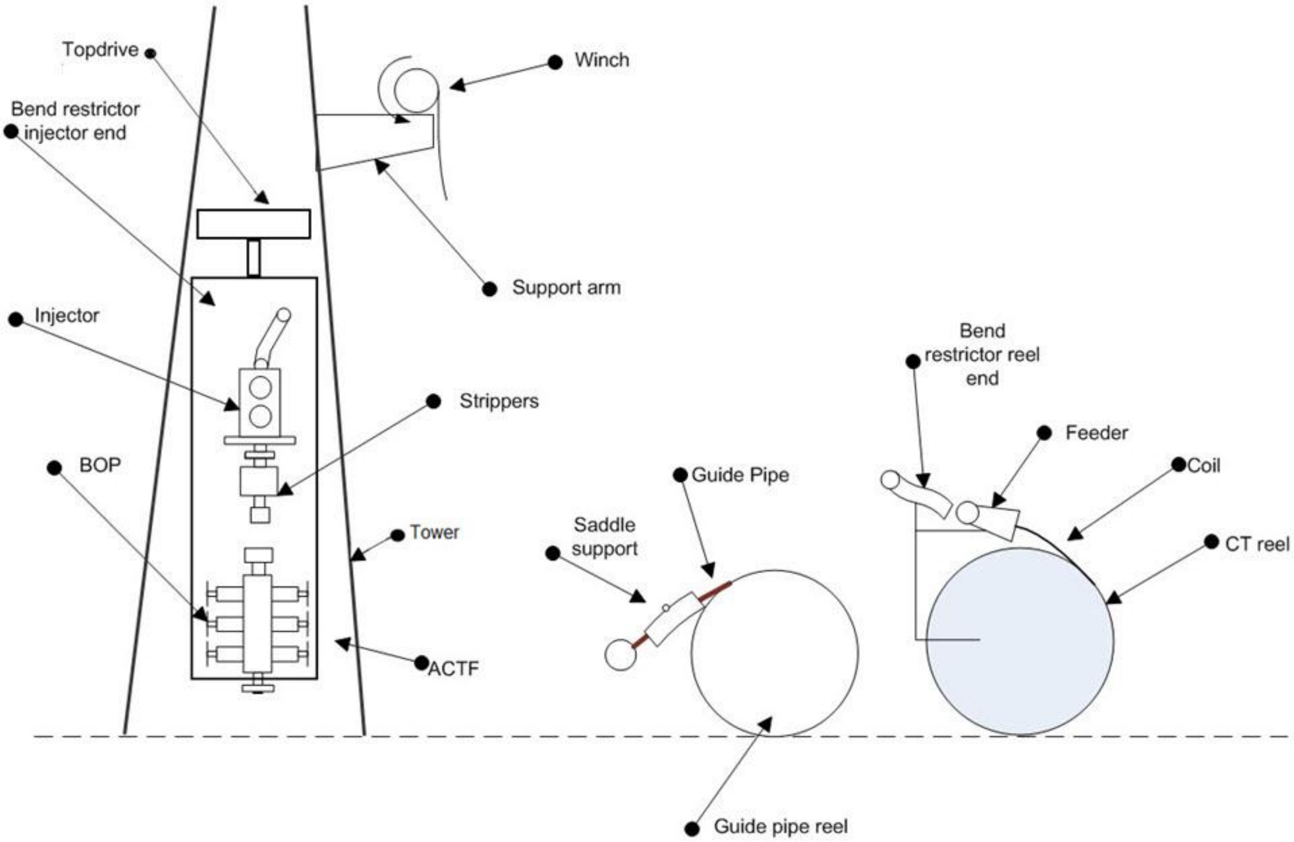


Fig 7.16 Start of guide pipe installation, separate guide pipe reel

Fig 7.16 illustrates the start of an alternative rig up of the guide pipe. The tower, ACTF and topdrive are illustrated in fig 7.16 to give an overview of the situation, but these elements are not shown in the following figures illustrating step 2b. In this case the coil and guide pipe are provided on different reels and the coil has to be feed or pulled through the entire guide pipe offshore.

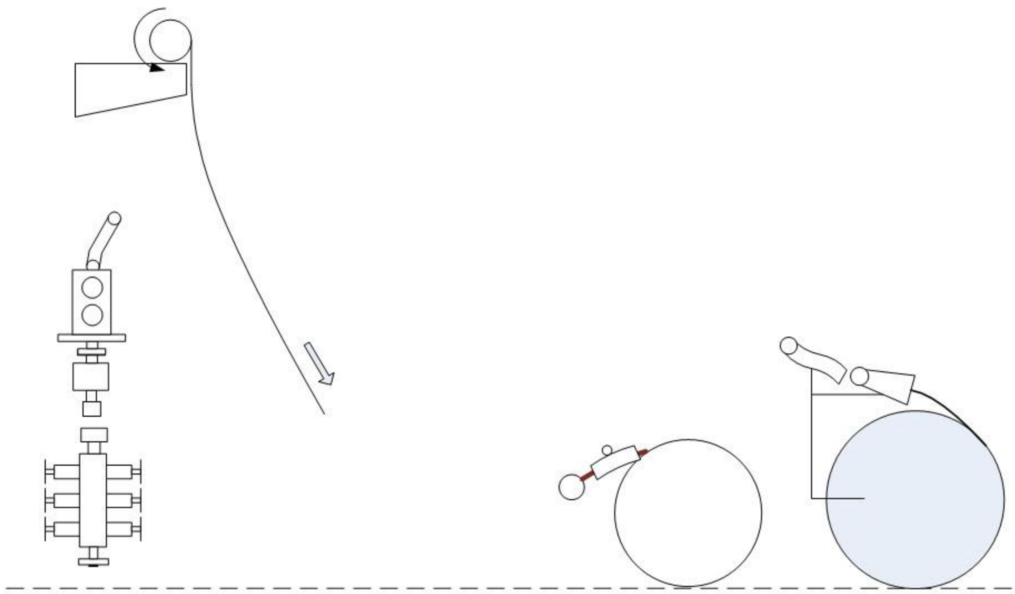


Fig 7.17 Lowering wire

WBS 2b.1: The wire is lowered from the support arm and pulled against the guide pipe reel as it reaches the ground as shown in fig 7.17.

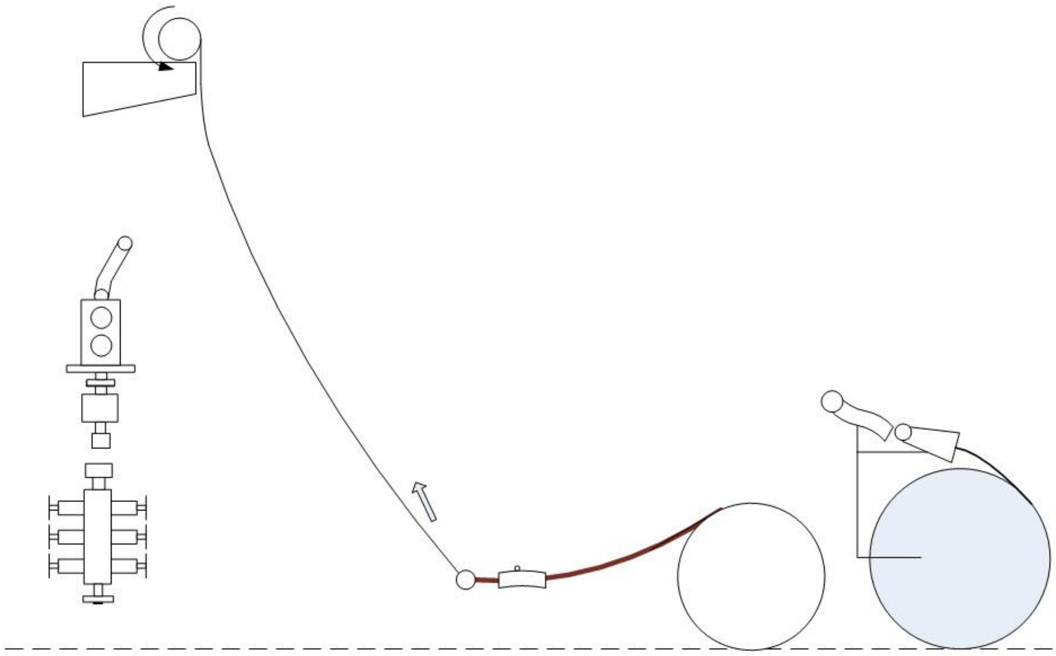


Fig 7.18 Connect to guide pipe and raise

WBS 2b.2: The wire is connected to the guide pipe; first assumption is that the guide pipe reel can be adapted so that work on ground level is possible.
WBS 2b.3: The guide pipe is then pulled by the winch upwards towards the injector as illustrated in fig 7.18.

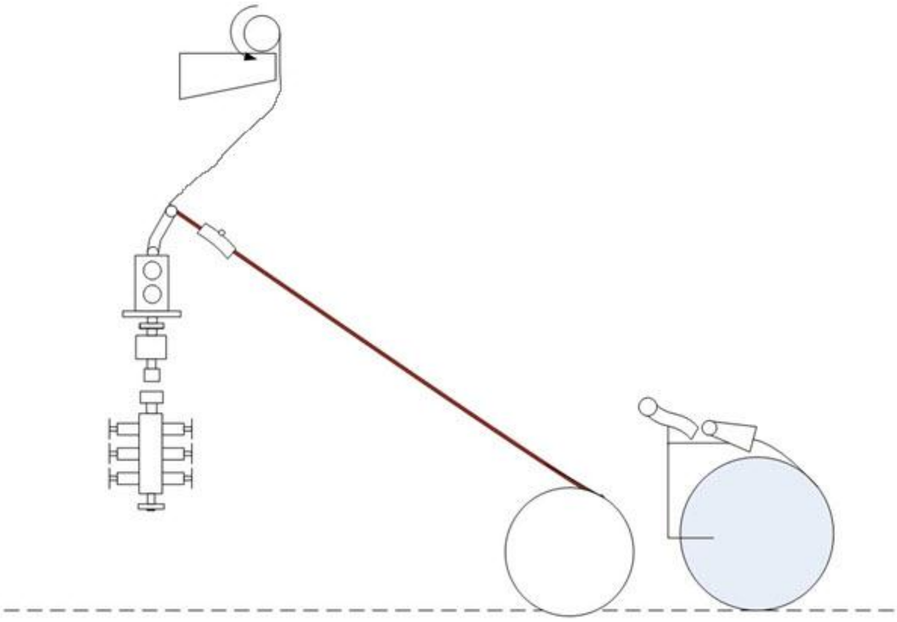


Fig 7.19 Connect to upper bend restrictor

WBS 2b.4: The guide pipe is connected to the upper bend restrictor as shown in fig 7.19. This operation will demand some manual interaction (hence access and working platform is needed (not shown)).

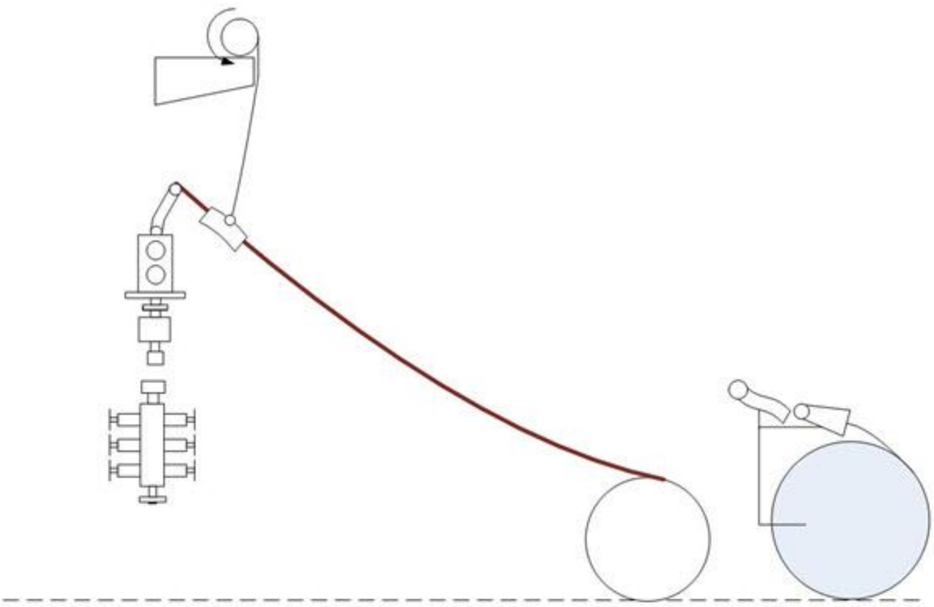


Fig 7.20 Connecting wire to saddle support

WBS 2b.5: The wire is released and connected to the pre-installed saddle support as illustrated in fig 7.20. This operation will demand some manual interaction (hence access and working platform is needed (not shown)).

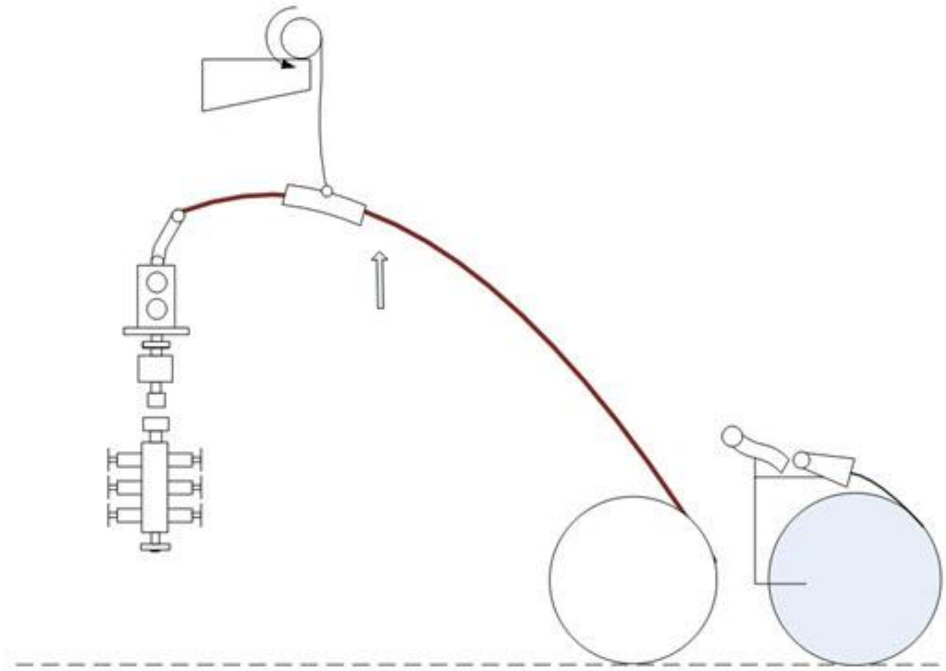


Fig 7.21 Raising guide pipe

WBS 2b.6: Release saddle support lock-mechanism.
WBS 2b.7: The guide pipe is raised further helped by the saddle support as illustrated in fig 7.21.

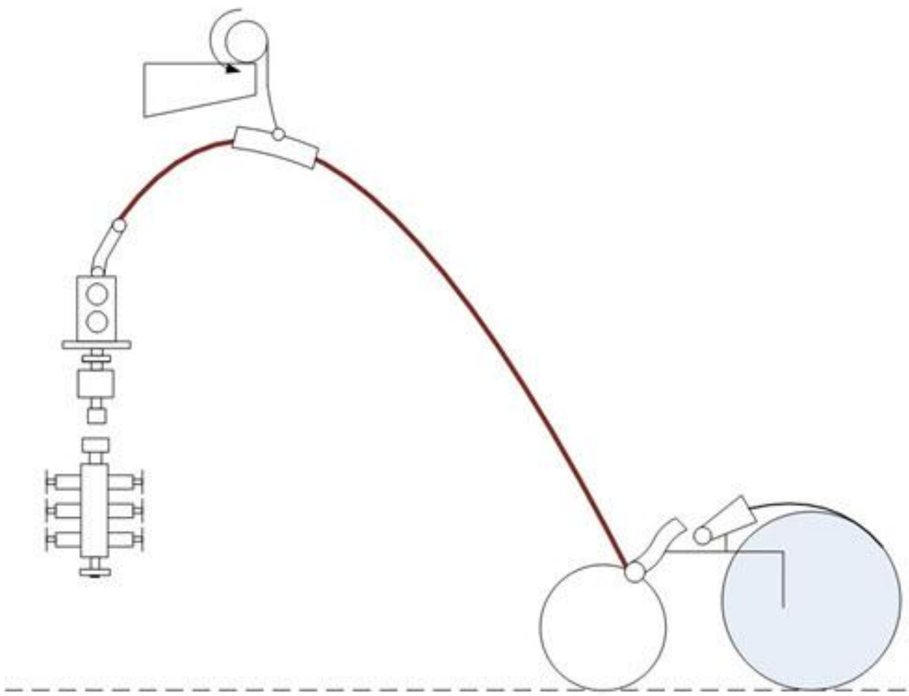


Fig 7.22 Connect to bend restrictor reel end

WBS 2b.8: When the complete guide pipe length is reeled off, the lower bend restrictor can be connected to the guide pipe. Some movement of components on the coil reel is assumed to be needed as illustrated in fig 7.22.

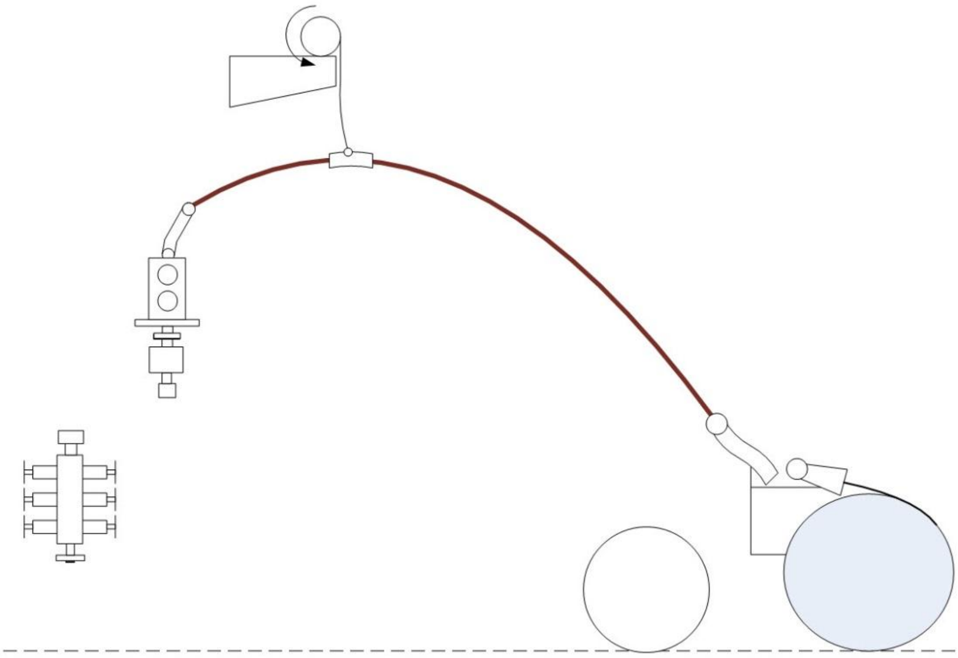


Fig 7.23 Aligning

WBS 2b.9: Necessary alignment to end up as illustrated in fig 7.23

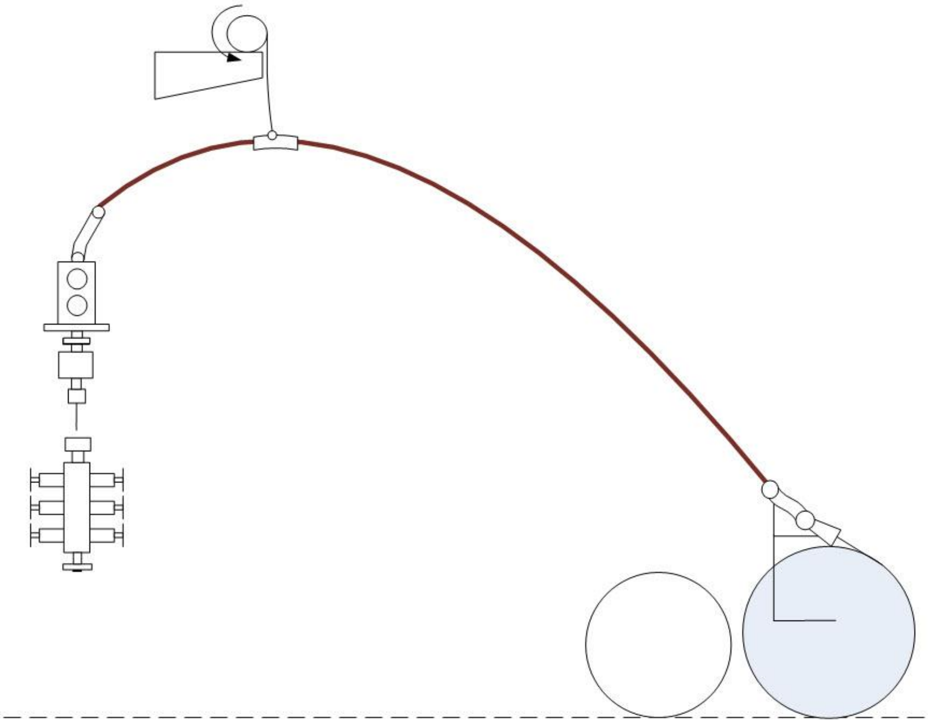


Fig 7.24 Feeding the coil

WBS 2b.10: Then the feeder can be connected and the coil fed through guide pipe, bend restrictor and injector. The injector runs the CT the last distance through the strippers before holding the coil in place as illustrated in fig 7.24.

Step 2c- Traditional coil installation 2c (TR)

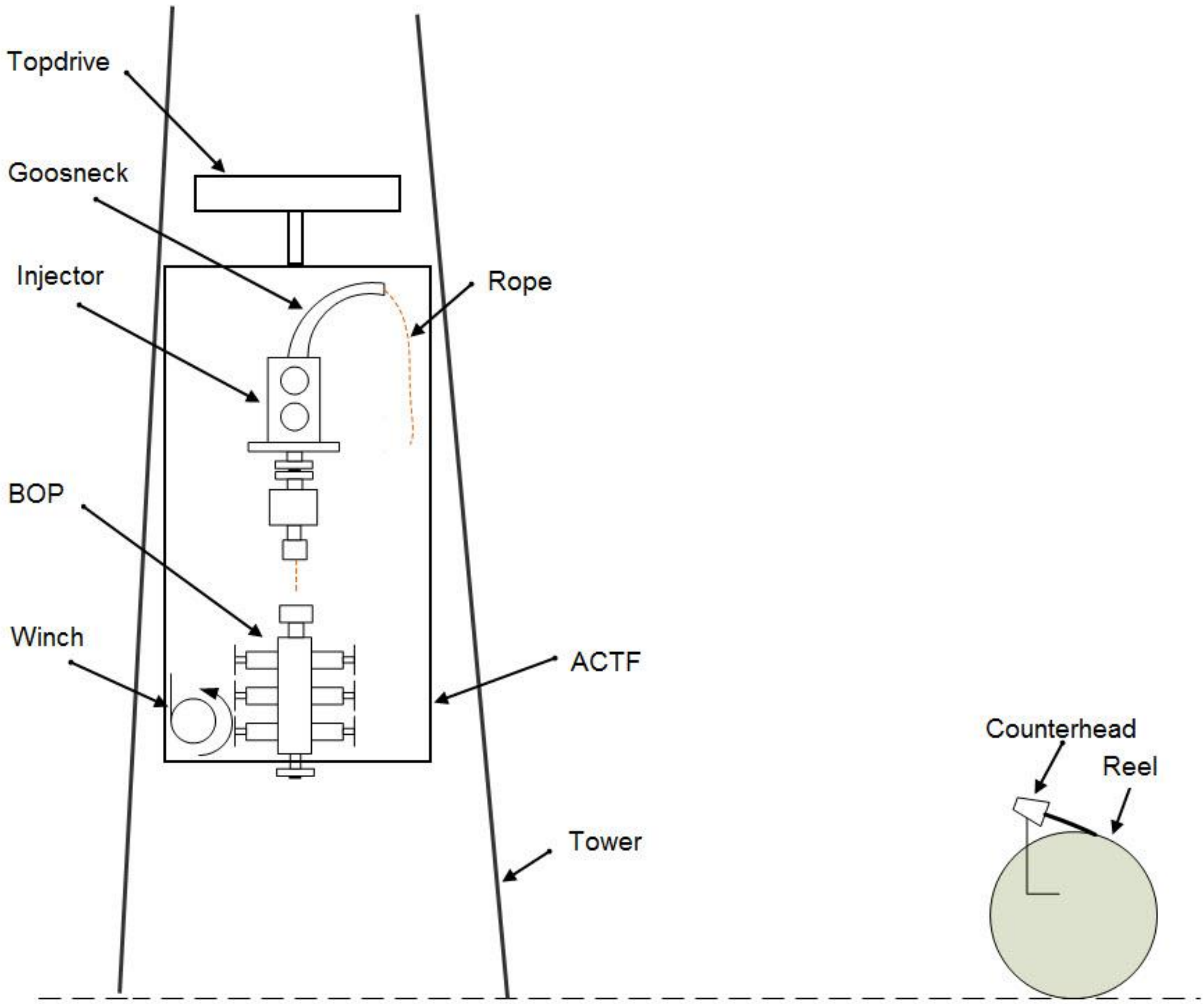


Fig 7.25 Start of Traditional rig up

A winch is located on the BOB platform under the injector. A rope should be pre-installed as illustrated in fig 7.25. Normally no feeder is used.

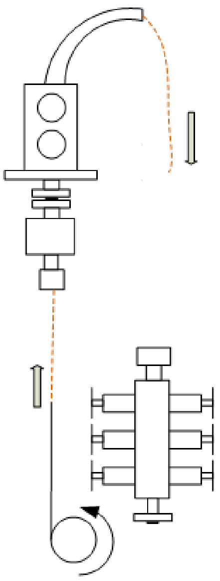
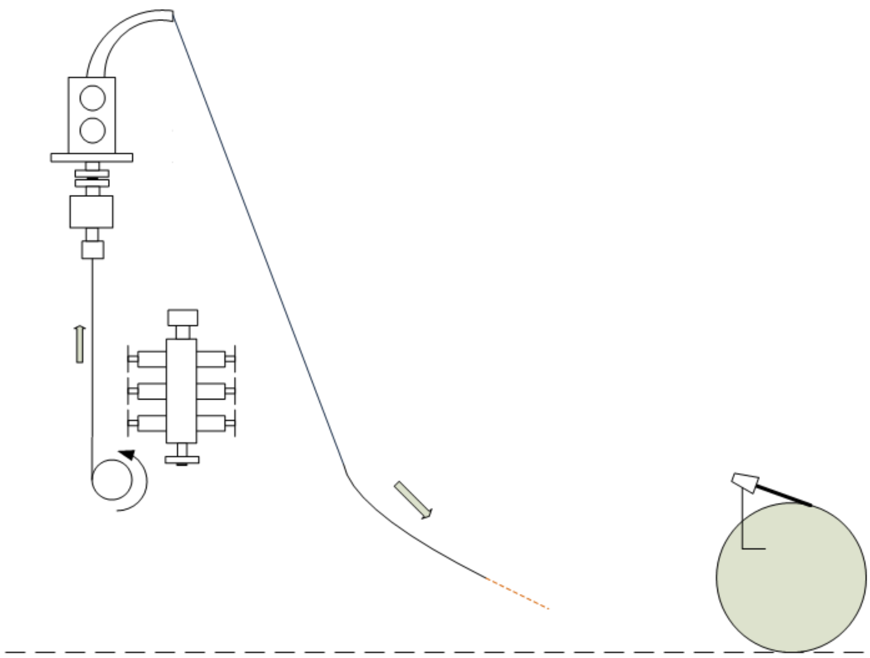


Fig 7.26 Tread wire

WBS 2c.1: A wire from the winch is pulled through the strippers, injector and over the gooseneck with a rope as illustrated in fig 7.26.



7.27 Spool off wire

WBS 2c.2: The wire is spooled off; the wire has to be pulled towards the reel until there is enough length to reach the coil on the reel as shown in fig 7.27. The coil end is located more than 1m off the ground, hence to connect the wire to the coil end one has to work on an elevated working platform (not shown).

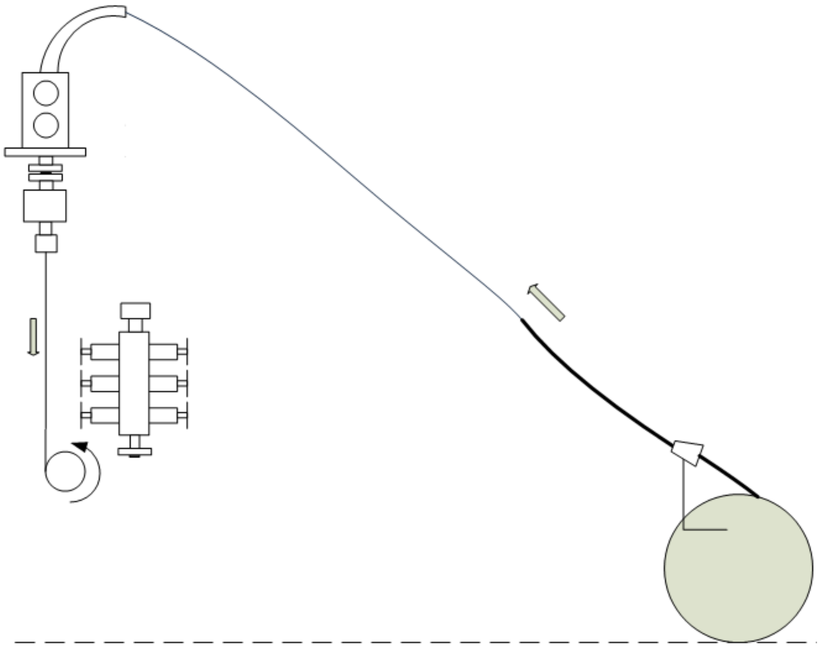


Fig 7.28 Connect wire to coil and retrieve coil

WBS 2c.3: Connect the wire to the coil end.
WBS 2c.4: Pull coil towards the injector as illustrated in fig 7.28.

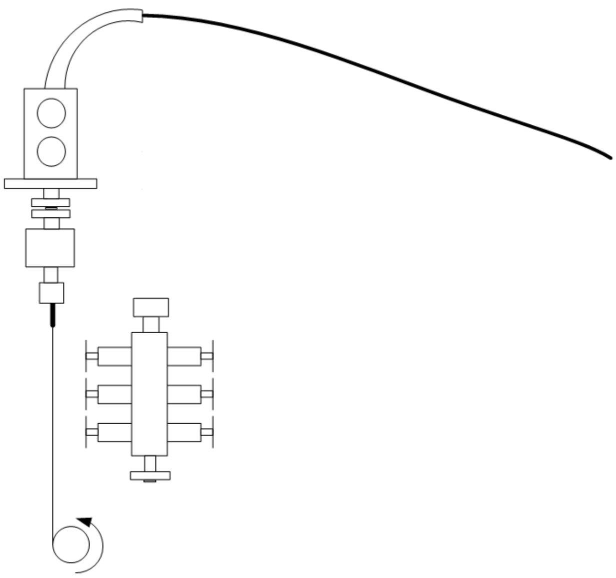


Fig 7.29 Coil in place

The winch pulls the coil over the gooseneck and down through the injector. The injector runs the CT the last distance through the strippers before holding the coil in place as illustrated in fig 7.29.

Step 2d- Guide pipe and coil installation suggestion after first round of risk analysis 2d (CiC)

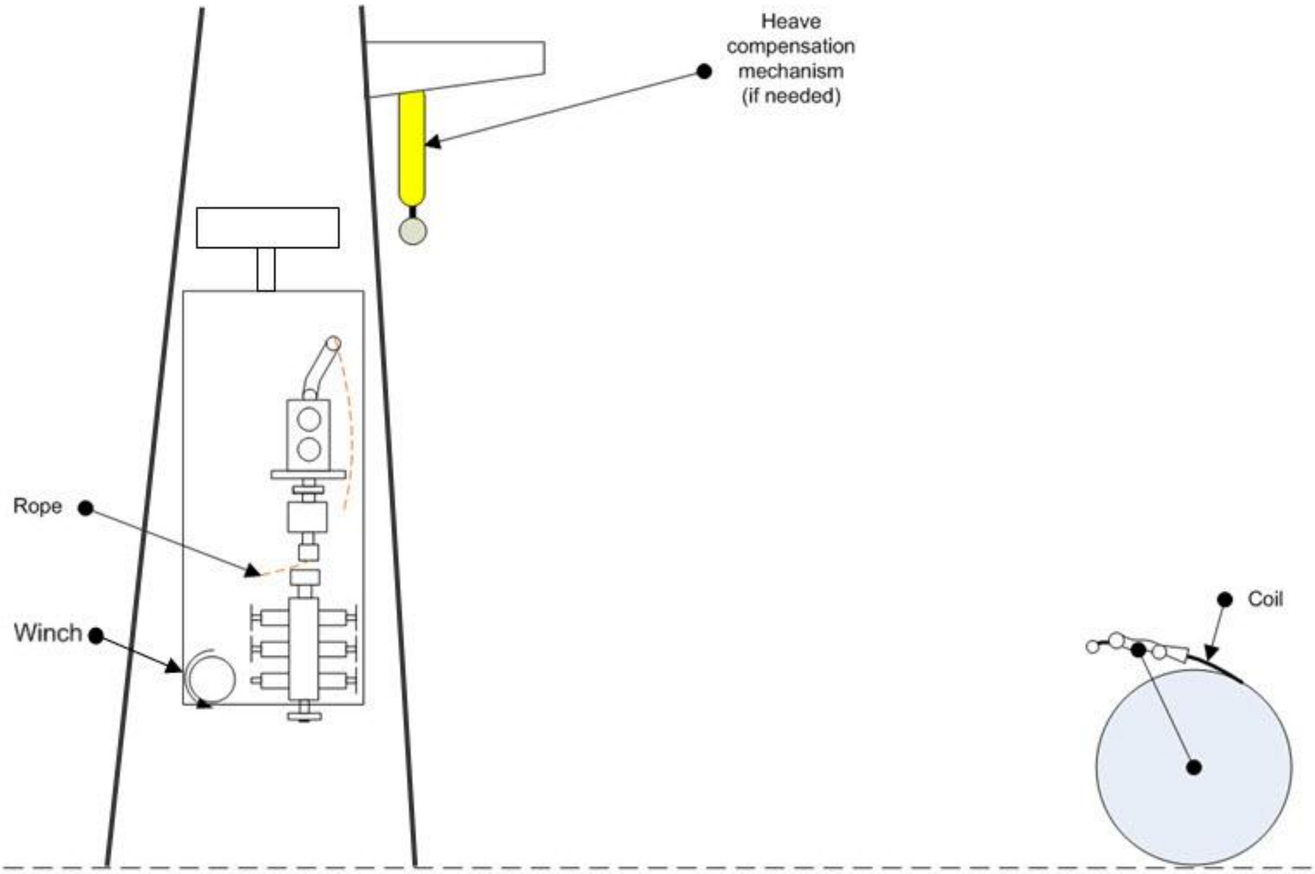


Fig 7.30 Start of guide pipe installation

Fig 7.30 illustrates how the components are located in the 2d way of installing coil and guide pipe, only the differences from the earlier guide pipe installation steps (2a and 2b) are pointed out. The feeder is included in the illustrations, but if everything works smoothly its function might not be needed. If it can be removed in the next rig up suggestion must be evaluated.

The differences are:
- the winch used under traditional coil installation is used (replaced with one with increased capacity if necessary), this winch is located in the bottom of the ACTF
-a rope is pre-installed in the injector as done in the traditional way of installing coil
-the first meters on the reel is coil, after a set length of coil is spooled off the guide pipe will appear
-the saddle support is not preinstalled, this will be illustrated further in a later figure
-the support arm in the tower structure contain a mechanism that is adapted to this way of rigging, if it must be able to heave compensate during operation is not yet known

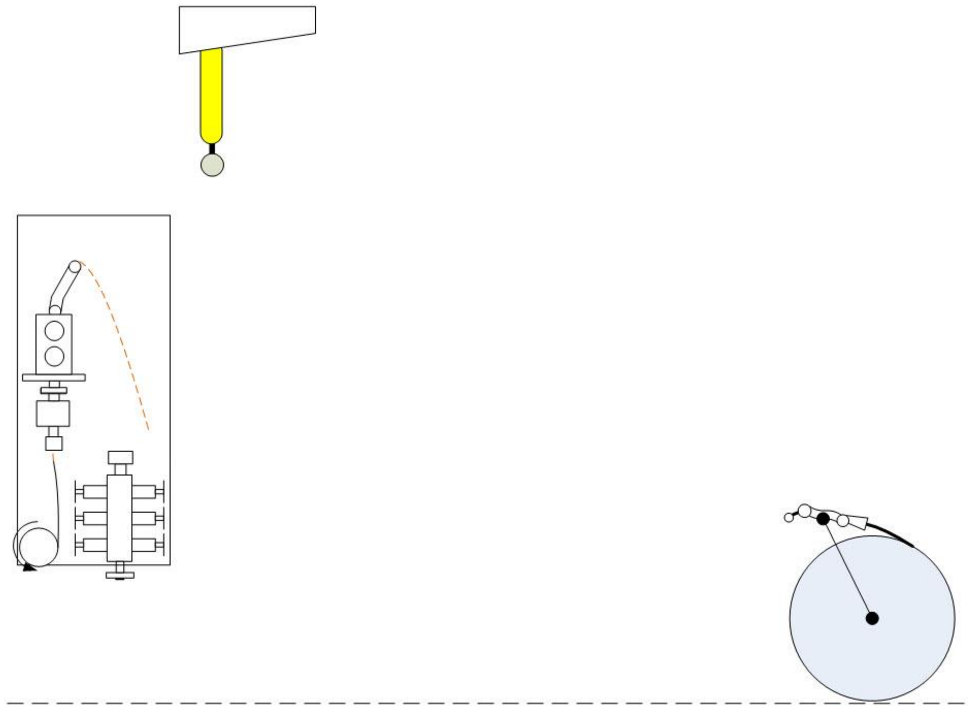


Fig 7.31 Pulling wire through injector assembly

WBS 2d.1: A wire from the winch is pulled through the strippers, injector and over the gooseneck with a rope (that should be pre-installed) as illustrated in fig 7.31.

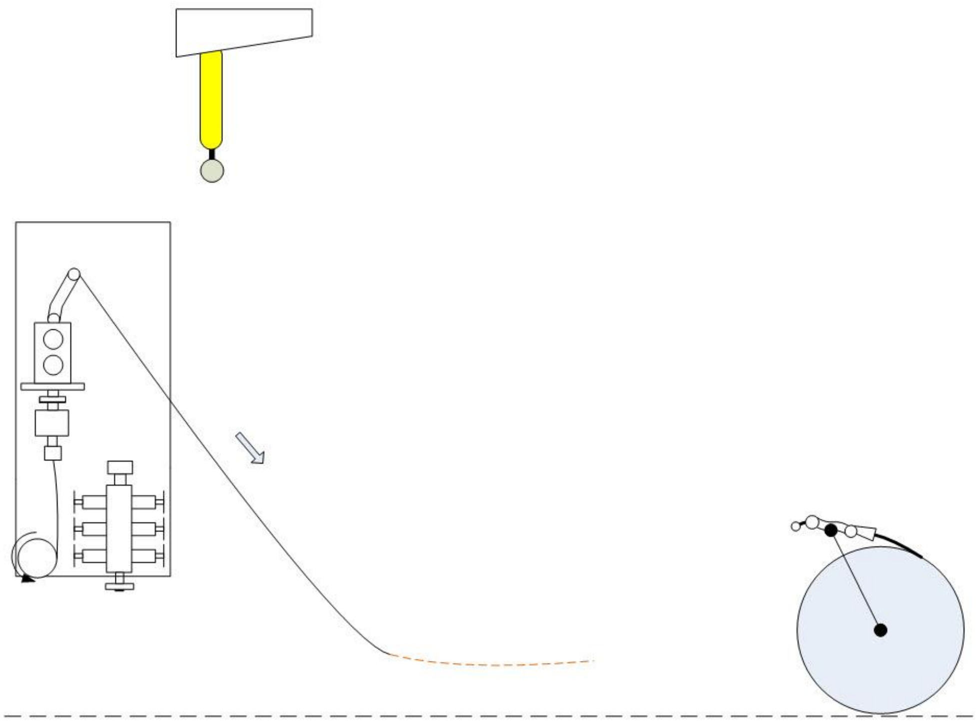


Fig 7.32 Lowering wire and pulling towards reel

WBS 2d.2: The wire is spooled off until it reaches the ground; then the wire has to be pulled towards the reel as shown in fig 7.32.

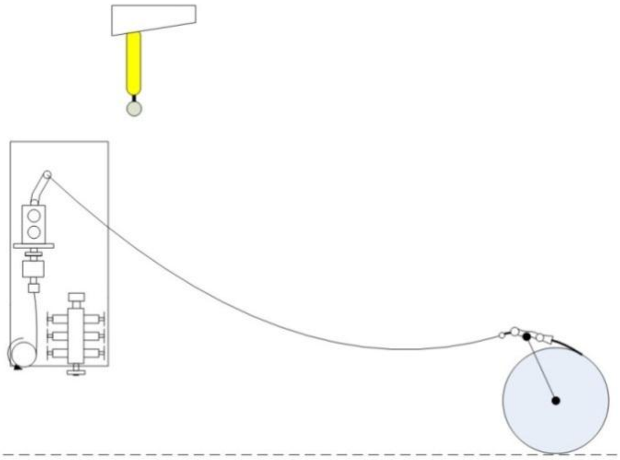


Fig 7.33 Connect wire and coil

WBS 2d.3: Connect the wire to the coil end as illustrated in fig 7.33. The coil end is located more than 1m off the ground, hence to connect the wire to the coil end one has to work on an elevated working platform (not shown).

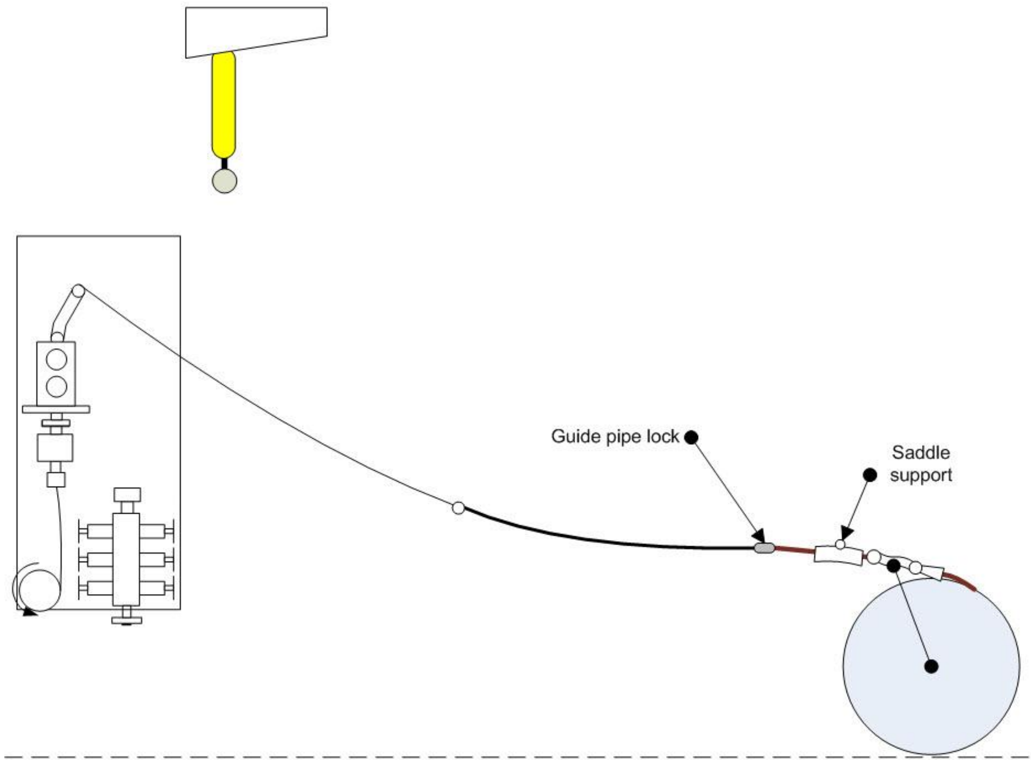
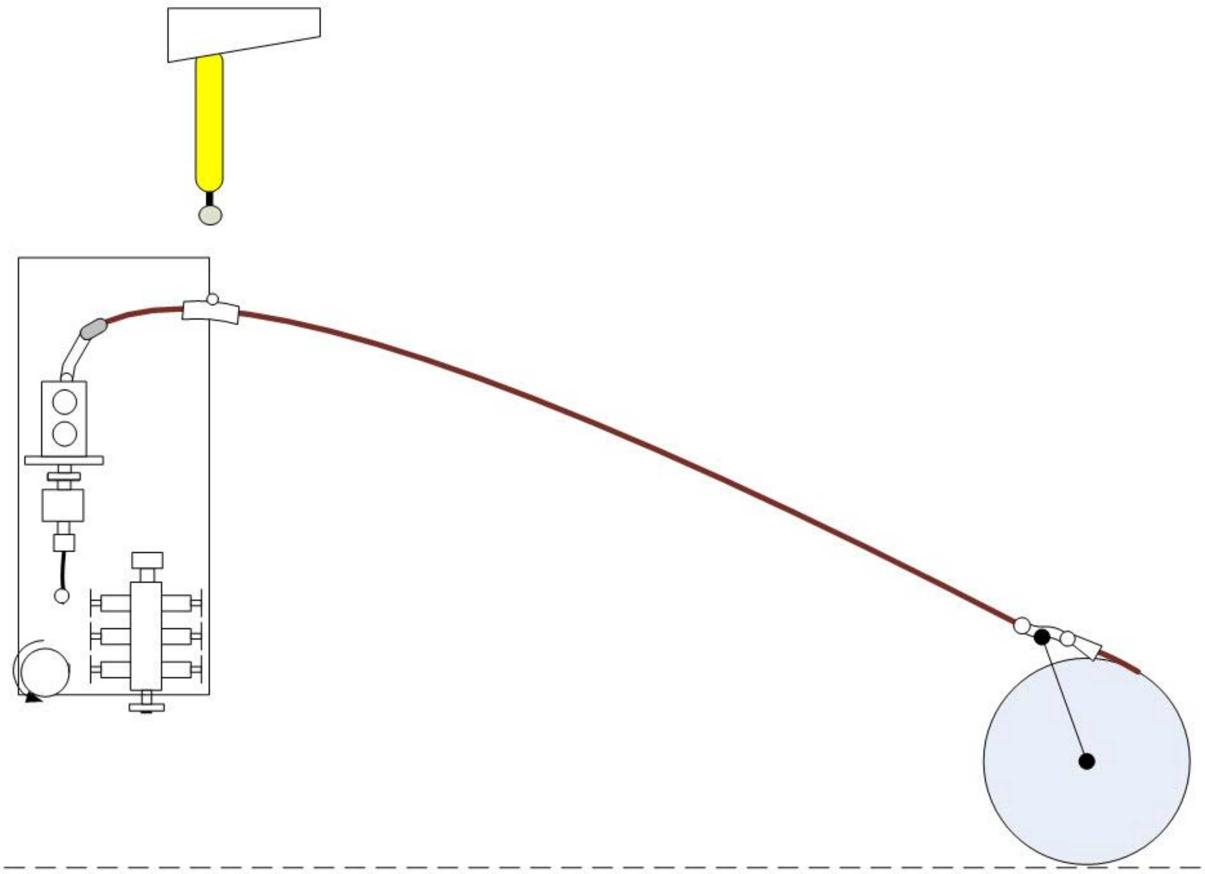


Fig 7.34 Retrieving coil/guide pipe and installing saddle support

The coil is tread inside and locked against the guide pipe in a suitable position onshore.

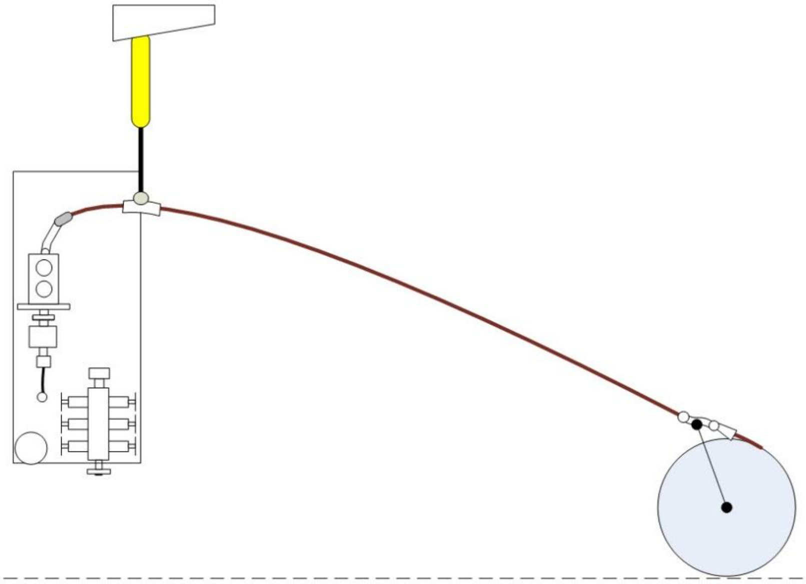
WBS 2d.4: The coil is pulled towards the injector as illustrated in fig 7.34. After a set length of coil is spooled off the guide pipe will appear.
WBS 2d.5: The saddle support must be installed to the guide pipe before the coil/guide pipe can be pulled further (work on an elevated working platform (not shown)).



7.35 Guide pipe locked to upper bend restrictor

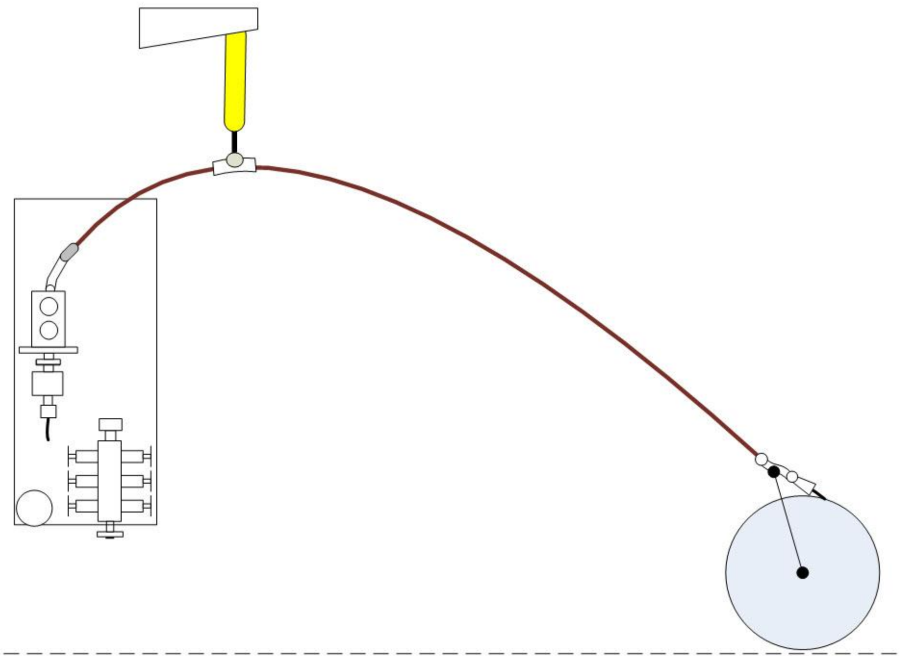
The length of coil is adapted so that the guide pipe lock has reached the upper bend restrictor as the coil is pulled through the injector and strippers as shown in fig 7.35.

WBS 2d.6: The injector pulls the coil the final piece through the strippers (as done in traditional coil rigging) as the guide pipe lock is pulled towards the upper bend restrictor it releases the coil (now secured by the injector) and locks to the bend restrictor.



7.36 Connect saddle support to tower

WBS 2d.7: Saddle support is connected to the tower as illustrated in fig 7.36.
WBS 2d.8: As the saddle support is secured the lock to the guide pipe can be released.



7.37 Complete guide pipe spooled out and guide pipe reel end locked inside bend restrictor

WBS 2d.9: The last guide pipe length is spooled off, helped by the mechanism in the tower (and feeder if necessary) as illustrated in fig 7.37.
WBS 2d.10: As the lower guide pipe end is pulled against the bend restrictor on the reel the guide pipe end is locked in place inside the bend restrictor.

Step 3-Insert tool (both TR and CiC)

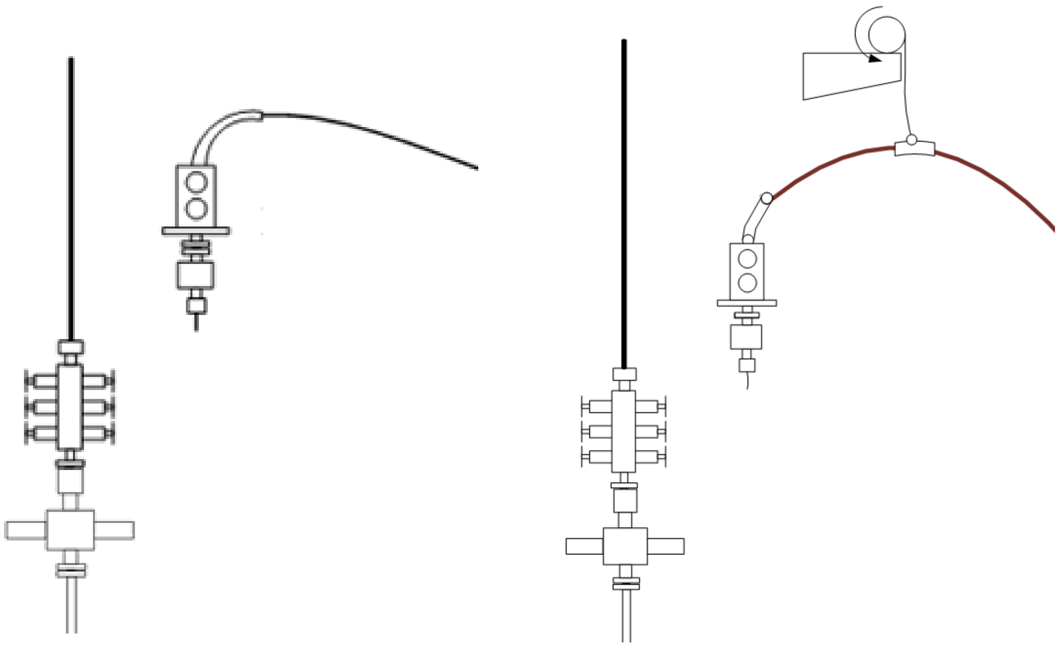


Fig 7.38 Insert tool

The BOB is connected to the riser stack, at the top of the riser stack sits the surface flow tree (SFT) which is illustrated in fig 7.38. The tool enters as shown. The tool is "hung of" in the BOB.

Step 4-Connect coil and tool (both TR and CiC)

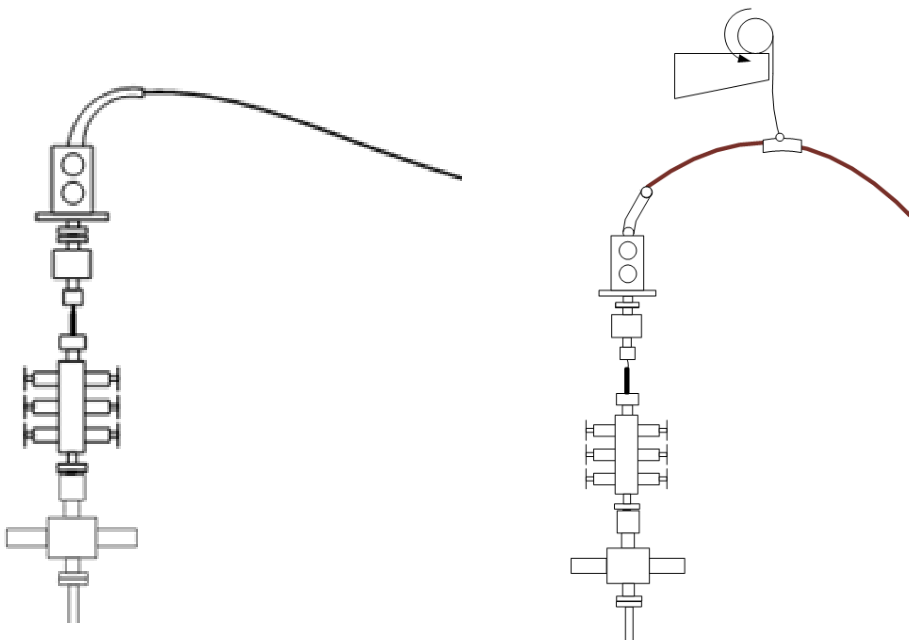


Fig 7.39 Connect coil and tool

Connect coil and tool as shown in fig 7.39.

Step 5-Run tests (both TR and CiC)

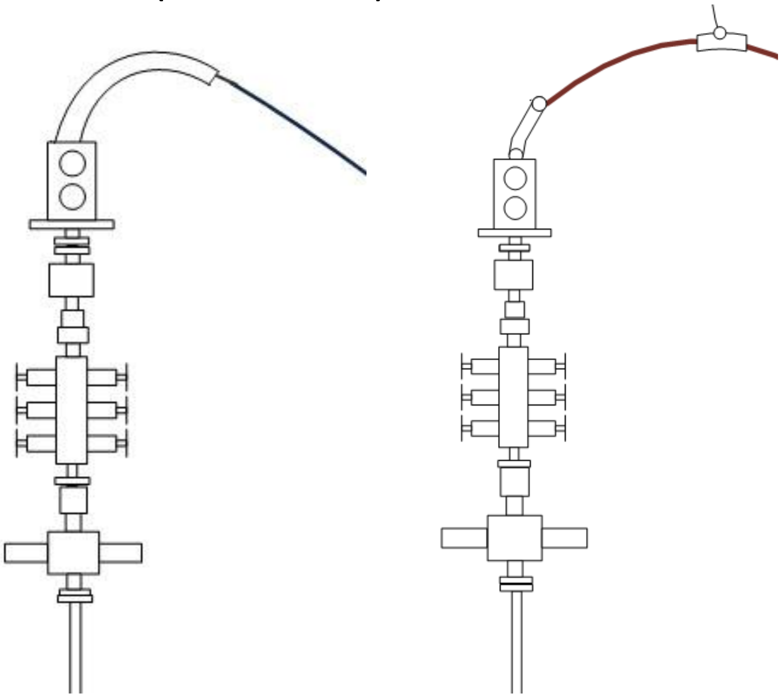


Fig 7.40 Prepare for operation

Connect strippers and BOB, as illustrated in fig 7.38, run tests to make sure it is safe to pressurize.

Step 6-Operation

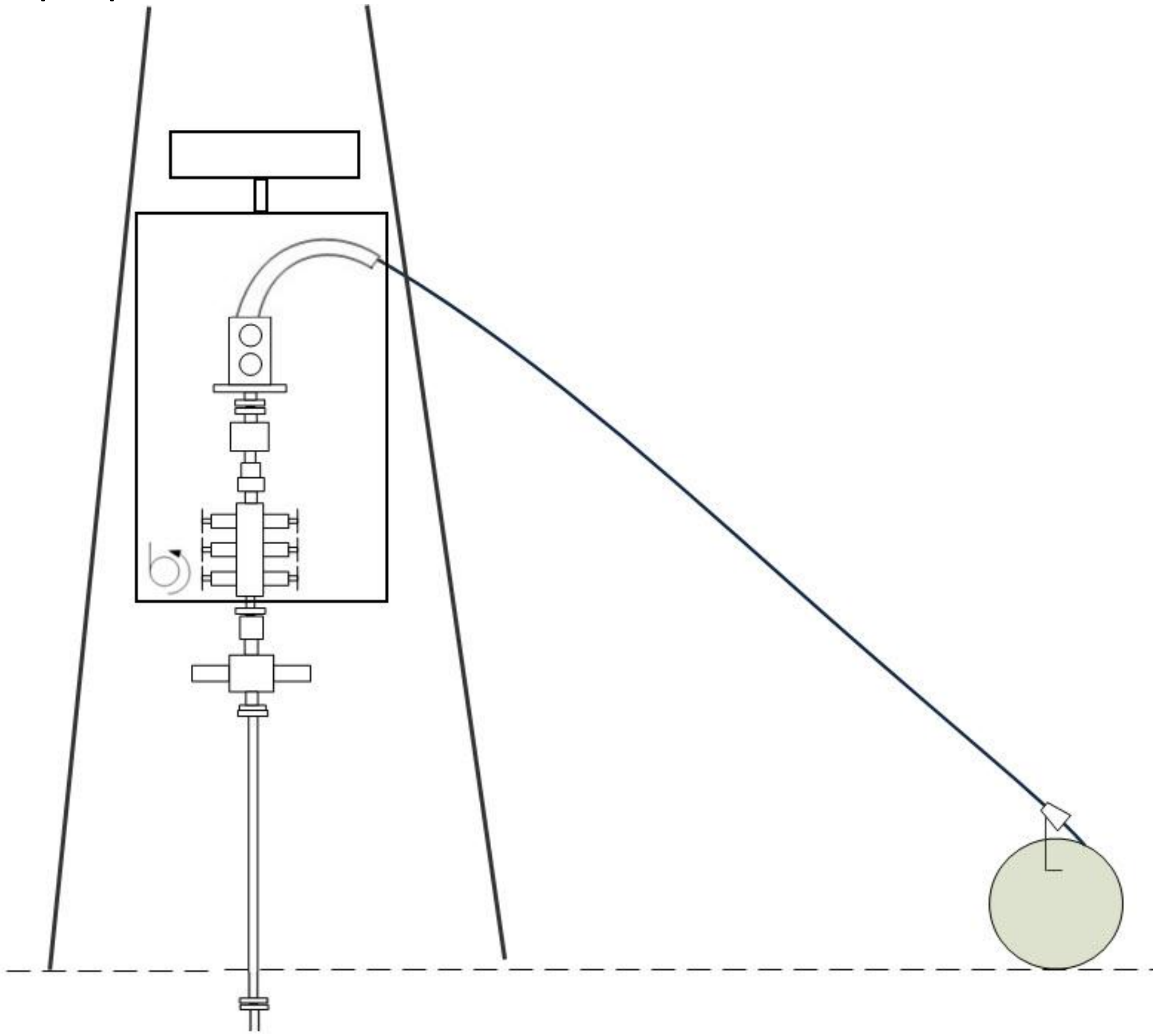


Fig 7.41 Operation with traditional gooseneck

WBS 6.1TR: The reel is placed on the deck of the vessel without any form of heave compensating, hence it moves with the vessel. The equipment mounted in the frame inside the tower is heave compensated and does not move relative to the seafloor. If the reel moves up relative to the injector faster than coil is run down in the well, the reel spools the excess coil back on the reel to keep constant tension in the coil (see fig 7.41).

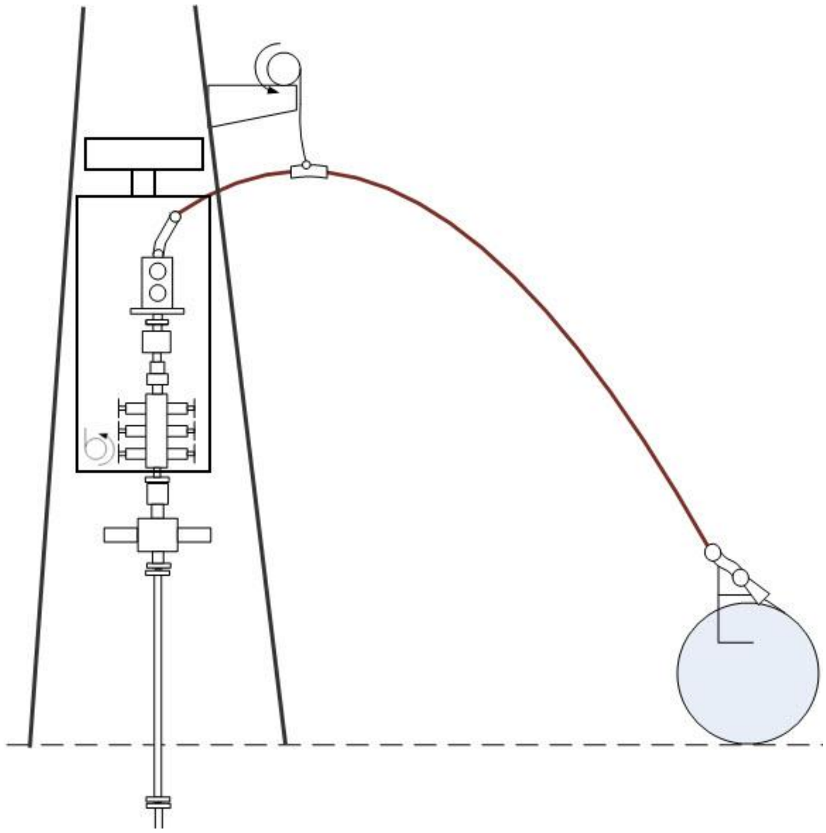


Fig 7.42 Operation with coil in coil

WBS 6.1CiC: The reel is placed on the deck of the vessel without any form of heave compensating, hence the reel moves with the vessel. The equipment mounted in the frame in the tower is heave compensated and does not move relative to the seafloor. When the reel moves up (away from the seafloor) faster than the excess coil in run down in the well, the guide pipe compensate for this by changing its loop to a greater radius. When the reel moves down the guide pipe decreases its radius. The saddle support supports the guide pipe. The hang off point might have to allow for some movement to make the situation for guide pipe and coil more optimal. The result is constant tension in the coil without spooling coil on and off the reel. See figs 7.42 and 8.1.

Step 7-End operation (both TR and CiC)

The coil and tool is pulled out of the well by the injector. Pressure in the upper section is then bleed off with the upper barrier (SFT), closed. Tests are run to check that it is safe to disconnect before coil and tool are disconnected as shown in fig 7.39 and the tool is removed as in fig 7.38.

Rigging down is assumed to be done in close to a reverse direction of the rig up steps and new hazards are not expected to be revealed at this stage of the design, the rig down is therefore not evaluated in this round. It is recommended to also review the rig down sequence at a later stage when the design is clearer.

8 Evaluation of Consepts

8.1 Material Evaluation

A steel pipe with an inner polymer glide layer is evaluated to be most promising candidate for the guide pipe.

Steel pipe coiled up on reels are widely available; hence suitable standard dimensions provided in required length with the required properties can be provided cheap and fast compared to the other possible options. Steel also possess the most known behavior under the expected load conditions. The steel pipe would give the required “safety shell” and stiffness needed for the principle to function satisfactory and limit the polymer deformation.

Polymer coating or an inner polymer glide pipe will reduce the force needed to pull the coil through the guide pipe and limit coil damage. The most promising polymer candidate found is a 70-80% PTFE and 20-30% PEEK composite. This composite had a COF of under 0.15 against steel, which would minimize the force needed to pull the coil through the guide pipe without lubricant. Material volume lost after a sliding distance of as much as 100km was very low and elongation before break was over 250%.

The surface roughness of the coil is probably rougher than in the steel used in the experiment by Burris and Sawyer (2005) and presence of impurities is likely, this are sources of uncertainty, but as the sliding distance is much shorter for a coil operation than in the experiment (5-15km vs. 100km) the results indicate that PTFE-PEEK could be a promising candidate. The test load was found to be high, which is probably better than a too low test load, but this is also a source of uncertainty. Extensive testing of coil wear against different polymer composites will be needed to check the hypothesis and select the qualified material.

8.2 Bennefits Evaluation

Guide pipe behavior depends on many factors:
-shape, size and stiffness of saddle support
-placement and size of the support arm
- if the saddle support is heave compensated , how and how much
-the properties of the guide pipe, the coil inside and how their properties correlate
- vessel movements and other environmental loads
-horizontal and vertical distance to reel

As many of the factors are completely or partly unknown the shape of the guide pipe is guesstimated after best knowledge in this first evaluation of a simplified case.

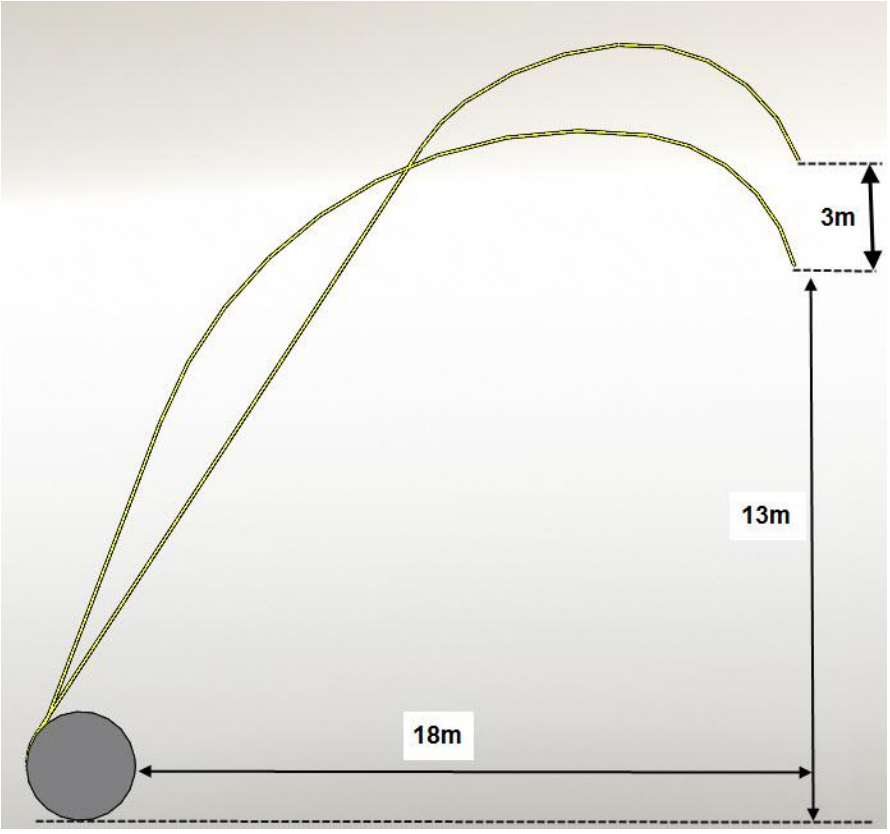


Fig 8.1 Illustration of possible guide pipe behavior

How the guide pipe is guesstimated to behave is shown in figure 8.1. The guide pipe length is 32m in this case. In the appendix chapter 11.5.1 some figures with more dimensions to this case are given.

A 3.5" coil is used to illustrate how the strain will vary from the case of using TR to using CiC.

Realistic reel and gooseneck sizes are found by using NORSOK D-002. According to NORSOK D-002 the gooseneck radius should be minimum 48 times the outer diameter (OD) of the coil and the coiled tubing reel core diameter shall, as a minimum be 48 times the OD of the coil. This gives a gooseneck with a radius of 168"/4267mm and reel with a reel core diameter of 168"/4267mm.

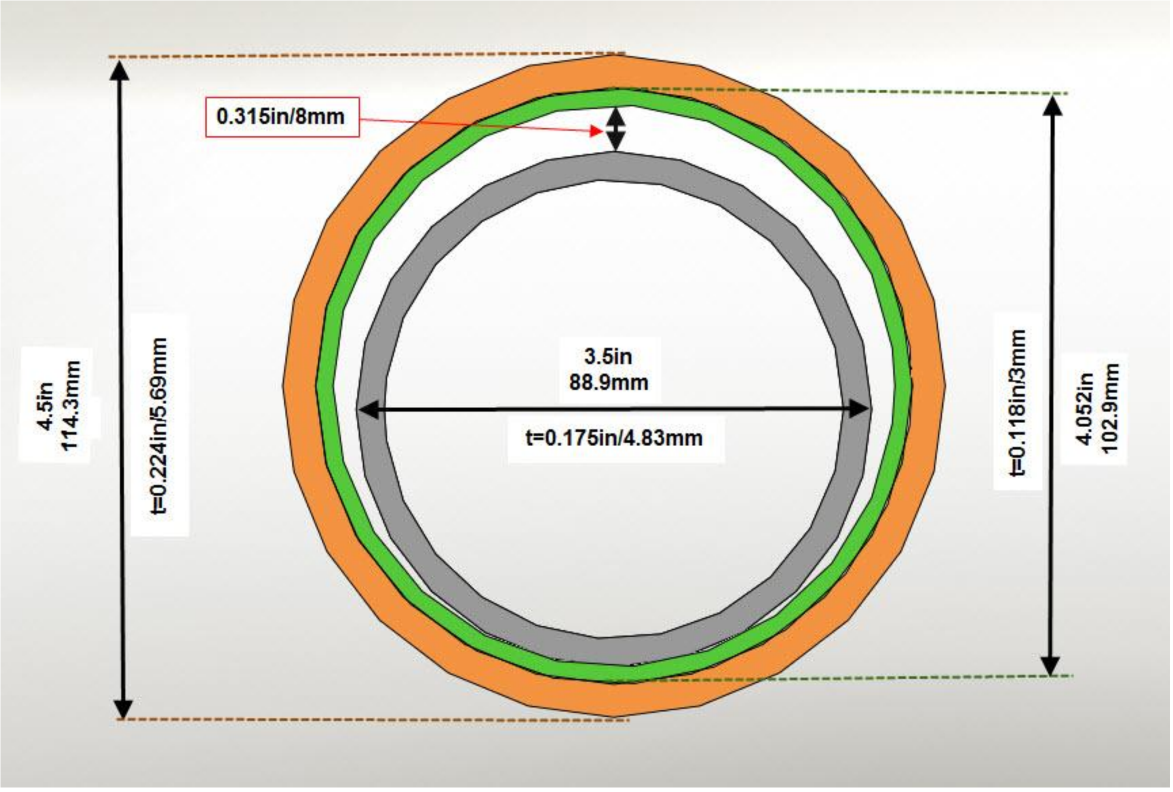


Fig 8.2 Typical Guide pipe-coil relation

For CiC the case illustrated in fig 8.1 is used. Relevant bend radiuses are shown in the appendix figures A8.2 and A8.4. The minimum bend radius of 4900mm is on the injector side of the saddle support. Fig 8.2 shows the guide pipe coil relation if a 4.5” OD guide pipe is used with a 3mm thick low friction layer on the inside. The coil and guide pipe dimensions are taken from Global Tubing’s standard coil selection.

ASME section I PG-19 defines strain as: $\varepsilon = \frac{r}{R}$

R = nominal bending radius to centerline of pipe or tube
r = nominal outside radius of pipe or tube

In the case of a 4.5” guide pipe (D=114.3mm, r=57.15mm) and 3.5” coil (D=88.9mm, r=44.45mm) and the minimum bend radius of 4900mm that occurred in the illustrated example in fig 8.1 the strain in the case of CiC are:

$$\frac{57.15mm}{4900mm} \approx 0.01$$

$$\frac{44.45mm}{4900mm} \approx 0.01$$

The maximum strain is about 1% on the injector side of the saddle support for both guide pipe and coil if the case is as in figure 8.1.

The radius in the part of the guide pipe that is compensating the most for the heave motion is the part that is on the reel side of the saddle support. Here the radius varies from about 8590mm as the reel and injector are at a maximum distance to 12700mm when the distance is at the minimum level. This gives:

$$\frac{44.45mm}{8590mm} \approx 0.005$$

$$\frac{44.45mm}{12700mm} \approx 0.0035$$

The strains vary back and forth from about 0.35% to 0.5% each time the vessel moves up and down in this case, a variation of about 0.15 % (Δε=0.0015).

In the case of a 168” gooseneck (R=4267mm) and 3.5” coil (r=44.45mm) the strain in the coil as it is guided over the gooseneck is:

$$\frac{44.45mm}{4267mm} \approx 0.01$$

In the case of a 168”reel (R=2133.5mm) and 3.5”coil (r=44.45mm) the strain in the coil as it is guided over the minimum core diameter is:

$$\frac{44.45mm}{2133.5mm} \approx 0.02$$

The strain is about 1% over the gooseneck and 2% over the reel (as a maximum). It is as an approximation assumed that the coil will experience about the same minimum strain going from reel to gooseneck as when using a guide pipe, about 0.0035 (in reality it will be a lower value compared to the guide pipe scenario, but using 0.0035 gives a conservative result), this gives a strain variation of about 1.65 % (Δε=0.0165).

From this is it is made clear that the strain over the gooseneck is about same as the strain induced on the injector side of the saddle support in the guide pipe/CiC case. If a smaller coil would be used (as is often the case, as discussed in chapter four, 3.5” is a relatively large coil) the gooseneck would be smaller and CiC would give a more beneficial situation compared to TR. But as the coil is only guided over the gooseneck twice if everything goes as planned (in and out of the well) the strain over the gooseneck is of less concern than the repeated strains in the parts of the coil being coiled on and of the reel in the case of TR or moving with the guide pipe in the case of CiC.

In the case of CiC there will probably be some strain variation on the injector side of the saddle support which are not present today, but it seems possible to keep these on a very low level as the variation in radius in our not optimized example case was less than 0.01%.

With the numbers used in this case the strain variation induced by keeping constant tension by reeling the coil on and of the reel is much larger than the strain variation induced when using a guide pipe ($\Delta\varepsilon$=0.0165 vs. $\Delta\varepsilon$=0.0015). As the difference is so large it is quite certain that the strain variation when using CiC will be less also under more conservative assumptions (as not using the minimum reel diameter) and when comparing against guide pipe cases that are less ideal than he one illustrated in fig 8.1.

To estimate the increase in tolerated load cycles before failure the Coffin-Manson relation is used. Calculations, justifications and some more examples on how the curves (and amount of tolerated cycles) change with material properties are included in the appendix chapter 11.5.2.

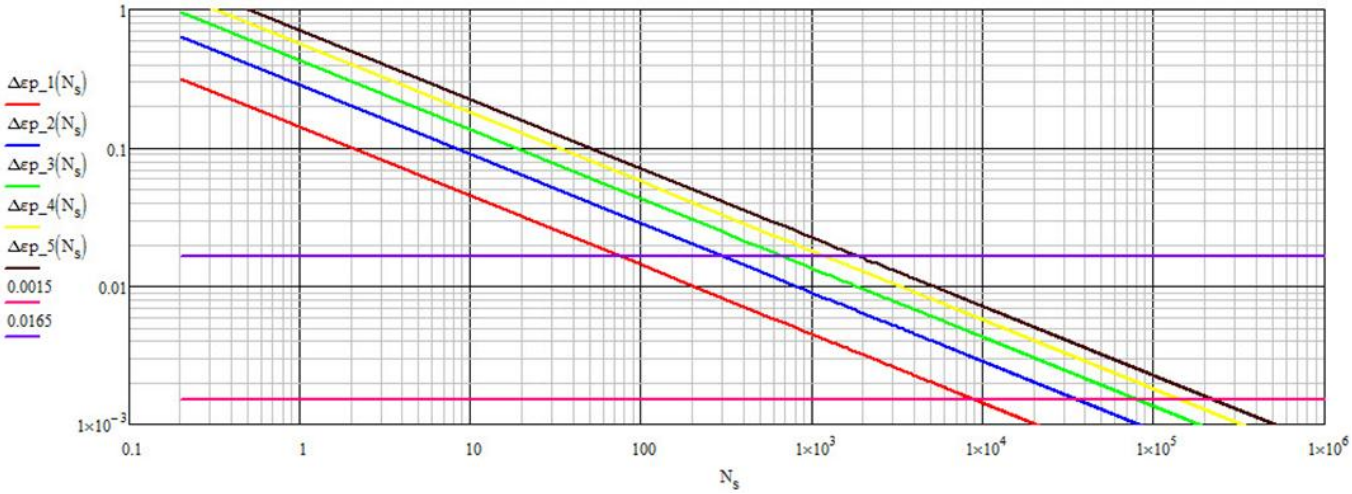


Fig 8.3 Improvement cycles to failure by reducing $\Delta\varepsilon$ from 0.0165 to 0.0015

Fig 8.3 illustrates how the number of tolerated cycles before failure (N_s) increase as the strain variation in each cycle ($\Delta\varepsilon$) is lowered from 0.0165 to 0.0015. As an estimation $\Delta\varepsilon$ is used directly instead of in $\Delta\varepsilon_p$. The fracture strain is 0.1 in $\Delta\varepsilon_p$_1 (N_s) and increase in intervals of 0.1 up to 0.5 in $\Delta\varepsilon_p$_5 (N_s). The impact of increased fracture strain on the increase in N_s is considerable, but the contribution decreases as ε_f increase (greatest increase from 0.1-0.2, less increase when going from 0.2-0.3 etc.). A fracture strain of about 0.2-0.3 is found to be most suitable for steel types considered to be coil material candidates.

If an estimated fracture strain of 0.2 is assumed $\Delta\varepsilon_p$_2 (N_s) is the relevant curve. This gives an increase in number of tolerated cycles from about 300 to about 2000 cycles.

Degree of pipe ovality, internal pressure, uniformities in the material because of welds or insufficient material harmonization, together with surface and internal defects will reduce the tolerated number of cycles. But as the decrease in N_s for both TR and CiC because of these factors are assumed to be the same (maybe less for CiC because the lower stress value gives lower stress concentrations) the conclusion is that a lower strain variation per load cycle will have a significant impact on N_s.

8.3 Risk Evaluation

First step 2a, 2b, 2c and the operation was evaluated. This evaluation resulted in a third way of rigging up the guide pipe. This alternative is illustrated in chapter 7.2.2 under step 2d. The operations after the guide pipe is in place are the same for step 2d as for 2a, 2b and 2c. Even if there are some difference in equipment and equipment placement it is not considered that this influence the operation in a measurable way at this stage, the illustrated steps after 2d are therefore not adapted to the 2d illustrations.

As most of the identified risk and consequence reducing measures were evaluated as common engineering practice, offshore routine or easy/non-expensive to implement compared to the risk/consequence reduction effect, the risk after these risk and consequence reducing measures are implemented are discussed.

A summation of the elements considered implemented where needed/possible:
-design check (user-friendliness, provide access/space to do necessary/potentially necessary work, use of standard components, robust design/protection of exposed elements)
- calculation check (dimension structure and components for expected load plus appropriate safety factor)
-know expected loads; always check against component/structure capacities
-perform safe job analysis (SJA) adapted to the specific operation with involved personnel
-close of area under hanging load/working personnel
-double securement of hanging load where possible
-protective gear (helmet, gloves, glasses, shoes and coverall)
-satisfactory training
-drilling of emergency procedures
-inspection/testing of equipment before and after operation where considered relevant

In the cases where it was unclear if a measure was possible to implement or the effect the implementation would give was not considered optimal, the effect of this measure were not considered implemented. These cases are discussed in the evaluation.

Many of the hazardous events are considered to be similar at this stage even if they occur at different stages of the operation or at different locations; at this point it was considered acceptable to evaluate these events partly or entirely together in categories. The chosen categories are:
-squeezing of hand/fingers in connection mechanism
-failure of connection mechanism or other mechanical function
-failure of support structure
-operation leading to event

Many of the events can occur at different stages of the operation, but mostly the event is only evaluated once. The complete analysis can be found in the appendix chapter 11.5.3.

8.3.1 Step 2a

Guide pipe and coil provided on the same reel, coil pre-installed inside the guide pipe.

Squeezing of hand/fingers in connection mechanism (2a.1-1, 2a.4-1, 2a.5-1, 2a6-1, 2a.8-1)
All manual operations induce some risk for the personnel involved. Even with training and user-friendly equipment accidents can happen and this is accepted as long as the probability-consequence combination induces a risk considered to be low enough. Because of unclear design it is not possible to state that the risk is acceptable at this stage, but it should be possible to get the risk down on an acceptable level.

Furthermore; the possibility for more automatic locking should be considered.

Failure of connection mechanism or other mechanical function (2a.3-2, 2a.3-3, 2a.7-3, 2a.7-4, 2a.7-7, 2a.9-2, 2a.9-3)
The events in the yellow area related to failure of operational functions are related to failure, malfunction or wrong use of feeder, winch and connection points including bend restrictors.

The hazards related to the feeder are rated with a moderate consequence even after risk reducing measures are taken because of unclear design. There are made some feeders, these have been for feeding coil, it is therefore considered likely that it is possible to get a feeder that is flexible and reliable enough for the needed purpose in the 2a method of rigging up.

Regarding the winch only complete failure or loss of control during rising of the guide pipe/coil is considered to need some further evaluation, because the consequence could be moderate even with measures taken. This operation is performed routinely at this point, without the extra guide pipe load, so it is considered likely that it is possible to get the risk down on an acceptable level. When the loads and operational possibilities of the winch is more set the event can be evaluated again.

Failure of connection point wire-guide pipe or guide pipe-saddle support during rising of the guide pipe, and guide pipe-upper bend restrictor or tower structure-saddle support during the further rigging, have a moderate consequence even after measures are taken because of the downtime, harmed reputation and material damage this would cause. With god design solutions and thoroughly testing it is considered likely that one can attain locks that can function satisfactory.

The bend restrictors are potentially more complicated than some of the other locks as they probably need to maintain quite much flexibility during rig up and less during operation. As the needed limitations and interfaces are clearer design suggestion can be made that can be evaluated more thoroughly, but it is evaluated to be achievable to get functional bend restrictors.

Failure of support structure (2a.3-1, 2a.3-5, 2a.7-1, 2a.7-6)
The consequence if the support arm should fail is considered to be moderate even if the consequence reducing measures are implemented because of the induced downtime, material damage and damaged reputation of the involved parties. The probability is not put down to the lowest level because of the unclearness in the design, but with more calculation/design work it is considered likely that the risk of failure can be set low enough to put this event in the ALARP area.

Failure of the support structure on the reel could lead to failure of components on the reel; even if that is not the case this would cause long downtime and loss of reputation for involved parties. It should be possible to get the probability of failure and severe damage down to an acceptable level as the reel design is not considered to need much change from proven design. The event has to be evaluated again when the needed design change is more set and loads are known.

Operation leading to event (2a.4-2, 2a.5-2)
Component failure alone is considered covered in the discussion to the other categories. The events leading to the operational hazards are related to broken procedures caused by lack of training, tough working conditions/stress, human error/disobedience etc. The operations found to be critical are the connection of the guide pipe to the upper bend restrictor and the connection of the saddle support to the tower structure.

The hazardous events in this category have moderate consequence after consequence reducing measures are taken. Especially the operation where the guide pipe shall be connected to the upper bend restrictor is considered to be a problematic manual operation as the guide pipe is stiff and heavy, securement of the guide pipe must be remembered/sustained and the working environment can never be ideal because of limited space/access/control and distance to ground. These factors will be present to some extent even though every risk reducing measure is taken. Even if the probability is low it is considered to be unlikely that the probability can be put down to not likely (NL) as the operation is now.

8.3.2 Step 2b
The guide pipe is provided on a separate reel and pre-installed before coil is feed through the guide pipe and into the injector.

Squeezing of hand/fingers in connection mechanism (2b.2-1, 2b.4-1, 2b.5-1, 2b.6-1, 2b.8-4)
As discussed under step 2a, only there is need for at least one additional lock/locking operation during the shift from guide pipe reel to coil reel.

Failure of connection mechanism or other mechanical function (2b.3-2, 2b.3-3, 2b.7-2, 2b.7-3, 2b.9-4, 2b.10-1, 2b.10-2, 2b.10-3, 2b.10-4)
The events in the yellow area related to failure of operational functions are, as in 2a, related to failure, malfunction or wrong use of feeder, winch, bend restrictors and connection mechanisms.

Failure of feeder or feeder damaging the coil in the case of a 2b rig up will have more severe consequences and more related hazards than the 2a rig up as the complete coil length have to be feed through the guide pipe. It is considered less likely that a feeder can be made powerful enough to feed the complete coil length without damaging the coil unacceptably and more likely that the feeder will fail during the feeding operation as it is more demanding compared to 2a.

The risk of winch and bend restrictor failure/misuse are considered to be as during the 2a rig up.

The comments to hazardous events related to lock failure as are considered to be as discussed under step 2a. But there is need for at least two additional locks/locking operations during the shift from guide pipe reel to coil reel in step 2b.

Failure of support structure (2b.3-1, 2b.6-3, 2b.9-3)
Failure of support structure in tower as discussed in 2a.

Failure of sport structure on reel(s) is considered to be as discussed under 2a at this stage.

Operation leading to event (2b.4-2, 2b.5-2, 2b.8-2, 2b.8-3, 2b.9-2)
The events related to connecting the guide pipe to the upper bend restrictor and saddle support to the tower structure are very much the same as in 2a. In addition there are hazards related to the switch from guide pipe to coil reel that are considered to be critical.

Some hazards involve remotely controlled parts between the two reels. These have a rated high consequence. As unclear as the design, user limitations and detailed rigging sequence is now, it is not known that the consequence will not be one or more fatalities should someone be located in the zone of movement during rigging, or if there is movement by mistake at any time.

There is also evaluated to be an additional risk during the shift from guide pipe fastened to the guide pipe reel to the coil reel as the operation is potentially complicated and dependent of correctly performed manual operations.

8.3.3 Step 2c

The 2c method of rigging up is the traditional way of getting the coil installed. As the procedures here are known and the technology is proven the risk is not raised because of unclearness, as a result the hazards had an assigned acceptable risk. A little discussion is still included under each category to reason for the results.

Squeezing of hand/fingers in connection mechanism

The connection mechanism used when connecting wire and coil is known and thoroughly tested. The probability for the unwanted event to occur is therefore put to not likely, one category below the locks used in the guide pipe rig up. The consequence is probably also lower as the weights are lower than if a guide pipe should be involved.

Failure of connection mechanism or other mechanical function

If the lock between wire and coil or winch should fail the consequence are evaluated to be less than if a guide pipe would be involved because the weight is lower and the resumption of the operation when a guide pipe is used would probably take longer. The probability for failure compared to a lock against a guide pipe is also estimated to be a bit lower because of the lower weight and known technology, but not as low as to a not likely level as there will always be some risk of component failure.

Failure of support structure

Because of the long history of coiled tubing with traditional reels/equipment offshore the risk induced by failure of support structure on the reel is considered to be on an acceptable level.

Operation leading to event

The operations involving rigging up the coil are evaluated to be on acceptable level as the operations are well known and considered to be less complicated than the operations in step 2a and 2b.

8.3.4 First Discussion of the Risk Evaluation Results

Step 2b induced the highest amount of critical operations, most offshore work and the uncertainties regarding the feasibility of some of the steps were high. If it is impossible to pre-install the coil inside the guide pipe and transport guide pipe and coil on the same reel, the feasibility of 2b could be further evaluated, eventually it could be evaluated if it should be possible to have this way of rigging up the guide pipe as a backup solution should something fail during the intended way of rigging up.

During the evaluation of 2a and 2c some of the operations found to be critical in 2a were found to be eliminated if they were changed to be more similar to the well proven 2c way of rigging the coil. By doing this a way of eliminating the manual shift of hanging load from wire to the bend restrictor emerged. The operations performed high above ground in the ACTF were found to be most critical, it was therefore a goal to minimize the need for manual operations in the ACTF to an as great as possible extent by making them automatic, eventually with a possibility to adjust/correct manually should the automatics fail.

8.3.5 Step 2d

Squeezing of hand/fingers in connection mechanism (2d.5-1, 2d.7-1, 2d.8-1)
As the same wire-coil lock as used in traditional rigging can be used (probably in a strengthened version) the risk of misuse is considered to be low.

The design of the saddle support lock and installation is not clear and need further evaluation at a later stage, but it is considered likely that an acceptable risk can be achieved.

It is assumed that it is possible to make the rest of the locks completely or partially automatic (at least the part of the operation that involves risk of squeezing body parts). If this cannot be achieved the increased risk more manual locking induce must be considered.

Failure of connection mechanism or other mechanical function (2d.4-1, 2d.4-22d.4-5, 2d.6-1, 2d.8-4, 2d.9-1)
The events in the yellow area related to failure of operational functions are related to failure, malfunction or wrong use of winch, connection points or bend restrictors. At this stage the operation seems to be achievable without a feeder, and if it is needed the involved operations are not found to be as critical as in 2a and especially 2b. If a feeder is needed the risks involved should be included in the next evaluation round.

The risk of losing the guide pipe because of lock or winch failure is considered to need some further evaluation because of the increased weight, possible lock adjustment and other possible adjustments that might be reviled at a later stage. It is considered very likely that since the operation is very similar to a traditional rig up the events can be put down in the ALARP at a later stage.

The hazard involving guiding of coil over the upper bend restrictor is potentially more critical than during 2a and 2b where the guide pipe is connected to the tower structure and a large guide radius is achieved by aligning guide the guide pipe before the coil is feed through the bend restrictor. In this case the guide radius is provided by the bend restrictor alone. As long as this is considered a solution is likely to be found.

Failure of support structure (2d.8-3, 2d.9-2)
Failure of support structure in tower and reel as discussed in 2a.

Operation leading to event (2d.5-2, 2d.7-2)
Installation of the saddle support is considered to be a critical operation because it is a potentially complicated operation to perform under the conditions that the operation has to be performed in. It is not possible to evaluate the risk more accurate than that it is in the yellow zone at this point because the size of the saddle support is unknown (but it is

estimated to be larger/heavier than one man can carry), if it can be mounted on ground level and how much manual work that is needed. Connection of the saddle support to the tower is also considered to be critical as the operation is unclear and the working conditions so high above ground are far from ideal. But in total these operations are evaluated to be less critical than the operations leading to event in the case of rigging up ad described in 2a or 2b.

8.3.6 Operation

Only the hazards relevant for the guide pipe versus gooseneck discussion are considered. Since there are not that many hazardous events they are not categorized.

Use of gooseneck (6.1TR-1, 6.1TR-2)

As mentioned earlier there is relative motion between the subsea well and the equipment placed on the vessel deck when CT operations are performed from floaters. To keep constant tension in the coil the excess coil is coiled on and off the reel with the vessel motions, this cause repeated strain as described in chapter one, two and three.

This lead to the hazardous event: fatigue damage to coil. As long as the remaining fatigue life is under control the consequence need not be worse than that parts of the coil must be scraped, but since both material behavior and coil operations are not 100% predictable there will always be a probability for exceeding the fatigue life and the consequences it that case are severe. Combined the probability for excessive coil damage and severe consequence create a risk that is not that high but with an unpleasant uncertainty.

Use of guide pipe (6.1 CiC-1, 6.1 CiC-2, 6.1 CiC-3, 6.1 CiC-4)

In chapter 8.2 it was found that the guide radius achieved by replacing the gooseneck with a guide pipe is not that much more ideal than when using a gooseneck with recommended size (as the coil dimension gets as large as 3.5”). But eliminating the need for spooling coil on and of the reel with the vessel motions gave a significant increase in fatigue life.

Several hundred meters of coil shall be guided through the guide pipe. How and how fast guide pipe and coil wear must be known to avoid unacceptable damage to the coil or guide pipe. Damaged coil is, as discussed in chapter three and four, more exposed to failure. Even if it does not go as far as failure, the economic consequence of having to replace the whole coil more often than is needed with TR is considerable. The whole point of using the CiC concept would probably be lost under these circumstances (except from the benefits in the arctic).

It is expected to find a material combination that does not damage the coil. The challenge is to find combination that does not damage the coil and at the same time provides a guide pipe which function satisfactory through the entire operation. Thoroughly testing is needed before a conclusion can be taken.

The risk of complete failure of guide pipe is considered to be low if an outer wear resistant layer is implemented as a safety shell (that can also provide the needed stiffness). As the material/design/practical aspect is further evaluated it is likely that the probability of failure can be put down to a level that would make the risk acceptable.

8.4 Cost Evaluations

Life cycle cost (LCC) analyses are used to determine which solution to implement if there are different solutions that are equally technically acceptable for carrying out the same task. The benefits a new CT concept generates must be higher than the total costs of the investment during its complete lifecycle. The total cost is not only what it costs to develop and build the equipment. The cost of using the equipment over the anticipated lifetime including maintenance, repairs, insurance and losses caused by downtime etc. must be considered and compared to a traditional CT rig up.

8.4.1 Costs and Drawbacks

Support structure

The expense that is estimated to be largest is the rebuilding of existing tower structures to being able to accommodate the guide pipe solution. Here it is necessary to evaluate each tower separately to find the best possible solutions for the individual tower adjustments and the actual construction work will occupy the rig or ship for some time. If the work can be done simultaneously with other planned maintenance the rebuild costs are reduced.

Heave compensation mechanism

A mechanism in the tower in connection with the support arm that would give support during rigging and possibly heave compensate during operation is a mechanical function that is potentially complicated and in need of thorough inspection and maintenance. Since it is placed in a poorly accessible location this will complicate matters compared with the situation today.

Feeder

If a feeder is needed on the reel is not yet certain. If the 2d way of rigging up function satisfactory without, and the force needed to pull the coil is low enough it is not needed. In the case that it is needed, this will induce an extra cost compared with today. Design, testing and purchase are onetime expenses, in addition there will be operational and maintenance costs.

Bend restrictors vs. gooseneck

The design is still too unclear to conclude for certain that two bend restrictors will be more complicated/expensive than one gooseneck. The difference is not expected to be very large, but this has to be evaluated further at a later stage.

Locks and saddle support
The extra locks and saddle support will induce an extra onetime cost in design, testing and purchase and some extra cost in operation and maintenance.

Extended rig up time
Even the best rig up solution available at this point will induce some extra operations both onshore and offshore, offshore operations are the ones that cost the most. If it is possible to carry out the 2d way of rigging up and possibly improve the rig up sequence even more, this expense is not expected to be very high.

8.4.2 Earnings and Gains

Cost of guide pipe vs. extended coil life
If the coil in coil concept works as expected the result is an extended coil life and lower risk of a fatigue incident if the CT operation is performed under the same conditions as today. An extended coil life is expected to result in more savings than the cost of having to replace or repair (as in replacing the polymer pipe or coating) guide pipes when necessary. The profit a reduced risk of severe incidents induces is difficult to measure, but as the focus on operational safety is very high it is likely to be a significant contribution.

Extended weather window
As discussed in chapter 4.6 even a relatively small increase in tolerated expected wave height increases the operational window significantly. CT from floaters during the winter and autumn months is impossible in many areas with the existing technology and variations in wave height makes it hard to plan exactly when it is possible to perform an operation even with weather statistics and forecasts available. This is especially true with a vessel that cannot operate in waves above H_s 2-3m. To be able to operate when H_s is up to 4-5m would mean a significant increase in weather window.

Semisubmersible vs. more use of ship
The guide pipe solution makes the coil conditions more beneficial. It is therefore likely that CT operations that are performed from semisubmersibles today because of their favorable motion behavior in many common sea states (ref. chapter 4.6) can be performed from monohull vessels. It is not certain that both increasing the operational window and performing CT operations from monohull vessels instead of a semisubmersibles is possible, but with more thorough analysis the possibility can be explored.

	Semi Sub Typical full package Day Rate	£300,000 - £450,000 (2.7-4mill NOK)
	Cat A++ High Intervention Vessel Typical full package Day Rate	172,000 - £210,000 (1.5-1.9 mill NOK)
	DP II Intervention Vessel Typical full package Day Rate	£ 99,800 (0.9mill NOK)

Fig 8.4 Rough day rate estimates for different interventions vessels (Geoprober, 2012)

As fig 8.4 illustrates, the day rate of a semisubmersible is much higher than for monohull vessels. Hence being able to use a monohull vessel and perform the operation in the same amount of time, will give large cost savings. Ships are also faster to mobilize than semisubmersibles so CT operations can potentially be performed even faster than today. In case of an urgent CT operation where the production is stopped, faster mobilizing can induce even more cost savings that the savings in rent alone.

Possibilities in the Arctic

If the CiC technology with small adjustments can open closed doors in the potentially large arctic market, which is considered to be likely, there will be great possibilities for covering the development cost of the technology plus an unknown (but expectedly high) profit.

9 End Discussion/Conclusion

The results of the work done strongly indicate that the operational gains of using coil in coil are significant. How the gains are balanced between increased coil life, increased operational window and more use of monohull vessels is a dynamic choice to be evaluated before every operation. This flexibility is seen as a possibility more than a disadvantage.

When starting the work, operational gains were expected to be found, but it was questioned whether it would be possible to find an acceptable rig up solution in respect of risk and rig up time and find a guide pipe material that would function satisfactory.

These challenges are not considered to be fully solved at this point as the solutions suggested need more design work, testing and evaluation, but I consider the possibility for the coil in coil concept to be achievable and profitable higher now than at the beginning of my work and it is hoped that the thesis can be a valuable contribution in this respect.

In summary:

The main goals for this thesis were all achieved:

- to find a feasible rig up suggestion
- to identify a promising material candidate
- to obtain some numerical values on the effect the CiC solution could give
- to evaluate if it is probable that it is worth taking the design solutions further.

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11 Appendix

11.1 To Chapter 3

11.1.1 Pierson Moskowitz Spectra Calculations

Final wind speed (eq. 4, NS 3491-4):

$V_f = C_r(z)*C_t(z)*V_b$

V_b is the basic wind speed. The mean wind speds in each of the 13 categorys in the Beaufort scale are used directly.

C_r is the terain factor. This factor correct the wind speed to the terrain above which the wind is blowing (eq. 6, NS 3491-4):

$C_r(z) = K_t*\ln(z/Z_0)$

Constants for use over open sea (table 1, NS 3491-4):

$Kt := 0.16 \quad Z0 := 0.003 \quad Zmin := 2$

C_r 19.4m above sea level:

$$Cr := Kt \cdot \ln\left(\frac{19.4}{Z0}\right) = 1.404$$

Ct is the topography factor (eq. 10 in NS 3491-4).

Over open sea:

$Ct := 1$

Beaufort scale

0. Calm sea, wind speed under 0.3m/s, flat sea

1. Light air, wind speed 0.3-1.5 m/s, 0-0.2m waves

2. Light breeze, wind speed 1.6-3.4m/s, 0.2-0.5m waves

3. Gentle breeze, wind speed 3.5-5.4 m/s, 0.5-1m waves

4. Moderate breeze, wind speed 5.5-7.9m/s, 1-2m

5. Fresh breeze, wind speed 8-10.7 m/s, 2-3m

6. Strong breeze, wind speed 10.8-13.8m/s, 3-4m waves

7. High wind/moderate gale, wind speed 13.9-17.1 m/s, 4-5.5m waves

8. Fresh gale, wind speed 17.2-20.7m/s, 5.5-7.5m

9. Strong gale, wind speed 20.8-24.4 m/s, 7-10m waves

10. Storm/whole gale, wind speed 24.5-28.4m/s, 9-12.5m waves

11. Violent storm, wind speed 28.5-32.6 m/s, 11.5-16m waves

12. Hurricane force, wind speed over 32.7m/s, huge vaves (above 14m)

Average intervall values of basic wind speed (V_b) times level/terrain factor at 19.4m (use equation defined earlyer: $V_f=V_b*C_r(z)*C_t(z)$)

$$Vf1 := \frac{\left(0.3\frac{m}{s} + 1.5\frac{m}{s}\right)}{2}\cdot Cr = 1.264\frac{m}{s}$$

$$Vf2 := \frac{\left(1.6\frac{m}{s} + 3.4\frac{m}{s}\right)}{2}\cdot Cr = 3.51\frac{m}{s}$$

$$Vf3 := \frac{\left(3.5\frac{m}{s} + 5.4\frac{m}{s}\right)}{2}\cdot Cr = 6.247\frac{m}{s}$$

$$Vf4 := \frac{\left(5.5\frac{m}{s} + 7.9\frac{m}{s}\right)}{2}\cdot Cr = 9.406\frac{m}{s}$$

$$Vf5 := \frac{\left(8\frac{m}{s} + 10.7\frac{m}{s}\right)}{2}\cdot Cr = 13.127\frac{m}{s}$$

$$Vf6 := \frac{\left(10.8\frac{m}{s} + 13.8\frac{m}{s}\right)}{2}\cdot Cr = 17.268\frac{m}{s}$$

$$Vf7 := \frac{\left(13.9\frac{m}{s} + 17.1\frac{m}{s}\right)}{2}\cdot Cr = 21.761\frac{m}{s}$$

$$Vf8 := \frac{\left(17.2\frac{m}{s} + 20.7\frac{m}{s}\right)}{2}\cdot Cr = 26.604\frac{m}{s}$$

$$Vf9 := \frac{\left(20.8\frac{m}{s} + 24.4\frac{m}{s}\right)}{2}\cdot Cr = 31.728\frac{m}{s}$$

$$Vf10 := \frac{\left(24.5\frac{m}{s} + 28.4\frac{m}{s}\right)}{2}\cdot Cr = 37.133\frac{m}{s}$$

$$Vf11 := \frac{\left(28.5\frac{m}{s} + 32.6\frac{m}{s}\right)}{2}\cdot Cr = 42.889\frac{m}{s}$$

Pierson Moskowitz Spectra

Define distrubution of energy with wave frequency, ω, with: $Spm(\omega)=\frac{(\alpha\cdot g^2)}{(\omega)^5}e^{\left[-\beta\cdot\left[\frac{g}{(\omega\cdot Vf)}\right]^4\right]}$

Defined constants:

$e = 2.718$ (natural logaritm)

$\alpha := 0.0081$ (intensity factor)

$g = 9.807\frac{m}{s^2}$ (gravitational constant)

$\beta := 1.25$ (shape factor)

Intervall wave frequency shall be plotted in (0.01s between each point):

$$\omega := \left[0\left(\frac{1}{s}\right), 0.01\left(\frac{1}{s}\right) .. 2\left(\frac{1}{s}\right)\right]$$

$$Spm1(\omega) := \frac{(\alpha\cdot g^2)}{(\omega)^5}e^{\left[-\beta\cdot\left[\frac{g}{(\omega\cdot Vf1)}\right]^4\right]}$$

$$Spm2(\omega) := \frac{(\alpha\cdot g^2)}{(\omega)^5}e^{\left[-\beta\cdot\left[\frac{g}{(\omega\cdot Vf2)}\right]^4\right]}$$

$$Spm3(\omega) := \frac{(\alpha\cdot g^2)}{(\omega)^5}e^{\left[-\beta\cdot\left[\frac{g}{(\omega\cdot Vf3)}\right]^4\right]}$$

$$Spm4(\omega) := \frac{(\alpha\cdot g^2)}{(\omega)^5}e^{\left[-\beta\cdot\left[\frac{g}{(\omega\cdot Vf4)}\right]^4\right]}$$

$$Spm5(\omega) := \frac{(\alpha\cdot g^2)}{(\omega)^5}e^{\left[-\beta\cdot\left[\frac{g}{(\omega\cdot Vf5)}\right]^4\right]}$$

$$Spm6(\omega) := \frac{(\alpha\cdot g^2)}{(\omega)^5}e^{\left[-\beta\cdot\left[\frac{g}{(\omega\cdot Vf6)}\right]^4\right]}$$

$$Spm7(\omega) := \frac{(\alpha\cdot g^2)}{(\omega)^5}e^{\left[-\beta\cdot\left[\frac{g}{(\omega\cdot Vf7)}\right]^4\right]}$$

$$Spm8(\omega) := \frac{(\alpha\cdot g^2)}{(\omega)^5}e^{\left[-\beta\cdot\left[\frac{g}{(\omega\cdot Vf8)}\right]^4\right]}$$

$$Spm9(\omega) := \frac{(\alpha\cdot g^2)}{(\omega)^5}e^{\left[-\beta\cdot\left[\frac{g}{(\omega\cdot Vf9)}\right]^4\right]}$$

$$Spm10(\omega) := \frac{(\alpha\cdot g^2)}{(\omega)^5}e^{\left[-\beta\cdot\left[\frac{g}{(\omega\cdot Vf10)}\right]^4\right]}$$

$$Spm11(\omega) := \frac{(\alpha\cdot g^2)}{(\omega)^5}e^{\left[-\beta\cdot\left[\frac{g}{(\omega\cdot Vf11)}\right]^4\right]}$$

Wave period to be plotted along the x-axis: $T := \frac{2\pi}{\omega}$

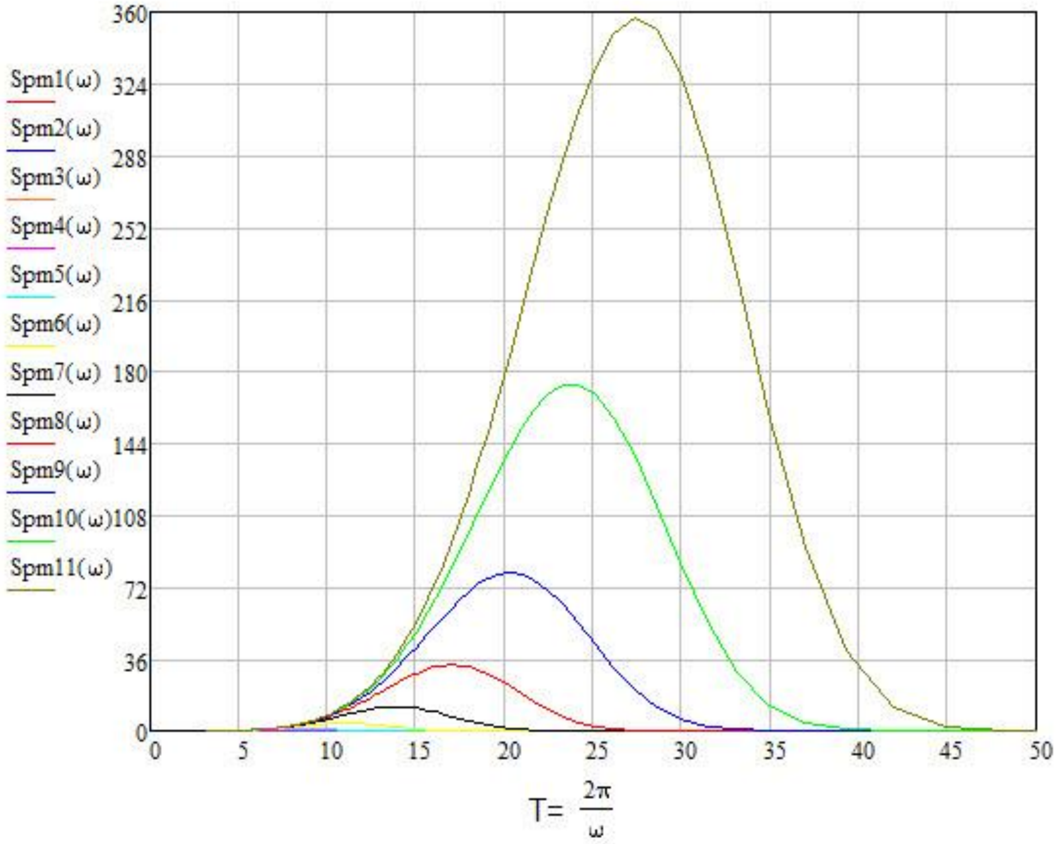

Fig A3.1 Energy distribution (m^2*s) vs. return periods (s) (Beaufort scale 1 to 11)

Fig A3.1 shows that the wave periods gets unrealistically high as the wind speeds increases beyond approximately Beaufort scale 8. Table A3.1 shows that for the spectra 4-7 given in figure A3.2 the results can be used for the discussion in chapter 3.

Table A3.1 Pierson - Moskowitz Sea Spectrum vs. Beaufort Force (Example from Sea Kayak Chesapeake Bay, 2012)

Force	Sea State	Hs (feet)	Feet/m	Hs (m)	Significant Range of Periods (Sec)	Average Period (Sec)	Average Length of Waves (FT)	Average Length of Waves (m)
1	0	below 0.5	0,3048	below 0.15	0.5-1	1,00	2	0,61
2	1	0,5	0,3048	0,15	1-2,5	1,50	9,5	2,90
3	2	2,0	0,3048	0,61	1,5-5	3,00	26	7,92
4	3	3,5	0,3048	1,07	2-6,5	4,00	50	15,24
5	4	6,0	0,3048	1,83	2,5-8,5	5,00	80	24,38
6	5	8,0	0,3048	2,44	3.-10	6.-7	130	39,62
7	6	18,0	0,3048	5,49	4.-13	8.-9	220	67,06
8	7	32,0	0,3048	9,75	5,5-17	10.-12	400	121,92
9	8	52,0	0,3048	15,85	7,5-23	13.-15	650	198,12
10								
11	9	60-100	0,3048	18,29-30,48	9-28,5	16.-19	800-1200	243,84-365,76
12								

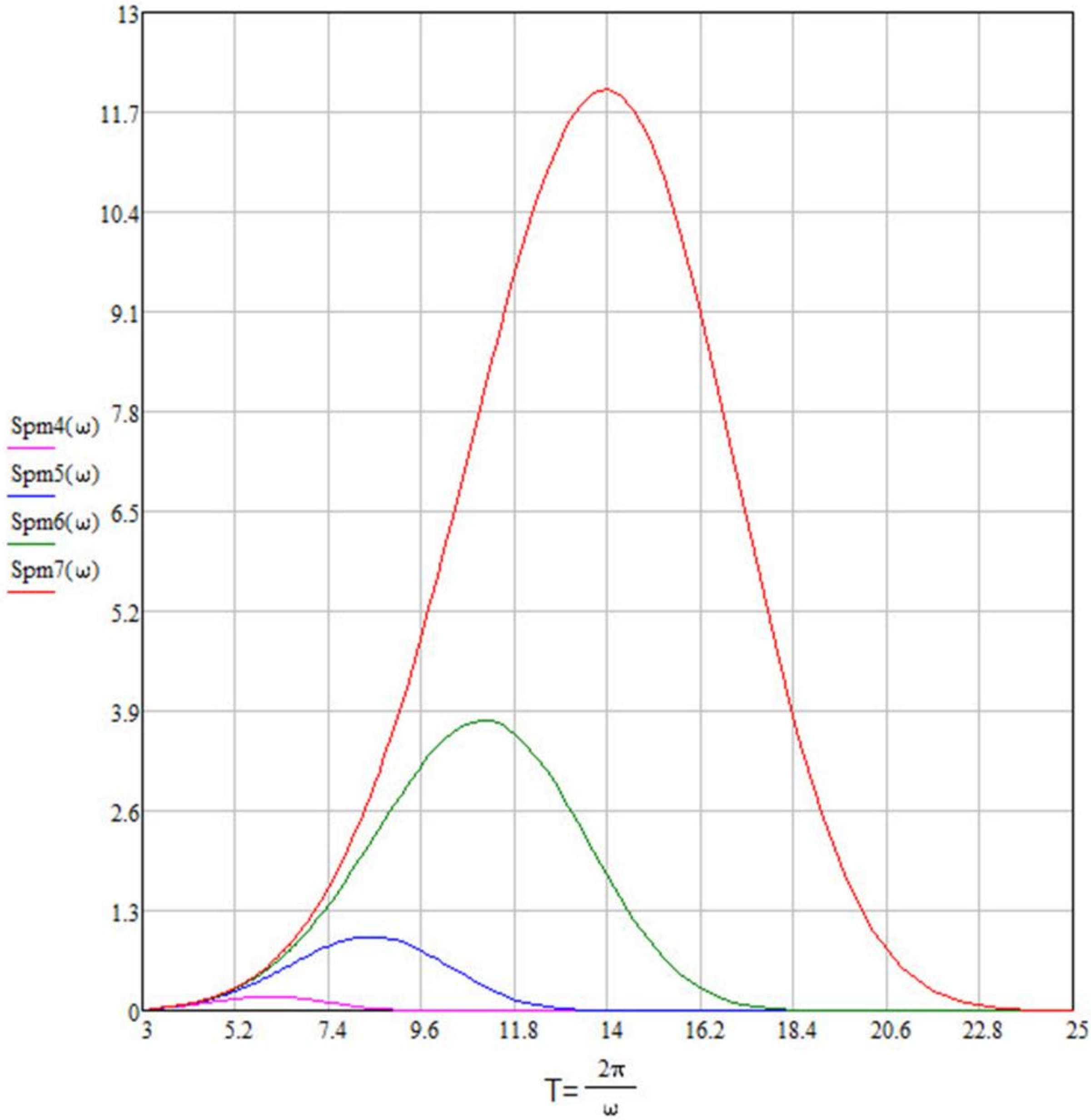

Fig A3.2 Energy distribution (m2*s) vs. return periods (s) (Beaufort scale 4 to 7)

11.2 Expected Sea State Variation

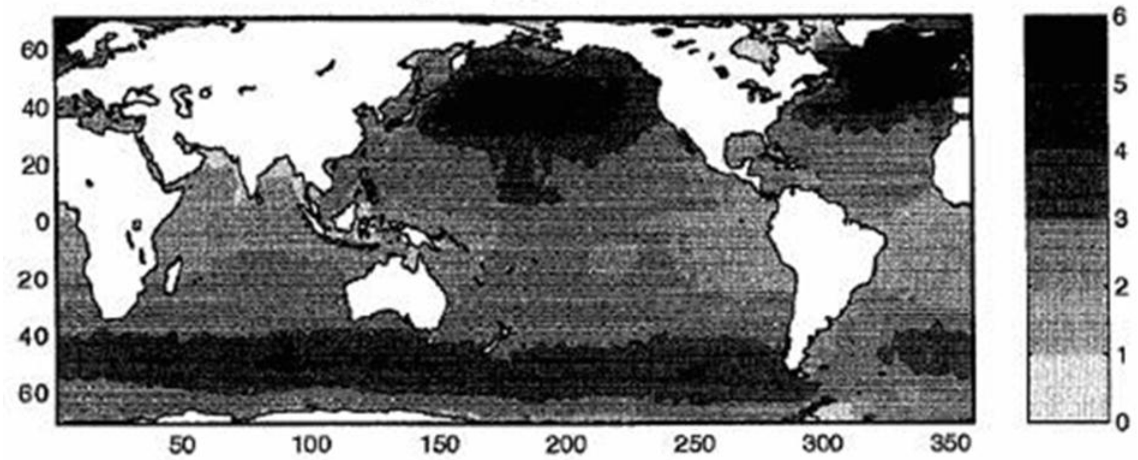

Fig A3.3 H_s (m) in January (Young, 1999)

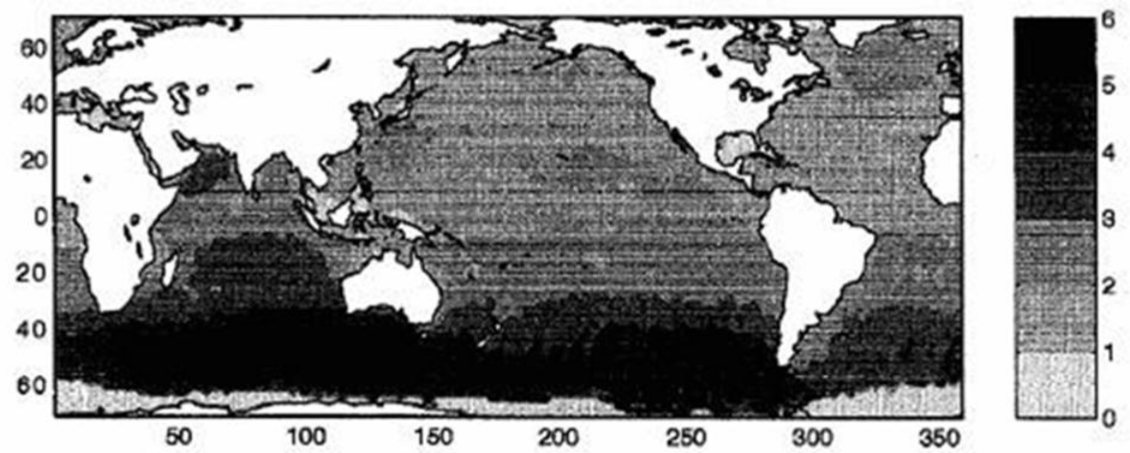

Fig A3.4 H_s (m) in August (Young, 1999)

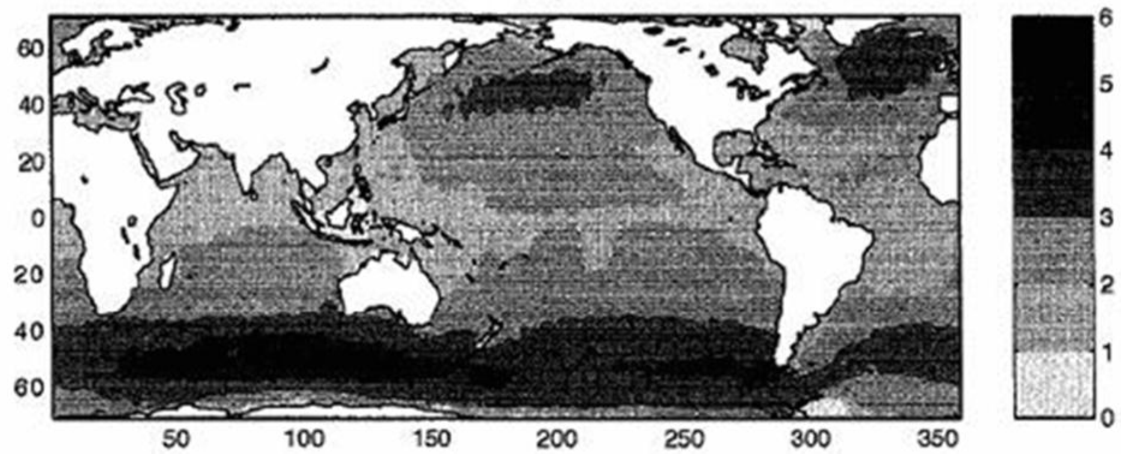

Fig A3.5 Contours of H_s which should be expected to be exceeded 50% of the time (Young, 1999)

Figures A3.3 and A3.4 show how H_s vary with season and area, fig A3.5 indicates variations.

11.3 To Chapter 6

11.3.1 Estimate Contact Pressure Coil-Guide Pipe

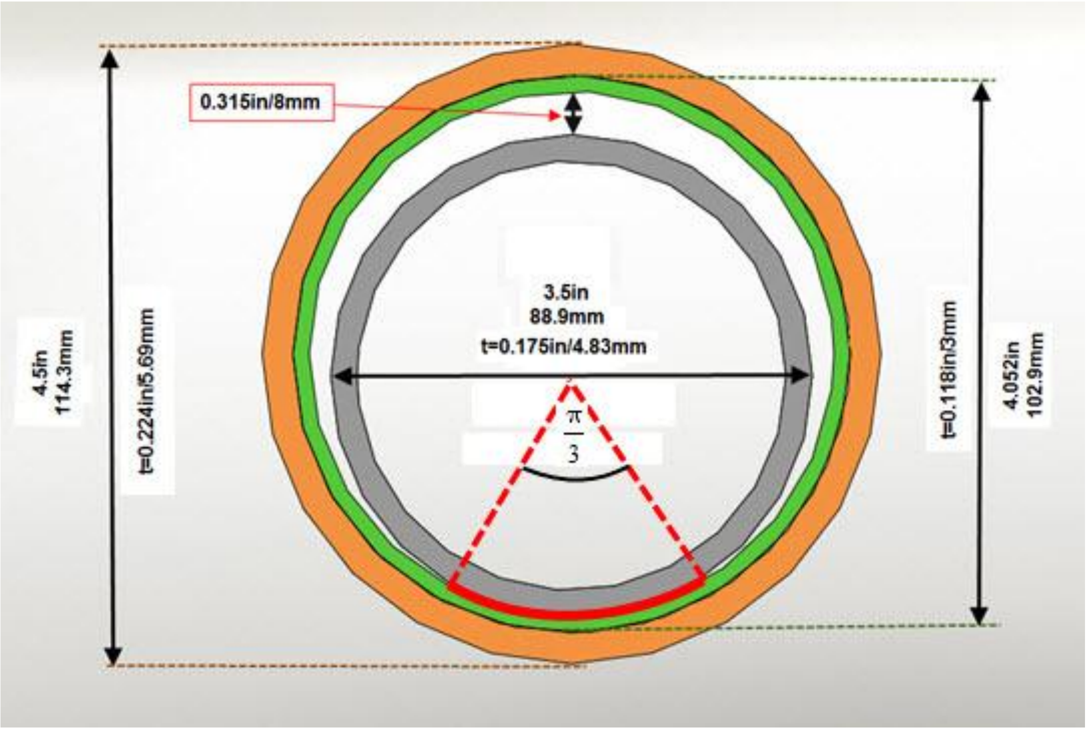

Fig A6.1 Contact area

To have an idea in which range the maximum contact pressure between coil and guide pipe is distributed a simplified case is assumed. The coil-guide pipe relation from chapter 8 is used. A contact radius of π/3 and a coil filled with fluid with the density of water is assumed.

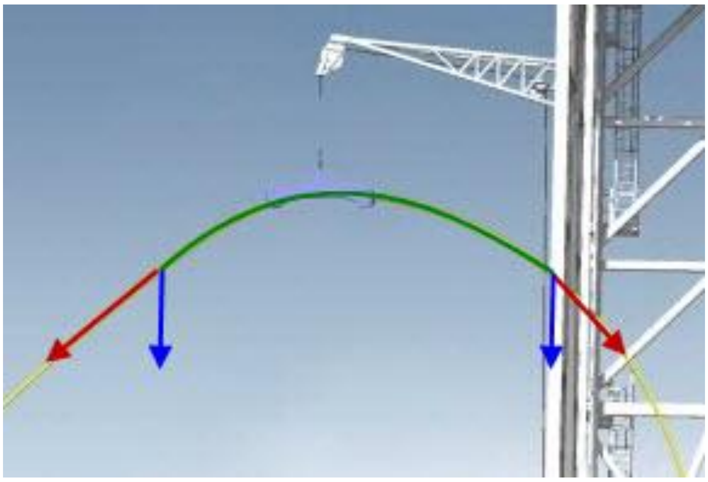

Fig A6.2 Exposed part of guide pipe

Different coil content and contact area are sources of errors, but the largest will be size of the additional load caused by the bending over the saddle support as illustrated in fig A6.2.

Firstly the contact pressure for a horizontal pipe segment was found:

Pipe with inner radius r and outer radius R_ (same pipe as in fig.8.2)

$$r := 0.03962\,m$$

$$R\_ := 0.04445\,m$$

$$g = 9.807\,\frac{m}{s^2}$$

Density steel: $\rho s := 7800\,\frac{kg}{m^3}$

Density water: $\rho v := 9180\,\frac{kg}{m^3}$

Contact radius assumed to be π/3

Contact area one meter pipe:

$$A\_ := \left[\left(\frac{\pi}{3}\right)\cdot R\_\right]\cdot 1m = 0.047\,m^2$$

Steel volume one meter pipe:

$$Vs := \pi\left(R\_^2 - r^2\right)\cdot 1m = 1.276\times 10^{-3}\cdot m^3$$

Fluid volume (water asumed):

$$Vv := \left(\pi\cdot r^2\right)\cdot 1m = 4.931\times 10^{-3}\cdot m^3$$

Total weight pr m pipe:

$$Vt := Vs\cdot\rho s + Vv\cdot\rho v = 55.221\,kg$$

Total force:

$$Ft := (Vt\cdot g) = 541.537\,N$$

Contact preasure coil-guide pipe:

$$P\_ := \frac{Ft}{A\_} = 1.163\times 10^{4}\,Pa$$

Then it was found that the force resulting from the entire coil length plus additional 28 tons of tension could act on the same 1 m segment to achieve a pressure close to the contact pressure of 6.25MPa used in the experiments by Burris and Sawyer (2005):

Amount of extra load that can be applyed before reaching a value colse to 6.25MPa:

$Fa1 := 30 \cdot Ft = 1.625 \times 10^{4} N$ Weight of coil inside entire guide pipe

$Fa2 := 28000kg \cdot g = 2.746 \times 10^{5} N$ Additional tension load

$$P\_2 := \frac{(Ft + Fa1 + Fa2)}{A\_} = 6.26 \cdot MPa$$

The forces will be taken up by more than 1m of the guide pipe and the whole force will not act normal to the guide pipe wall. Still 28 tons of additional tension in addition to the coil weight is way above what is expected. The conclusion is therefore that the contact force of 6.25MPa in the paper Burris and Sawyer (2005) is a high contact force compared to what is expected to occur inside the guide pipe.

11.4 To Chapter 7

11.4.1 Guidance regarding categorization by Risk Martix

Likelihood Class	Likelihood of Occurrence for Safety Consequences (events/year)	Likelihood of Occurrence for Environmental and Public Concern Consequences (events/year)
Not Likely (NL)	<0.01% chance of occurrence	<0.1% chance of occurrence
Low (L)	0.01 - 0.1% chance of occurrence	0.1 - 1% chance of occurrence
Moderate (M)	0.1 - 1% chance of occurrence	1 - 10% chance of occurrence
High (H)	1 - 10% chance of occurrence	10 - 50% chance of occurrence
Expected (E)	>10% chance of occurrence	>50% chance of occurrence

Table A7.1 Probability definitions (Robertson and Shaw, 2012)

Consequences Severity	Biological Impacts and Land Use	Regulatory Impacts and Censure	Public Concern and Image	Health and Safety	Lost Time
Extreme (5)	Catastrophic impact on habitat (irreversable and large)	Unable to meet regulatory obligations; shut down or severe restriction of operations	Local, international and NGO outcry and demonstrations, results in large stock devaluation; severe restrictions of 'license to practice'; large compensatory payments etc.	Fatality or multiple fatalities expected	Shut down of activityes other than involved in actual CT operation for longer time period
High (4)	Significant, irreversible impact on habitat (large but reversable)	Regularly (more than once per year) or severely fale regulatory obligations or expectations - large increasing fines and loss of regulatory trust	Local, international or NGO activism resulting in political and financial impacts on company's 'license to do business' and in major proceedure or practice changes	Severe injury or disability likely; or some potential for fatality	Long time period of lost time, shut down of activities other than involved in actual CT operation possible for some time
Moderate (3)	Significant, reversible impact on habitat	Occasionally (less than one per year) or moderately fail regulatory obligations or expectations - fined or censured	Occasional local, international and NGO attention requiring minor proceedure changes and additional public relations and communications	Lost time or injury likely; or some potential for serious injuries; or small risk of fatality	Considerable amount of lost time (only for activities involving CT operation)
Low (2)	Minor impact on habitat	Seldom or marginally exceed regulatory obligations or expectations. Some loss of regulatory tolerance, increasing reporting.	Infrequent local, international and NGO attention addressed by normal public relations and communications	First aid required; or small risk of serious injury	Some lost time (only for activities involving CT operation)
Negligible (1)	No measurable impact	Do not exceed regulatory obligations or expectations	No local, international, or NGO attention	No concern	No or negligible amount of lost time lost time (only for activities involving CT operation)

Table A7.2 Consequence definitions (Robertson and Shaw, 2012)

The defined acceptance criteria are set after guidance by fig A7.1 and A7.2 by Robertson and Shaw (2012). Since the concept is in such an early phase the uncertainty in numerical probabilities are very high and the assigned probability class must be considered with this in mind. Time loss is only mentioned once in figure A7.1 under health and safety and moderate consequence. Since lost time offshore has a high cost lost, time is added as an own column that was not included in the original figure.

11.5 To Chapter 8

11.5.1 Guide Pipe Configurations

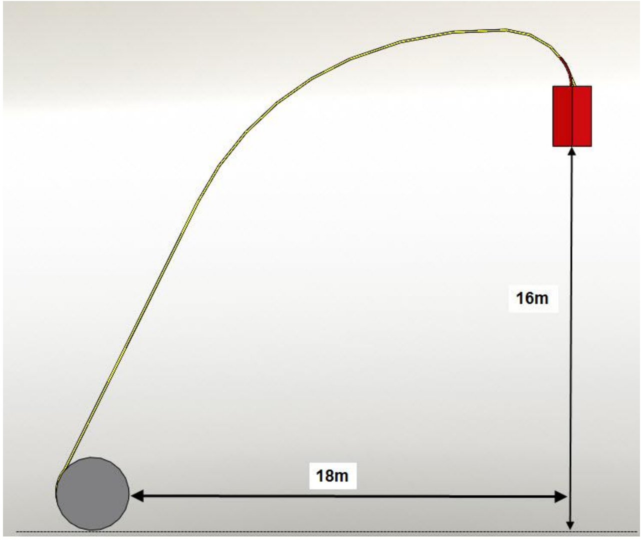

Fig A8.1 Max distance

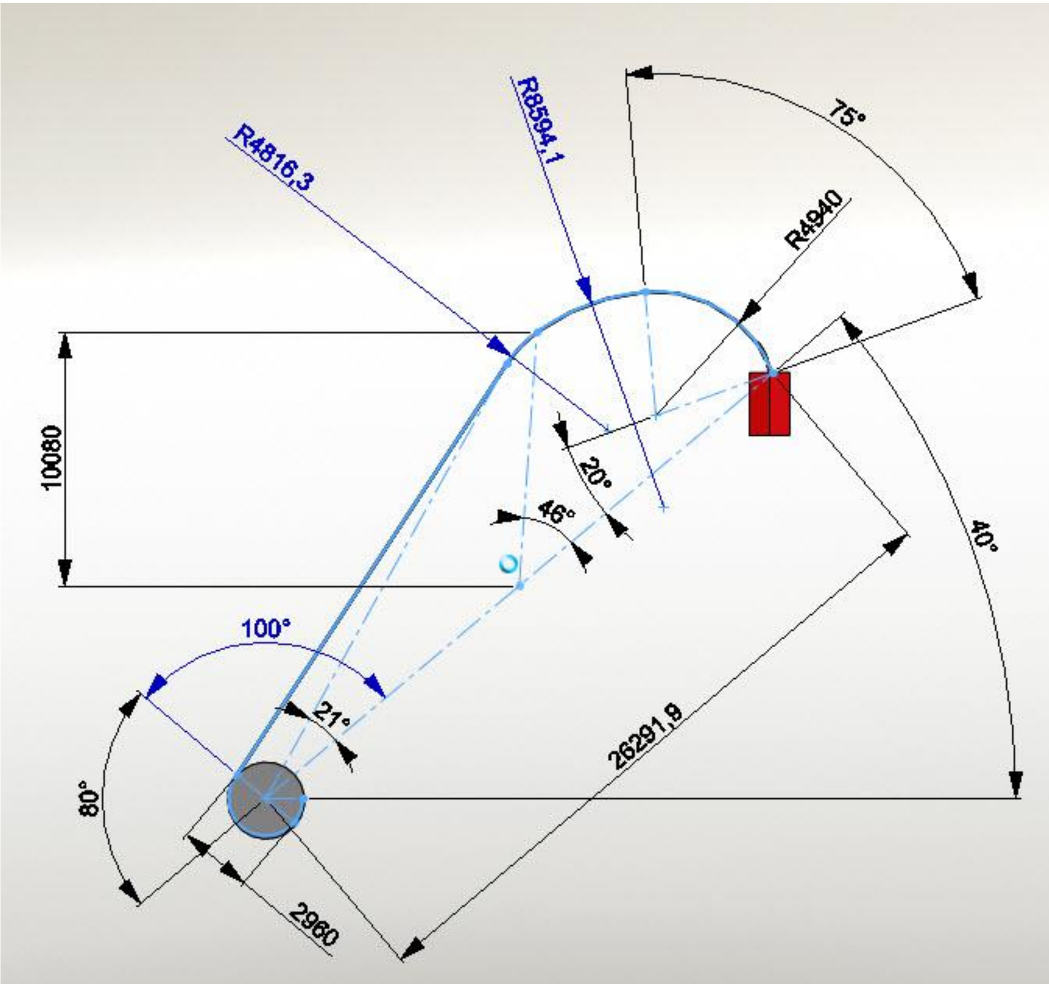

Fig A8.2 Typical guide pipe dimensions, max distance

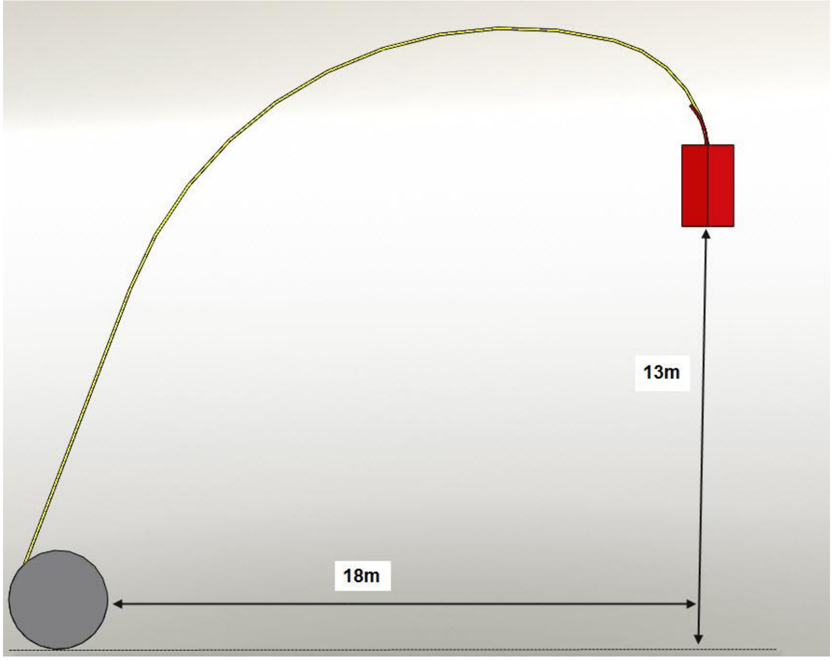

Fig A8.3 Min distance

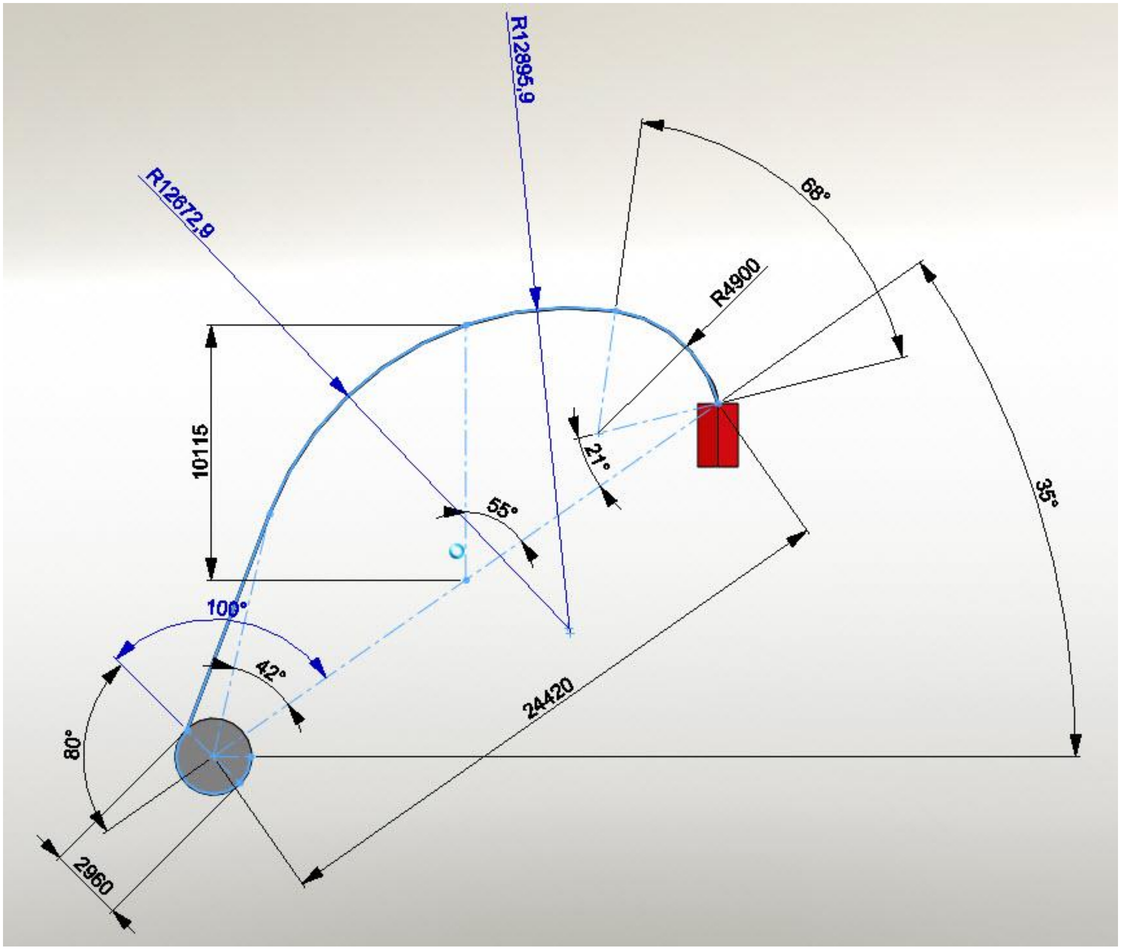

Fig A8.4 Typical guide pipe dimensions, min distance

11.5.2 Coffin-Manson Calculations and Figures

The Coffin Manson relation:

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f^{`} * (2N)^C$$

ε_f' is defined as strain intercept at 2N=1.For many metals is ε_f' is approximately equal to true fracture strain ε_f.

Some potential values of ε_f' to se how a variation in ε_f' influence fatigue life:

$\varepsilon f1 := 0.1$

$\varepsilon f2 := 0.2$

$\varepsilon f3 := 0.3$

$\varepsilon f4 := 0.4$

$\varepsilon f5 := 0.5$

C is defined as the ductility exponent, it usually varies between -0.5 and -0.7.
To se how a change in C influence fatigue life some values of C are defined:

$C1 := -0.5$

$C2 := -0.6$

$C3 := -0.7$

$N._s$ is number of cycles, defined interval: $N_s := [((0.2, 100..\ 1000000))]$

C1 combined with the range of ε_f' conssiddered to be relevant:

$$\Delta\varepsilon p\_1(N_s) := 2\cdot\varepsilon f1\cdot(2\cdot N_s)^{C1}$$

$$\Delta\varepsilon p\_2(N_s) := 2\cdot\varepsilon f2\cdot(2\cdot N_s)^{C1}$$

$$\Delta\varepsilon p\_3(N_s) := 2\cdot\varepsilon f3\cdot(2\cdot N_s)^{C1}$$

$$\Delta\varepsilon p\_4(N_s) := 2\cdot\varepsilon f4\cdot(2\cdot N_s)^{C1}$$

$$\Delta\varepsilon p\_5(N_s) := 2\cdot\varepsilon f5\cdot(2\cdot N_s)^{C1}$$

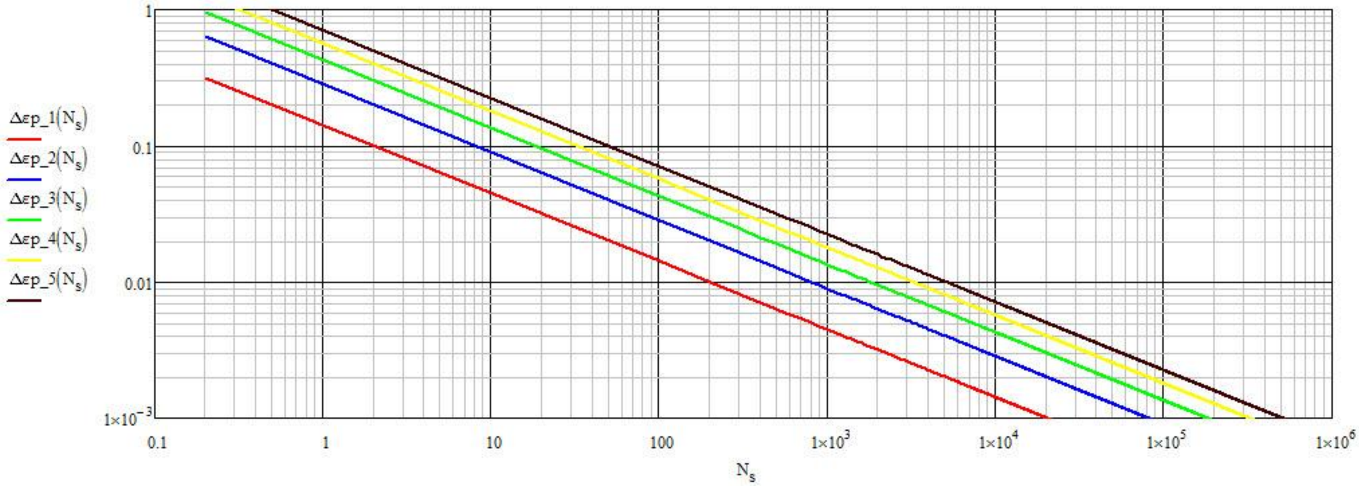

Fig A8.5 Plastic strain variation, $\Delta\varepsilon_p$ vs. number of cycles to failure, N_s for C=-0.5

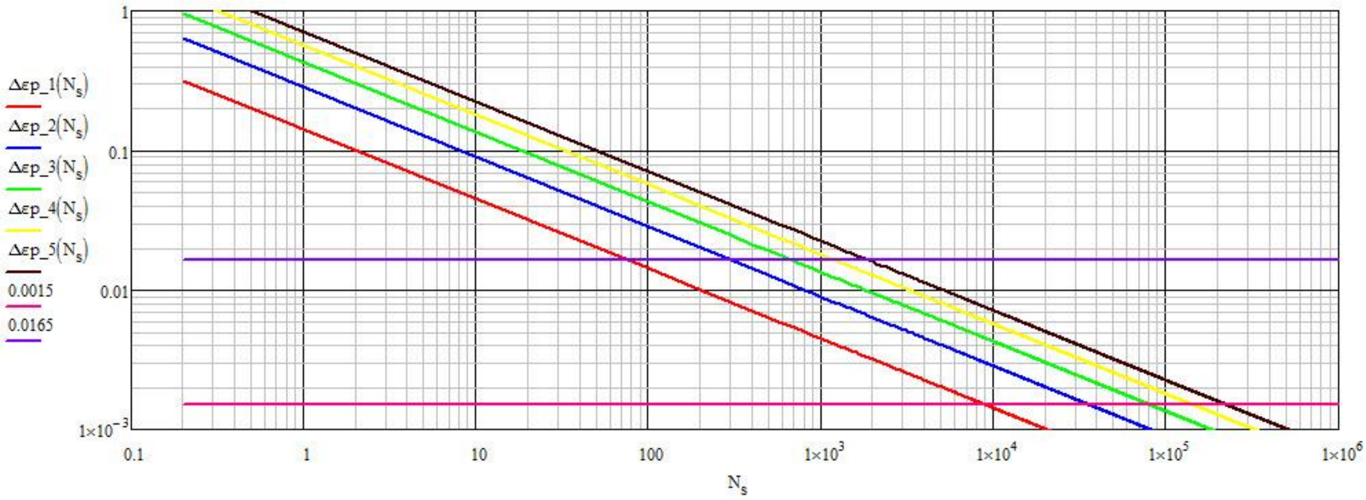

Fig A8.6 $\Delta\varepsilon_p$ vs. N_s for C=-0.5 including improvement cycles to failure by reducing $\Delta\varepsilon$ from 0.0165 to 0.0015

C2 combined with the range of ε_f' considdered to be relevant:

$$\Delta\varepsilon p\_6(N_s) := 2\cdot\varepsilon f1\cdot(2\cdot N_s)^{C2}$$

$$\Delta\varepsilon p\_7(N_s) := 2\cdot\varepsilon f2\cdot(2\cdot N_s)^{C2}$$

$$\Delta\varepsilon p\_8(N_s) := 2\cdot\varepsilon f3\cdot(2\cdot N_s)^{C2}$$

$$\Delta\varepsilon p\_9(N_s) := 2\cdot\varepsilon f4\cdot(2\cdot N_s)^{C2}$$

$$\Delta\varepsilon p\_10(N_s) := 2\cdot\varepsilon f5\cdot(2\cdot N_s)^{C2}$$

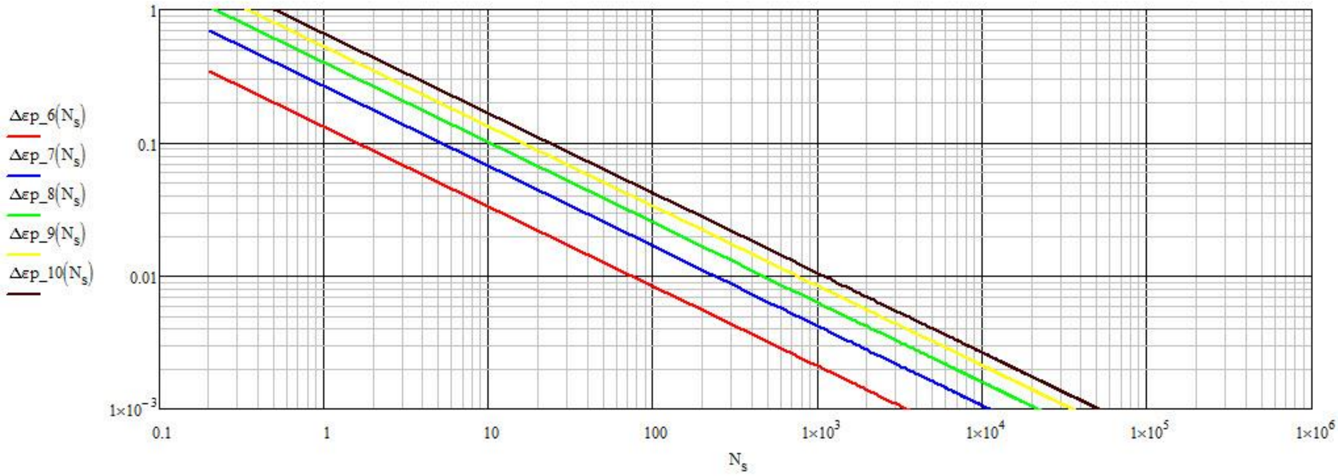

Fig A8.7 Plastic strain variation, $\Delta\varepsilon_p$ vs. number of cycles to failure, N_s for C=-0.6

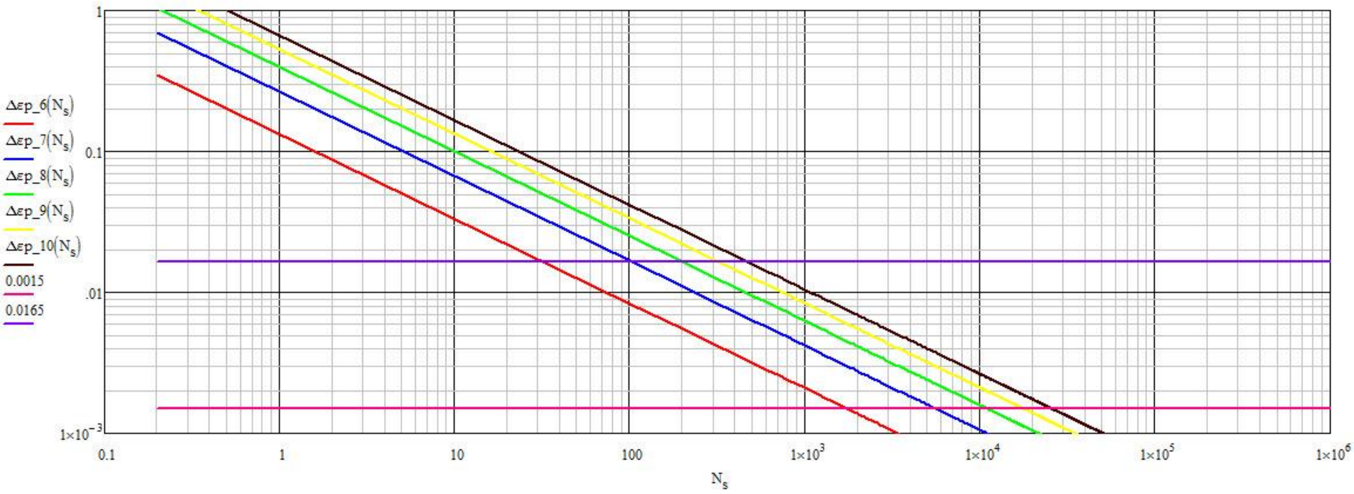

Fig A8.8 $\Delta\varepsilon_p$ vs. N_s for C=-0.6 including improvement cycles to failure by reducing $\Delta\varepsilon$ from 0.0165 to 0.0015

C3 combined with the range of ε_f' considdered to be relevant:

$$\Delta\varepsilon p\_11(N_s) := 2\cdot\varepsilon f1\cdot(2\cdot N_s)^{C3}$$

$$\Delta\varepsilon p\_12(N_s) := 2\cdot\varepsilon f2\cdot(2\cdot N_s)^{C3}$$

$$\Delta\varepsilon p\_13(N_s) := 2\cdot\varepsilon f3\cdot(2\cdot N_s)^{C3}$$

$$\Delta\varepsilon p\_14(N_s) := 2\cdot\varepsilon f4\cdot(2\cdot N_s)^{C3}$$

$$\Delta\varepsilon p\_15(N_s) := 2\cdot\varepsilon f5\cdot(2\cdot N_s)^{C3}$$

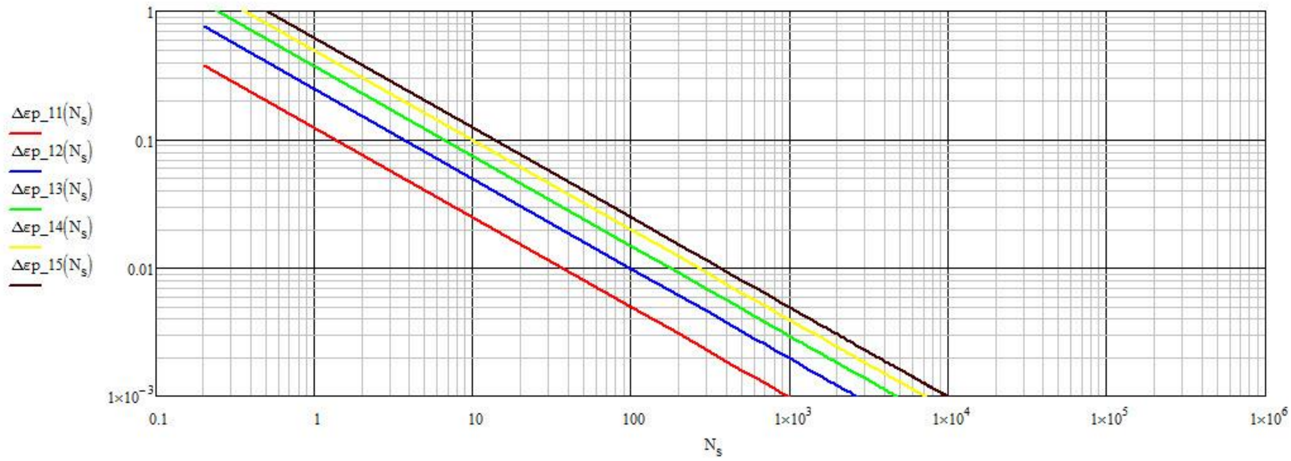

Fig A8.9 Plastic strain variation, $\Delta\varepsilon_p$ vs. number of cycles to failure, N_s for C=-0.7

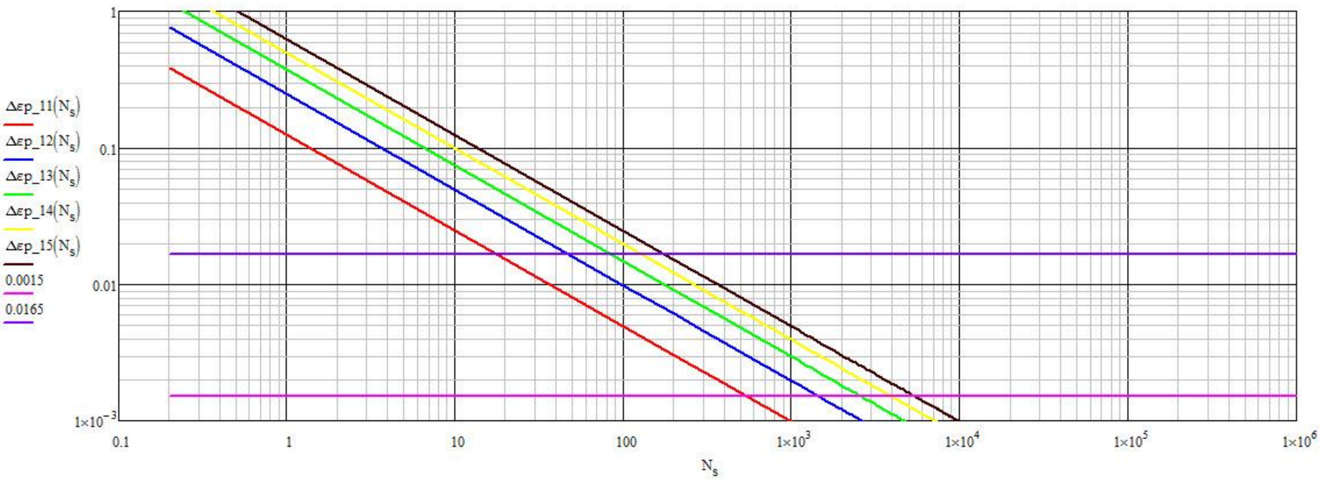

Fig A8.10 $\Delta\varepsilon_p$ vs. N_s for C=-0.7 including improvement cycles to failure by reducing $\Delta\varepsilon$ from 0.0165 to 0.0015

Tipton (1998) quoted that the dominant operating regime for coiled tubing is in the range below 1000 cycles. If a strain variation of 0.0165 is assumed, fig A8.6 gives a cycle range of 300-600 for ε_f 0.2-0.3 which is considered to be the most likely interval for coil material. The impact of increased fracture strain on the increase in N_s is considerable, but the contribution decreases as ε_f increases (greatest increase from 0.1-0.2, less increase when going from 0.2-0.3 etc.).

The theory in chapter three stated that a larger value of C means a longer fatigue life; this tendency clearly shows up in the figures. Hence a C of -0.5 indicates good fatigue properties, but it is considered to be a likely value for the coil since it is heat treated to achieve the small grinded structure that is most optimal with respect to fatigue. The hypothesis is therefore that the curves $\Delta\varepsilon_p$_2, $\Delta\varepsilon_p$_3 and $\Delta\varepsilon_p$_4 in figure A8.6 best represent coil behavior. Fig A8.6 is therefore chosen to be the figure for discussion in chapter 8.2.

0.0165 is a quite high strain variation as the value is found assuming the coil being coiled on and off at the minimum radius of the reel. Had a more intermediate value been used, the interval would have been more in the range of 400-1000 and fig A8.8 might have been as suitable, but as the assumptions are many and fault margins are high, more to find the most suitable graph is not carried out.

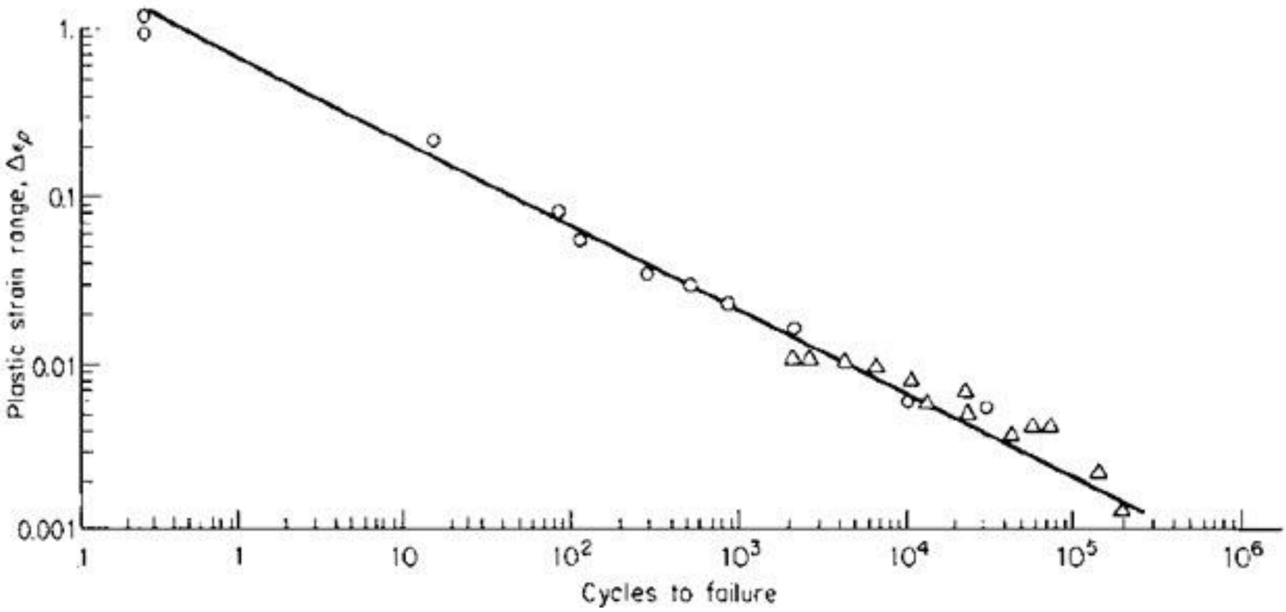

Fig A8.11 $\Delta\varepsilon_p$ vs. N for 347 stainless steel (Energy, 2012)

To check that the results where reasonable the graph given in fig A8.11 for 347 stainless steel where checked against the relevant curves in fig A8.5-10. The curve found to be most similar were $\Delta\varepsilon_p$_4 (N_s) that is based on a fracture strain of 0.4 and a C of -0.5. The fracture strain of 347 stainless steel is given as 0.4 by Masteel (2012) and the mechanical properties are claimed to be excellent, hence a C of -0.5 does not seem unlikely. From this one also sees that the true fracture strain ε_f is a good approximation to ε_f\`.

The conclusion is that the assumptions that are made, used together with the Coffin Manson relation, seem to reflect the reality to a sufficient extent to draw a conclusion on the potential for improving coil life.

11.5.3 Results Risk Analysis

Table A8.12 Step 2a page 1

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2a.1: Lowering wire	2a.1-1	*Dependent of a fully functional winch	*Regular testing *Keep recomended maintenance plan *Certifiy winch	Failure of winch	*Defect/damaged winch	*Provide possible access to winch for corrective repair *Evaluate need for available spare parts *Use of standard components	3	M	3M	2	L	2L
	2a.1-2	*Personell must retrieve wire and pull towards reel	*Guide rope (soft as possible to remain functional) at the end of wire	Wire whipping/cutting working personnel	*Personnel has to be near/ interact with moving wire	*Protective gear (helmet, gloves, glasses, shoes and coverall)	3	M	3M	2	M	2M
	2a.1-3	*Wire is coming from a location far from where it is needed and without optimal control because of distance to control cabin/panel	*Design structure to avoid entanglement *Provide safe guiding of wire *Evaluate need for installing a camera to follow wire movement	Wire gets stuck	*Structure provide opportunity for entanglement	*Provide possible access to winch for corrective actions	3	M	3M	2	L	2L

Table A8.13 Step 2a page 2

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2a.2: Connecting wire to guide pipe	2a.2-1	*Need for manual work when connecting wire and guide pipe	*Keep installation in mind when designing lock *Training of personnel on how to use lock *SJA (prevent operation of winch/reel components while locking)	Squeezing of hand/fingers in connection mechanism	*Procedures not kept *Poor lock design *Unsatisfactory training/lack of information *Time pressure	*Protective gear (gloves etc.)	3	H	3H	3	L	3L
	2a.2-2	*Wrong/carless way of locking *Winch pulls back (wrongfully)	*Keep installation in mind when designing lock *Training of personnel on how to use lock *SJA (prevent operation of winch/reel components while locking)	Wire vipping working personel (if lost from working platform)	*Procedures not kept *Failure of locking mecanism	*Protective gear (helmet, glases etc.) *Close of area to avoid ingury of personel not involved in operation	3	H	3H	2	M	2M

Table A8.14 Step 2a page 3

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2a.3:Pull guide pipe up towards injector	2a.3-1	•Support arm in tower must handle significant load	•Calculation check of design •Design check by senior designer •Use of suitable safety factors •Satisfactory NDT of welds •Control of loading	Failure of support arm	•Overloaded structure	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.)	5	M	5M	3	L	3L
	2a.3-2	•Connection point wire-guide pipe must handle significant load	•Training of personnel •SJA •Design/calculation check •Control capacity against expected loads	Failure of connection point (wire-guide pipe)	•Wrong/carless way of locking •Procedures not kept •Overload/under-dimensioned lock	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.)	5	M	5M	3	L	3L
	2a.3-3	•Winch has to handle high loads and be correctly operated	•Know max load, not exceed max load •Training of personnel •Satisfactory maintenance/testing of winch	Failure of winch	•Procedures (maintenance/use) not kept •Lack of training	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.) •Provide access to winch	5	M	5M	3	L	3L

Table A8.15 Step 2a page 4

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
	2a.3-4	˚Gravity acting to move saddle point during raising of guide pipe	˚Training of personel ˚Check lists onshore to be controlled offshore ˚Design/calkulation check ˚Check lock before raising guide pipe	Failure of mechanism locking saddle support in position	˚Procedures not kept onshore˚Lack of training ˚Damaged lock	˚Design out risk of damage to equipment on reel caused by saddle support collition	3	M	3M	2	L	2L
	2a.3-5	˚Support structure/components on reel must handle significant loading	˚Design/calkulation check ˚Protect sensetive equipment during transport	Failure of support structure/components on the reel (very general hazard because of unclear design)	˚Support structure under-dimensioned or poorly designed ˚Fragile components used ˚Complex functionality ˚Poor maintenance ˚Insufficient testing/control before shipping	˚Robust design if possible ˚Use of standard components to ease/shorten repair time	4	L	4L	3	L	3L
	2a.3-6	˚Gravity work against the coil moving upwards	˚Check lock before raising guide pipe ˚Training of personnel ˚Design/calculation check of lock	Preinstalled coil slips `backwards`	˚Failure of lock coil-guide pipe ˚Wrongly installed lock	˚Use of feeder that can feed the coil forward if necessary ˚Provide tools/stab winch on injector platform that can pull the coil back	3	M	3M	2	L	2L

Table A8.16 Step 2a page 5

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2a.4: Connect guide pipe to upper bend restrictor	2a.4-1	•Need for manual work when connecting guide pipe and bend restrictor	•Keep installation in mind when designing lock, access and working platform •Training of personnel •SJA (prevent operation of winch/reel components while locking)	Squeezing of hand/fingers in connection mechanism	•Poor lock design •Unsatisfactory training/lack of information •Time pressure •Tough working conditions	•Protective gear (gloves etc.) •Drilling of safety procedures	3	M	3M	3	L	3L
	2a.4-2	•Guide pipe and bend restrictor must be connected	•Correct strength calculations •Good lock design (for purpose) •Training of personel •Double securement, safety line or similar holding guide pipe while locking •Design/calkulation check	Guide pipe faling to the ground	•Poor training •Tough working conditions (limited area high above ground) •Potentially difficult operation	•Extra safety line between guide pipe and tower structure while locking •Dimention/design structure on reel to handle pipe faling (limit damage) •Close of area under hanging load	5	H	5H	3	M	3M
	2a.4-3	•Wire must be released from guide pipe	•Training of personel on how to use lock •SJA (prevent operation of winch while unlocking)	Wipping/slaming of body parts with wire/lock	•Procedures not kept •Personnel not familiarized with equipment	•Possibility to secure wire to structure before unlocking (to prevent lost wire/lock to move unpredictable) •Safety gear (helmet, glasses etc.)	3	M	3M	2	L	2L

Table A8.17 Step 2a page 6

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2a.5: Connect saddle point to structure	2a.5-1	•Need for manual work when connecting saddle point to structure	•Keep installation in mind when designing lock, access and working platform •Training of personnel on how to use the equipment •SJA (prevent operation of winch/reel components while locking)	Squeezing of hand/fingers in connection mechanism	•Procedures not kept •Poor lock design •Unsatesfactory training •Tough working conditions	•Protective gear (gloves etc.) •Training in safety/emergency procedures	3	M	3M	3	L	3L
	2a.5-2	•Work on elevated working platform is needed	•Keep installation in mind when designing lock, access and working platform •Training of personnel on how to use the equipment •Secure items/tools if possible	Faling object	•Procedures not kept •Lack of training •Tough working conditions	•Close of area under working personnel	4	H	4H	3	L	3L

Table A8.18 Step 2a page 7

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2a.6:Release saddle point locking mechanism	2a6-1	•Possible need for manual work when releasing saddle support lock	•Keep instalation in mind when designing lock, access and working platform •Training of personel on how to use lock •SJA	Squeezing of hand/fingers in connection mechanism	•Unsatesfactory training/working conditions	•Protective gear (gloves etc.) •First aid kit available	3	M	3M	3	L	3L
	2a6-2	•Possible need for manual work when releasing saddle support lock	•Keep instalation in mind when designing lock, access and working platform •SJA (not allowed to lean out over handrails) •Evaluate remote control	Not able to reach locking mechanism	•Flex joint wrong positioned onshore •Flex joint has slipped when raising guide pipe	•Provide safe way of getting flex joint closer	3	M	3M	2	L	2L
	2a6-3	•Possible need for manual work when releasing saddle support lock	•Keep instalation in mind when designing lock, access and working platform •SJA (not allowed to lean out over handrails) •Evaluate remote control	Not able to unlock locking mechanism	•Damaged lock •Lock wrongfully used	•Provide access opportunity for corrective repair •Use of standard components	3	M	3M	2	L	2L

Table A8.19 Step 2a page 8

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2a.7:Raise guide pipe to final position	2a.7-1	•Support arm in tower must handle significant load	•Calculation check of design •Design check by senior designer •Use of suitable safety factors •Sattesfactory NDT of welds •Controll of loadig	Failure of support arm	•Overloaded structure	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.)	5	M	5M	3	L	3L
	2a.7-2	•Wire/winch must handle significant loads	•Training of personel •SJA •Design/calkulation check	Failure of winch/wire	•Overload/under dimensioning •Wrong/carless way of locking •Procedures not kept •Poor lock design	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.) •Dimension injector, bend restrictor etc. to handle load in case of failure	5	M	5M	2	L	2L
	2a.7-3	•Connection point has to handle high loads	•Know max load, not exceed max load •Training of personell •Satesfactory maintenance/testing	Failure of connection point wire-saddle point	•Procedures (maintenance/use) not kept •Overload/under dimensioning	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.) •Provide access to winch	5	M	5M	3	L	3L

Table A8.20 Step 2a page 9

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
	2a.7-4	Some flexibility in connection points is required when raising guide pipe to final position (guide pipe will need to change inclanation angle)	•Keep instalation in mind when designing conection points/locks (allow for movement untill locking in final position if necesary) •Calculation/design check •SJA	Failure of connection point upper bend restrictor	•Lack of training in how to use locks •Damaged locks (unsatesfactory maintenance)	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.) •Secure guide pipe by safety lines to structure	4	M	4M	3	L	3L
	2a.7-5	Guide pipe is pulled of reel, has to stop pulling guide pipe when complete lenght is spooled of	•End piece mounted on guide pipe end that cannot exit bend restrictor •Proper use of checklists onshore •Training •SJA •Training in use of winch •Evaluate use of camera on reel if poor overview	Guide pipe pulled out of lower bend restrictor	•Procedures broken onshore (wrongly preinstalled equipment) •Lack of training •Broken procedures offshore (overload)	•Close of area to prevent people to enter zone where there could be unexpected movement of equipment/hanging load •Possibility to reenter guide pipe safely without too much effort •Protective gear (helmet etc.) •Evaluate securement of guide pipe by safety lines to structure around reel	4	M	4M	2	L	2L
	2a.7-6	Support structure/components on reel must handle significant loads	•Design/calculation check •Protect sensitive equipment during transport	Failure of support structure/components on the reel (very general hazzard becauce of unclear design)	•Support structure under dimensioned or poorly designed •Fragile components used •Complex functionality •Poor maintenance •Insufficient testing/control before shipping	•Robust design if possible •Use of standard components to ease/shorten repair time	4	M	4M	3	L	3L

Table A8.21 Step 2a page 10

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
	2a.7-7	Some flexibility in bend restictors is required when raising guide pipe to final position (guide pipe will need to change inclanation angle)	•Keep instalation in mind when designing conection points/locks (allow for movement untill locking in final position if necesary) •Calculation/design check •SJA •Extensive testing onshore	Failure of bend restrictor (complete or functional)	•Lack of training •Damaged components •Unsatesfactory maintenance •Complex functionality	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.)	4	M	4M	3	L	3L

Table A8.22 Step 2a page 11

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2a.8: Lock bend restrictors	2a.8-1	•Bend restrictor might need some locking not to be to flexible during operation	•Keep all phases of instalation in mind when designing locks •Calculation/design check •SJA	Squeezing of hand/fingers in connection mechanism	•Poor design •Lack of training •Tough working conditions	•Drilling of emergency procedures	3	M	3M	3	L	3L
	2a.8-2	•Bend restrictor might need some locking not to be to flexible during operation	•Protect during transport •Inspection before shipping/use •Keep maintenance plan	Unable to lock	*Damage during transport or installation *Unsatisfactory maintenance *Damaged component	•Provide satisfactory access for corrective repair •Use of standard components	3	M	3M	2	L	2L

Table A8.23 Step 2a page 12

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2a.9: Feeding coil through to final position	2a.9-1	Coil has to be feed the final distance through bend restrictor and injector	•Rounded cone on coil end •Design considering this part of installation (smooth passing between the different components)	Coil get stuck	•Broken procedures/lack of training (end piece damaged/forgotten/wrongfully preinstalled)	•Make it possible to reverse and retry •Design for backup solution-pulling coil	3	M	3M	2	L	2L
	2a.9-2	Coil has to be feed the final distance through bend restrictor and injector	•Load factor to compensate for unexpected high load •Extensive testing before offshore use •Maintenance/controll procedures	Failure of feeder	•Poor design •Lack of realistic testing •Damage during transport or installation •Unsatisfactory maintenance •Control sensitive equipment before shipping/use	•Use of standard parts to ease repair •Design for backup solution-pulling coil	3	M	3M	3	L	3L
	2a.9-3	Coil has to be feed the final distance through bend restrictor and injector	•Only use feeder when needed •Extensive testing before offshore use	Feeder damaging coil	•Wheels gripping coil wrongly alligned	•Implement adjustment possibility if needed •Limit use of feeder	3	M	3M	3	L	3L

Table A8.24 Step 2a page 13

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
	2a.9-4	Feeder pushes and injector pulls	•Training of personnel •SJA	Feeder and injector unsynchronized	•Broken procedures/lack of training	•Signal if owerload •Use of standard compoents	2	M	2M	2	L	2L

Table A8.25 Step 2b page 1

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2b.1: Lowering wire	2b.1-1	•Dependent of a fully functional winch	•Regular testing •Keep recomended maintenance plan •Certifiy winch	Failure of winch	•Defect/damaged winch	•Provide possible access to winch for corrective repair •Evaluate need for available spare parts •Use of standard components	3	M	3M	2	L	2L
	2b.1-2	•Personell must retrieve wire and pull towards reel	•Guide rope (soft as possible to remain functional) at the end of wire	Wire whipping/cutting working personnel	•Personnel has to be near/ interact with moving wire	•Protective gear (helmet, gloves, glasses, shoes and coverall)	3	M	3M	2	M	2M
	2b.1-3	•Wire is coming from a location far from where it is needed and without optimal control because of distance to control cabin/panel	•Design structure to avoid entanglement •Provide safe guiding of wire •Evaluate need for installing a camera to follow wire movement	Wire gets stuck	•Structure provide opportunity for entanglement	•Provide possible access to winch for corrective actions	3	M	3M	2	L	2L

Table A8.26 Step 2b page 2

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2b.2: Connecting wire to guide pipe	2b.2-1	•Need for manual work when connecting wire and guide pipe	•Keep installation in mind when designing lock •Training of personnel on how to use lock •SJA (prevent operation of winch/reel components while locking)	Squeezing of hand/fingers in connection mechanism	•Wrong/carless way of locking •Procedures not kept	•Protective gear (gloves etc.)	3	M	3M	3	L	3L

Table A8.27 Step 2b page 3

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2b.3: Pull guide pipe up towards injector	2b.3-1	•Support arm in tower must handle significant load	•Calculation check of design •Design check by senior designer •Use of suitable safety factors •Satisfactory NDT of welds •Control of loading	Failure of support arm	•Overloaded structure	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.)	5	M	5M	3	L	3L
	2b.3-2	•Connection point wire-guide pipe must handle significant load	•Training of personnel •SJA •Design/calculation check •Control capacity against expected loads	Failure of connection point (wire-guide pipe)	•Wrong/carless way of locking •Procedures not kept •Overload/under-dimensioned lock	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.)	5	M	5M	3	L	3L
	2b.3-3	•Winch has to handle high loads and be correctly operated	•Know max load, not exceed max load •Training of personnel •Satisfactory maintenance/testing of winch	Failure of winch	•Procedures (maintenance/use) not kept •Lack of training	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.) •Provide access to winch	5	M	5M	3	L	3L

Table A8.28 Step 2b page 4

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
	2b.3-4	Gravity acting to move saddle point during raising of guide pipe	•Training of personel •Check lists onshore to be controlled offshore •Design/calkulation check •Check lock before raising guide pipe	Failure of mechanism locking saddle support in position	•Procedures not kept onshore•Lack of training •Damaged lock	•Design out risk of damage to equipment on reel caused by saddle support collition	3	M	3M	2	L	2L

Table A8.29 Step 2b page 5

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2b.4: Connect guide pipe to upper bend restrictor	2b.4-1	•Need for manual work when connecting guide pipe and bend restrictor	•Keep installation in mind when designing lock, access and working platform •Training of personnel •SJA (prevent operation of winch/reel components while locking)	Squeezing of hand/fingers in connection mechanism	•Poor lock design •Unsatisfactory training/lack of information •Time pressure	•Protective gear (gloves etc.) •Drilling of safety procedures	3	M	3M	3	L	3L
	2b.4-2	•Guide pipe and bend restrictor must be connected	•Correct strength calculations •Good lock design (for purpose) •Training of personel •Double securement, safety line or similar holding guide pipe while locking •Design/calkulation check	Guide pipe faling to the ground	•Poor training •Tough working conditions (limited area high above ground) •Potentially difficult operation	•Extra safety line between guide pipe and tower structure while locking •Dimention/design structure on reel to handle pipe faling (limit damage) •Close of area under hanging load	5	H	5H	3	M	3M
	2b.4-3	•Wire must be released from guide pipe	•Training of personel on how to use lock •SJA (prevent operation of winch while unlocking)	Wipping/slaming of body parts with wire/lock	•Procedures not kept •Personnel not familiarized with equipment	•Possibility to secure wire to structure before unlocking (to prevent lost wire/lock to move unpredictable) •Safety gear (helmet, glasses etc.)	3	M	3M	2	L	2L

Table A8.30 Step 2b page 6

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2b.5: Connect saddle point to structure	2b.5-1	•Need for manual work when connecting saddle point to structure	•Keep installation in mind when designing lock, access and working platform •Training of personnel on how to use the equipment •SJA (prevent operation of winch/reel components while locking)	Squeezing of hand/fingers in connection mechanism	•Unsatesfactory training •Tough working conditions	•Protective gear (gloves etc.) •Training in safety/emergency procedures	3	M	3M	3	L	3L
	2b.5-2	•Work on elevated working platform is needed	•Keep installation in mind when designing lock, access and working platform •Training of personnel on how to use the equipment •Secure items/tools if possible	Faling object	•Procedures not kept •Lack of training •Tough working conditions	•Close of area under working personnel	4	H	4H	3	L	3L

Table A8.31 Step 2b page 7

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2b.6: Release saddle support locking mechanism	2b.6-1	•Possible need for manual work when releasing saddle support lock	•Keep instalation in mind when designing lock, access and working platform •Training of personel on how to use lock •SJA	Squeezing of hand/fingers in connection mechanism	•Unsatesfactory training/working conditions	•Protective gear (gloves etc.) •First aid kit available	3	M	3M	3	L	3L
	2b.6-2	•Possible need for manual work when releasing saddle support lock	•Keep instalation in mind when designing lock, access and working platform •SJA (not allowed to lean out over handrails) •Evaluate remote control	Not able to reach locking mechanism	•Flex joint wrong positioned onshore •Flex joint has slipped when raising guide pipe	•Provide safe way of getting flex joint closer	3	M	3M	2	L	2L
	2b.6-3	•Support arm in tower must handle significant load	•Calculation check of design •Design check by senior designer •Use of suitable safety factors •Sattesfactory NDT of welds •Controll of loadig	Failure of support arm (as discussed earlyer)	•Overloaded structure	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.)	5	M	5M	3	L	3L

Table A8.32 Step 2b page 8

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2b.7: Raise guide pipe	2b.7-1	•Wire/winch must handle significant loads	•Training of personel •SJA •Design/calkulation check	Failure of winch/wire	•Overload/under dimensioning •Wrong/carless way of locking •Procedures not kept •Poor lock design	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.) •Dimension injector, bend restrictor etc. to handle load in case of failure	5	M	5M	2	L	2L
	2b.7-2	•Connection point has to handle high loads	•Know max load, not exceed max load •Training of personell •Satesfactory maintenance/testing	Failure of connection point wire-saddle point	•Procedures (maintenance/use) not kept •Overload/under dimensioning	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.) •Provide access to winch	5	M	5M	3	L	3L
	2b.7-3	Some flexibility in connection points is required when raising guide pipe to final position (guide pipe will need to change inclanation angle)	•Keep instalation in mind when designing conection points/locks (allow for movement untill locking in final position if necesary) •Calculation/design check •SJA	Failure of connection point upper bend restrictor	•Lack of training in how to use locks •Damaged locks (unsatesfactory maintenance)	•Closing of area to prevent people to enter zone where there will be hanging load •Protective gear (helmet etc.) •Secure guide pipe by safety lines to structure	4	M	4M	3	L	3L

Table A8.33 Step 2b page 9

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
WBS 2b.8: Connecting to bend restrictor reel end	2b.8-1	Moving parts (Working platform on coil reel must "meet up" with guide pipe end to allow for guide pipe connection coil reel)	•Sensitive equipment not to be placed in a way that make it exposed during sequence •Personnel training •SJA	Collision of involved elements	•Sensitive equipment wrongly positioned	•Use of standard components to ease repair •Robust design	3	M	3M	2	L	2L
	2b.8-2	Moving parts (Working platform on coil reel must "meet up" with guide pipe end to allow for guide pipe connection coil reel)	•Remotely operated sequence, personell kept on safe distance •Personell training •SJA	Squeezing of body parts	•Procedures broken •Lack of training	•Drilling of emergency procedures (medical)	4	M	4M	3	L	3L
	2b.8-3	Guide pipe must be released from guide pipe reel	•Guide pipe secured to reel with safety line after uncoiled and untill connected to bend restrictor	Damage to equipment and/or body parts by loosened guide pipe	•Wrongful guide pipe installment (procedures broken/lack of training onshore)	•Keep personell on safe distance untill puide pipe is reeled off	4	M	4M	3	L	3L

Table A8.34 Step 2b page 10

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
	2b.8-4	Guide pipe must be connected to coil reel	•Keep instalation in mind when designing lock, access and working platform •Training of personel on how to use the equipment •SJA	Squeezing of hand/fingers in connection mechanism	•Unsatisfactory training •Tough working conditions •Poor lock design	•Protective gear (gloves etc.) •Drilling of emergency procedures	3	M	3M	3	L	3L
	2b.8-5	•Work on elevated working platform might be needed	•Keep instalation in mind when designing lock, access and working platform •Training of personel on how to use the equipment •Sequre items/tools if possible	Faling object	•Work in elevated height/limited space •Procedures not kept	•Close of area under working personel	4	H	4H	2	L	2L

Table A8.35 Step 2b page 11

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2b.9:Alligning guide pipe	2b.9-1	Moving parts (working platform on coil reel must probably move)	•Sensitive equipment not to be placed in a way that make it exposed during sequence •Personnel training •SJA	Collision of involved elements	•Sensitive equipment wrongly positioned	•Standard components to ease repair •Robust design	3	M	3M	2	L	2L
	2b.9-2	Moving parts (working platform on coil reel must probably move)	•Remotely operated sequence, personnel kept on safe distance •Personnel training •SJA	Squeezing of body parts	•Procedures broken •Lack of training		4	M	4M	4	L	4L
	2b.9-3	Support structure/components on reel must handle significant loads	•Design/calculation check •Protect sensitive equipment during transport	Failure of support structure/components on the reel (very general hazzard becauce of unclear design)	•Support structure under dimensioned or poorly designed •Fragile components used •Complex functionality •Poor maintenance •Insufficient testing/control before shipping	•Robust design if possible •Use of standard components to ease/shorten repair time	4	M	4M	3	L	3L

Table A8.36 Step 2b page 12

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2b.9:Alligning guide pipe	2b.9-1	Moving parts (working platform on coil reel must probably move)	•Sensitive equipment not to be placed in a way that make it exposed during sequence •Personnel training •SJA	Collision of involved elements	•Sensitive equipment wrongly positioned	•Standard components to ease repair •Robust design	3	M	3M	2	L	2L
	2b.9-2	Moving parts (working platform on coil reel must probably move)	•Remotely operated sequence, personnel kept on safe distance •Personnel training •SJA	Squeezing of body parts	•Procedures broken •Lack of training		4	M	4M	4	L	4L
	2b.9-3	Support structure/components on reel must handle significant loads	•Design/calculation check •Protect sensitive equipment during transport	Failure of support structure/components on the reel (very general hazzard becauce of unclear design)	•Support structure under dimensioned or poorly designed •Fragile components used •Complex functionality •Poor maintenance •Insufficient testing/control before shipping	•Robust design if possible •Use of standard components to ease/shorten repair time	4	M	4M	3	L	3L

Table A8.37 Step 2b page 13

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2b.10: Feeding coil	2b.10-1	Coil has to be feed through the entire guide pipe lenght	*Rounded cone on coil end *Design considering this part of installation (smooth passing between the different components)	Coil get stuck	*Broken procedures/lack of training (end piece damaged/forgotten/wrongfully preinstalled)	*Make it possible to reverse and retry *Design for backup solution-pulling coil	3	H	3H	3	M	3M
	2b.10-2	Coil has to be feed through the entire guide pipe lenght	*Design for backup solution-pulling the coil the entire or part of the distance	Feeder not powerful enough to feed coil without damaging the coil	*High friction and gravitational force acting against the coil moving throuhg the guide pipe *Extensive operation	NA	3	H	3H	3	H	3H
	2b.10-3	Coil has to be feed through the entire guide pipe lenght	*Load factor to compensate for unexpected high load *Extensive testing before offshore use *Maintenance/controll procedures	Failure of feeder	*Poor design *Lack of realistic testing *Damage during transport or installation *Unsatisfactory maintenance *Control sensitive equipment before shipping/use	*Use of standard parts to ease repair *Design for backup solution-pulling coil	3	M	3M	3	L	3L

Table A8.38 Step 2b page 14

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
	2b.10-4	Coil has to be feed through the entire guide pipe lenght	*Extensive testing before offshore use, feeder design that limit coil damage	Feeder damaging coil	*Wheels gripping coil wrongly alligned, wrong material etc.	*Adjustment possibility if needed	3	M	3M	3	L	3L

Table A8.39 Step 2c page 1

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2c.1: Run coil, tread wire	2c.1-1	*A rope must be tread through strippers, injector and over the gooseneck (manual operation that should be done onshore)	*Implement on check list to check pre-installment and securement before packing *Sufficient training	Rope not pre-installed or pulled out	*Lack of training *Broken procedures	*Provide a safe (as possible) working environment *Tread rope before installing injector in ACTF to minimize work in elevated height	3	M	3M	2	L	2L
	2c.1-2	*A wire must be pulled through strippers, injector and over the gooseneck with a rope	*Provide smooth wire-rope connection	Stuck wire/rope	*Lack of training *Broken procedures	*Safe working environment *Personel training	3	M	3M	2	L	2L
	2c.1-3	A wire must be pulled through strippers, injector and over the gooseneck with a rope	*Provide secure wrie-rope connection *Personell training	Lost wire	*Lack of training *Broken procedures	*Safe working environment *Personel training	3	M	3M	2	L	2L

Table A8.40 Step 2c page 2

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2c.2: Run coil, spool off wire untill reel can be reached	2c.2-1	*Dependent of functional winch	*Regular testing *Keep recommended maintenance plan *Use certified winch *Know (and not exceed) maximum loads (SJA)	Failure of winch	*Damaged winch *Lack of maintenance *Overload (broken procedures)	*Provide possible acces to winch for corrective repair	3	M	3M	2	L	2L
	2c.2-2	*Personell must retrieve wire and pull towards reel	*Keep guide rope at the end of wire *"Soft" rope end	Wire vipping/cutting working personel	*Personell has to be near moving wire	*Protective gear (helmet, gloves, glases; shoes and coverall)	3	M	3M	2	M	2M
	2c.2-3	*Wire is coming from a location far from where it is needed and without optimal control because of distance to control cabin/panel	*Design structure to avoid entanglement *Provide safe guiding of wire *Install camera to follow wire movement (if considered necessary)	Wire gets stuck	*Structure provide opportunity for entanglement	*Provide safe (as possible) way of accessing to winch/structure for corrective actions	3	M	3M	2	L	2L

Table A8.41 Step 2c page 3

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2c.3: Run coil, connecting wire and coil	2c.3-1	*Need for manual work when connecting wire and coil	*Keep installation in mind when designing/placing connection point (possible to work on ground level?)*Training of personnel *SJA (prevent operation of winch/reel components while connecting coil and wire)	Squeesing of hand/fingers in conection mechanism	*Wrong/carless way of locking *Procedures not kept	*Protective gear (gloves etc.) *Relevant emergency procedures known (training)	3	M	3M	3	NL	3NL
	2c.3-2	*Work on elevated working platform (CT reel) might be needed	*SJA *Personel training *Provide a safe (as possible) working environment (kick plates/handrail where possible)	Faling object/personel	*Tight working conditions *Procedures not kept	*No work simultaneously with work on level below *Relevant emergency procedures known (training)	3	M	3M	2	M	2M

Table A8.42 Step 2c page 4

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2c.4: Run coil, retrive coil	2c.4-1	Winch has to pull coil off the reel and up towards injector	*Training of personell *Suficcient inspection, maintenance and testing of equipment	Coil is lost when pulled uppvards (failure or wrong use of winch)	*Lack of training/broken procedures *Poor maintenance/inspection	*Close of area under hanging load	4	M	4M	2	L	2L
	2c.4-2	Winch has to pull coil off the reel and up towards injector	*Training of personell *Suficcient inspection, maintenance and testing of equipment	Coil is lost when pulled uppvards (failure of conection point wire-coil)	*Lack of training/broken procedures *Poor maintenance/inspection	*Close of area under hanging load	4	M	4M	2	L	2L
	2c.4-3	Coil must be pulled over goosneck and down in the injector	*Inspection of equipment before use *Maintenance *Personel training	Coil/wire get stuck	*Wrongful assembly *Damaged wire/coil/connection point	*Safe working environment (to fix problem) *No work simultainusly with work on level belov	3	M	3M	2	L	2L

Table A8.43 Step 2c page 5

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
	2c.4-4	*Support structure must handle appied loads	*Design/calkulation check *Protect sensetive equipment during transport	Failure of support structure/components on the reel	*Poor maintenance *Insufficient testing/control befor shipping	*Robust design if possible *Use of standard components to ease/shorten repair time	4	L	4L	3	NL	3NL

Table A8.44 Step 2d page 1

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2d.1: Pull wire through injector assembly	2d.1-1	•A rope must be tread through strippers, injector and over the gooseneck (manual operation that should be done onshore)	•Implement on check list to check pre-installment and securement before packing •Sufficient training	Rope not pre-installed or pulled out	•Lack of training •Broken procedures	•Provide a safe (as possible) working environment •Tread rope before installing injector in ACTF to minimize work in elevated height	3	M	3M	2	L	2L
	2d.1-2	•A wire must be pulled through strippers, injector and over the gooseneck with a rope	•Provide smooth wire-rope connection	Stuck wire/rope	•Lack of training •Broken procedures	•Safe working environment •Personel training	3	M	3M	2	L	2L
	2d.1-3	A wire must be pulled through strippers, injector and over the gooseneck with a rope	•Provide secure wrie-rope connection •Personell training	Lost wire	•Lack of training •Broken procedures	•Safe working environment •Personel training	3	M	3M	2	L	2L

Table A8.45 Step 2d page 2

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2d.2: Spool off wire and pull against reel	2d.2-1	*Dependent of functional winch	*Regular testing *Keep recommended maintenance plan *Use certified winch *Know (and not exceed) maximum loads (SJA)	Failure of winch	*Damaged winch *Lack of maintenance *Overload (broken procedures)	*Provide possible acces to winch for corrective repair	3	M	3M	2	L	2L
	2d.2-2	*Personell must retrieve wire and pull towards reel	*Keep guide rope at the end of wire *"Soft" rope end	Wire vipping/cutting working personel	*Personell has to be near moving wire	*Protective gear (helmet, gloves, glases; shoes and coverall)	3	M	3M	2	M	2M
	2d.2-3	*Wire is coming from a location far from where it is needed and without optimal control because of distance to control cabin/panel	*Design structure to avoid entanglement *Provide safe guiding of wire *Install camera to follow wire movement (if considered necessary)	Wire gets stuck	*Structure provide opportunity for entanglement	*Provide safe (as possible) way of accessing to winch/structure for corrective actions	3	M	3M	2	L	2L

Table A8.46 Step 2d page 3

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2d.3: Connect wire and coil	2d.3-1	•Need for manual work when connecting wire and coil	•Keep installation in mind when designing/placing connection point (possible to work on ground level?)•Training of personnel •SJA (prevent operation of winch/reel components while connecting coil and wire)	Squeesing of hand/fingers in conection mechanism	•Wrong/carless way of locking •Procedures not kept	•Protective gear (gloves etc.) •Relevant emergency procedures known (training)	3	M	3M	3	NL	3NL
	2d.3-2	•Work on elevated working platform (CT reel) might be needed	•SJA •Personel training •Provide a safe (as possible) working environment (kick plates/handrail where possible)	Faling object/personel	•Tight working conditions •Procedures not kept	•No work simultaneously with work on level below •Relevant emergency procedures known (training)	3	M	3M	2	M	2M

Table A8.47 Step 2d page 4

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2d.4:Retrive coil/guide pipe	2d.4-1	*Winch has to pull coil/guide pipe off the reel and up towards injector	*Training of personell *Suficcient inspection, maintenance and testing of equipment *Sertify winch	Coil is lost when pulled upwards	*Failure or wrong use of winch	*Close of area under hanging load	4	M	4M	3	L	3L
	2d.4-2	*Conecction point wire-coil must handle signifficant loads	*Correct strength calculations (calculation check) *Good lock design (for purpose) *Inspection before use *Training of personell *Suficcient inspection, maintenance and testing of equipment	Coil is lost when pulled upwards	*Lock not correctly used *Damaged lock	*Protective gear (helmet etc.) *Dimension/design structure on reel to handle a falling guide pipe/coil falling (limit damage) *Close of area under hanging load	5	M	5M	3	L	3L
	2d.4-3	*Guide pipe lock must be pulled through feeder and into bend restrictor	*Training of onshore personell *Testing onshore	Guide pipe lock stuck inside feeder or bend restrictor	*Poorly tested design *Use of wrong feeder/bend restrictor *Wrong alignment/adjustment of feeder/bend restrictor	*Implement possibility for manual adjustments offshore *Provide safe (as possible) way of access to winch/structure for corrective actions	3	M	3M	2	L	2L

Table A8.48 Step 2d page 5

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
	2d.4-4	•Guide pipe lock must hold guide pipe in place	•Training of personell •Suficcient inspection, maintenance and testing of equipment onshore	Failure of guide pipe lock	•Wrongful use of lock onshore •Damaged lock	•Implement possibility for manual locking offshore •Provide safe (as possible) way of access to winch/structure for corrective actions	3	M	3M	2	L	2L

Table A8.49 Step 2d page 6

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2d.5: Install saddle support	2d.5-1	*Need for manual work when connecting saddle point and guide pipe	*Keep installation in mind when designing lock, access and working platform *Training of personnel *SJA (prevent operation of winch/reel components while locking)	Squeezing of hand/fingers in connection mechanism	*Unsatisfactory training/working conditions *Poor design	*Protective gear (gloves etc.) *Training in safety/emergency procedures	3	M	3M	3	L	3L
	2d.5-2	*Work on elevated working platform is needed	*Keep installation in mind when designing lock, access and working platform *Training of personnel on how to use the equipment *Secure items/tools if possible	Faling object (s)	*Procedures not kept *Lack of training	*Close of area under working personel *Protective gear (helmet etc.)	4	H	4H	3	L	3L

Table A8.50 Step 2d page 7

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2d.6: Lock guide pipe to bend restrictor	2d.6-1	Coil must be pulled in the bend restrictor and down in the injector	˚Design bend restrictor to provide adequate guiding	Damage /reduced fatigue life to part of the coil	˚Bend restrictor provide insufficient guiding/bend radius	NA	3	H	3H	3	L	3L
	2d.6-2	Coil must be pulled in the bend restrictor and down in the injector	˚Inspection of equipment before use ˚Maintenance ˚Personel training	Coil/wire get stuck	˚Wrongful assembly ˚Damaged wire/coil/connection point	˚Safe working environment (to fix problem) ˚No work simultaneously with work on level below	3	M	3M	2	L	2L
	2d.6-3	Injector has to relieve the winch and pull the coil the last distance	˚Personel training ˚Robust design if possible	Unsynchronized action between injector and winch	˚Unsynchronized shift of "pull responsibility"	˚Use of standard components to ease/shorten repair time ˚Provide safe (as possible) way of access to winch/structure for corrective actions	3	M	3M	2	L	2L

Table A8.51 Step 2d page 8

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
	2d.6-4	Coil must be released from guide pipe lock	*Inspection of equipment before use *Maintenance *Personel training *Extensive testing onshore	Failure of lock, coil not released	*Wrongful assembly *Damaged lock *Poor maintenance *Poor design/testing	*Provide opportunity to unlock manually *Provide safe (as possible) way of access for corrective actions	3	M	3M	2	L	2L
	2d.6-5	Guide pipe lock must lock to bend restrictor	*Inspection of equipment before use *Maintenance *Personel training *Extensive testing onshore	Failure of lock, locking to bend restrictor failed	*Wrongful assembly *Damaged lock *Poor maintenance *Poor design/testing	*Provide opportunity to lock manually *Provide safe (as possible) way of access for corrective actions	3	M	3M	2	L	2L
	2d.6-6											

Table A8.52 Step 2d page 9

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2d.7: Conect saddle point to tower	2d.7-1	*Need for manual work when connecting saddle point and guide pipe	*Keep instalation in mind when designing lock, access and working platform *Training of personel on how to use lock *SJA (prevent operation of winch/reel components while locking)	Squeezing of hand/fingers in connection mechanism	*Unsatisfactory training/working conditions *Design not user friendly	*Protective gear (gloves etc.) *Training in safety/emergency procedures	3	M	3M	3	L	3L
	2d.7-2	*Work on elevated working platform is needed	*Keep installation in mind when designing lock, access and working platform *Training of personnel *SJA *Secure items/tools if possible	Faling object (s)	*Procedures not kept	*Close of area under working personel	4	H	4H	3	L	3L

Table A8.53 Step 2d page 10

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2d.8: Release saddle point from guide pipe	2d.8-1	*Possible need for manual work when releasing saddle point lock	*Keep installation in mind when designing lock, access and working platform *Training of personnel *SJA *Evaluate remotely controlled unlocking	Squeesing of hand/fingers between in locking mechanism or between locking mechanism and guide pipe	*Unsatesfactory training/working conditions *Poor design	*Protective gear (gloves etc.) *Training in safety/emergency procedures	3	M	3M	3	L	3L
	2d.8-2	*Possible need for manual work when releasing saddle point lock	*Keep installation in mind when designing lock, access and working platform *SJA *Evaluate remotely controlled unlocking	Not able to reach/unlock locking mechanism	*Saddle support wrongly positioned *Saddle support has slipped when raising guide pipe	*Provide safe way of getting saddle support closer (fishing tool, skidding of injector, remote control)	3	M	3M	2	L	2L
	2d.8-3	*Support arm in tower must handle significant load	*Calculation check of design *Design check by senior designer *Use of suitable safety factors *Sattesfactory NDT of welds *Controll of loadig	Failure of support arm in tower	*Overloaded structure/components	*Close of area to prevent people to enter zone where there will be hanging load *Dimension/chose to use bend restrictor, injector++ that handles the load in case of failure *Protective gear (helmet etc.)	5	M	5M	3	L	3L

Table A8.54 Step 2d page 11

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
	2d.8-4	•Link between support arm and saddle point must handle significant load	•Use of suitable safety factors •Control of loading against capacity •Sufficient maintenance •Control sensitive equipment before use	Failure of link tower-saddle support	•Overloaded components •Damaged components •Poor controll/maintenance	•Close of area to prevent people to enter zone where there will be hanging load •Dimension/chose to use bend restrictor, injector++ that handles the load in case of failure •Protective gear (helmet etc.)	5	M	5M	3	L	3L

Table A8.55 Step 2d page 12

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2d.9: Spool of entire guide pipe lenght	2d.9-1	Some flexibility in bend restictors is required when raising guide pipe to final position (guide pipe will need to change inclanation angle)	*Keep instalation in mind when designing conection points/locks (allow for movement untill locking in final position if necesary) *Calculation/design check *SJA *Extensive testing onshore	Failure of bend restrictor (complete or functional)	*Lack of training *Damaged components *Unsatesfactory maintenance *Complex functionality	*Closing of area to prevent people to enter zone where there will be hanging load *Protective gear (helmet etc.)	4	M	4M	3	L	3L
	2d.9-2	Support structure/components on reel must handle significant loads	*Design/calculation check *Protect sensitive equipment during transport	Failure of support structure/components on the reel (very general hazzard becauce of unclear design)	*Support structure under dimensioned or poorly designed *Fragile components used *Complex functionality *Poor maintenance *Insufficient testing/control before shipping	*Robust design if possible *Use of standard components to ease/shorten repair time	4	M	4M	3	L	3L

Table A8.56 Step 2d page 13

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
2d.10: Lock lower guide pipe end to lower bend restrictor	2d.10-1	Guide pipe must bepupped in position (lower end inside bend restrictor)	*Training of personel *Implement on check list to be checked before shipping	Guide pipe pulled out of bend restrictor	*Dependent on corectly installed "end stopp" on guide pppe end	*Provide opportunity to reenter guide pipe and install end stop offshore *Provide safe (as possible) way of access for corrective actions	3	M	3M	2	L	2L
	2d.10-2	Guide pipe must be locked of inside lower bend restrictor	*Keep installation in mind when designing lock, access and working platform *Control sensitive equipment before use *Extensive testing onshore	Guide pipe is not locked of automatically as it reaches its position inside the bend restrictor	*Damaged lock	*Provide safe (as possible) way of access for manual locking *Use standard components for easyer repair/replacement	3	M	3M	2	L	2L

Table A8.57 CiC operations

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Probability without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
6.1CiC: Operation, CiC	6.1CiC-1	Several hundred meters of steel pipe must slide through the guide pipe	•Choose material with low a low friction factor against steel •Consider use of lubricant •Use a material that can handle the expected load •Extensive testing	Damaging wear of guide pipe	•The coil surface is coarser than expected (damaged coil) •Unexpected material behaviour	•Use an outer layer in more wear resistant material as "safety shell" that is able to carry the load if the inner layer is worn	4	H	4H	3	L	3L
	6.1CiC-2	Steel pipe must slide through several meters of guide pipe	•Choose guide pipe material with low a low friction factor against steel •Consider use of lubricant •Use guide pipe material that wears faster than the coil material (but not no fast) •Extensive testing	Damage to coil	•Damaged guide pipe material •Failure/lack of lubricant system •Unexpected material behaviour	•Inspection of inner surface guide pipe after operation •Inspection of coil after operation	3	H	3H	3	M	3M
	6.1CiC-3	Hang off point must act as both support and allow for some movement, potentially complicated mechanism	•Extensive and realistic testing before use offshore •Limit operation window •Inspection before use •Proper maintenance	Unsatesfactory heave compensation/finction saddle support-tower conection	•Damage to mechanism •Unexpected behavior •Wrong use/assembly •To rough conditions	•Allow for quick and safe lowering of guide pipe if necesary •Double securement ("safety line")	4	H	4H	3	M	3M
	6.1CiC-4	Bend restrictors will experience loading during operation	•Design/calculation check •Testing •Operational limits	Failure of bend restrictor (s)	•Damage during transport or installation •Unsatisfactory maintenance	•Robust design (minimize damage in case of lock failure) •Guide pipe secured in case of lock failure bend restrictors	4	M	4M	3	L	3L

Table A8.58 TR operations

WBS element	Risk ID	Initiating Events (Threats)	Potential risk reducing measures (Barriers)	Hazzarous Event	Triggering Factor(s)	Potential Consequence Redusing Measures	Cons. without measures	Prob. without barriers	Risik no measures taken	Cons., measures taken	Prob. barriers impl.	Reduced risk
6.1TR: Operation	6.1TR-1	*Reel spools coil back and forth with the vessel motion to keep tension in the coil	*Running speed equal or above critical running speed *Lowering pressure if possible/needed *Use as small coil diameter as possible and as large wall thickness as economically justifiable *Limit operational window enough *Evaluate the uncertainty in weather forecasts	Fatigue damage to coil	*Operational limits exceeded *Unexpected weather conditions or other unexpected event (as stuck tool)	*Inspection of the most loaded parts of the coil after use, no reuse of coil with little fatigue life left	4	M	4M	3	L	3L
	6.1TR-2	*Reel spools coil back and forth with the vessel motion to keep tension in the coil	*Running speed equal or above critical running speed *Lowering pressure if possible/needed *Use as small coil diameter as possible and as large wall thickness as economically justifiable *Limit operational window enough *Evaluate the uncertainty in weather forecasts	Fracture of coil because of fatigue damage	*Operational limits exceeded *Unexpected weather conditions or other unexpected event (as stuck tool) *Damaged coil	*Limit other activities/ near operation *Personnel trained to carry out emergency procedures	5	M	5M	4	L	4L

Table A8.59 Summation of step 2a hazardous events part 1

WBS element	Risk ID	Hazardous Event	Reduced Risk
2a.1: Lowering wire	2a.1-1	Failure of winch	2L
	2a.1-2	Wire whipping/cutting working personnel	2M
	2a.1-3	Wire gets stuck	2L
2a.2: Connecting wire to guide pipe	2a.1-1	Squeezing of hand/fingers in connection mechanism	3L
	2a.1-2	Wire vipping working personel (if lost from working platform)	2M
2a.3:Pull guide pipe up towards injector	2a.3-1	Failure of support arm	3L
	2a.3-2	Failure of connection point (wire-guide pipe)	3L
	2a.3-3	Failure of winch	3L
	2a.3-4	Failure of mechanism locking saddle support in position	2L
	2a.3-5	Failure of support structure/components on the reel (very general hazard because of unclear design)	3L
	2a.3-6	Preinstalled coil slips `backwards`	2L
2a.4: Connect guide pipe to upper bend restrictor	2a.4-1	Squeezing of hand/fingers in connection mechanism	3L
	2a.4-2	Guide pipe faling to the ground	3M
	2a.4-3	Wipping/slaming of body parts with wire/lock	2L
2a.5: Connect saddle point to structure	2a.5-1	Squeezing of hand/fingers in connection mechanism	3L
	2a.5-2	Faling object	3L

Table A8.60 Summation of step 2a hazardous events part 2

WBS element	Risk ID	Hazardous Event	Reduced Risk
2a.6:Release saddle point locking mechanism	2a6-1	Squeezing of hand/fingers in connection mechanism	3L
	2a6-2	Not able to reach locking mechanism	2L
	2a6-3	Not able to unlock locking mechanism	2L
2a.7:Raise guide pipe to final position	2a.7-1	Failure of support arm	3L
	2a.7-2	Failure of winch/wire	2L
	2a.7-3	Failure of connection point tower structure-saddle point	3L
	2a.7-4	Failure of connection point upper bend restrictor	3L
	2a.7-5	Guide pipe pulled out of lower bend restrictor	2L
	2a.7-6	Failure of support structure/components on the reel (very general hazzard becauce of unclear design)	3L
	2a.7-7	Failure of bend restrictor (complete or functional)	3L
2a.8: Lock bend restrictors	2a.8-1	Squeezing of hand/fingers in connection mechanism	3L
	2a.8-2	Unable to lock	2L
2a.9: Feeding coil through to final position	2a.9-1	Coil get stuck	2L
	2a.9-2	Failure of feeder	3L
	2a.9-3	Feeder damaging coil	3L
	2a.9-4	Feeder and injector unsynchronized	2L

Table A8.61 Summation of step 2b hazardous events part 1

WBS element	Risk ID	Hazardous Event	Reduced Risk
2b.1: Lowering wire	2b.1-1	Failure of winch	2L
	2b.1-2	Wire whipping/cutting working personnel	2M
	2b.1-3	Wire gets stuck	2L
2b.2: Connecting wire to guide pipe	2b.2-1	Squeezing of hand/fingers in connection mechanism	3L
2b.3: Pull guide pipe up towards injector	2b.3-1	Failure of support arm	3L
	2b.3-2	Failure of connection point (wire-guide pipe)	3L
	2b.3-3	Failure of winch	3L
	2b.3-4	Failure of mechanism locking saddle support in position	2L
2b.4: Connect guide pipe to upper bend restrictor	2b.4-1	Squeezing of hand/fingers in connection mechanism	3L
	2b.4-2	Guide pipe faling to the ground	3M
	2b.4-3	Wipping/slaming of body parts with wire/lock	2L
2b.5: Connect saddle point to structure	2b.5-1	Squeezing of hand/fingers in connection mechanism	3L
	2b.5-2	Faling object	3L
2b.6: Release saddle point locking mechanism	2b.6-1	Squeezing of hand/fingers in connection mechanism	3L
	2b.6-2	Not able to reach locking mechanism	2L
	2b.6-3	Failure of support arm	3L

Table A8.62 Summation of step 2b hazardous events part 2

WBS element	Risk ID	Hazardous Event	Reduced Risk
2a.6:Release saddle point locking mechanism	2a6-1	Squeezing of hand/fingers in connection mechanism	3L
	2a6-2	Not able to reach locking mechanism	2L
	2a6-3	Not able to unlock locking mechanism	2L
2a.7:Raise guide pipe to final position	2a.7-1	Failure of support arm	3L
	2a.7-2	Failure of winch/wire	2L
	2a.7-3	Failure of connection point tower structure-saddle point	3L
	2a.7-4	Failure of connection point upper bend restrictor	3L
	2a.7-5	Guide pipe pulled out of lower bend restrictor	2L
	2a.7-6	Failure of support structure/components on the reel (very general hazzard becauce of unclear design)	3L
	2a.7-7	Failure of bend restrictor (complete or functional)	3L
2a.8: Lock bend restrictors	2a.8-1	Squeezing of hand/fingers in connection mechanism	3L
	2a.8-2	Unable to lock	2L
2a.9: Feeding coil through to final position	2a.9-1	Coil get stuck	2L
	2a.9-2	Failure of feeder	3L
	2a.9-3	Feeder damaging coil	3L
	2a.9-4	Feeder and injector unsynchronized	2L

Table A8.63 Summation of step 2c hazardous events

WBS element	Risk ID	Hazardous Event	Reduced Risk
2c.1: Run coil, tread wire	2c.1-1	Rope not pre-installed or pulled out	2L
	2c.1-2	Stuck wire/rope	2L
	2c.1-3	Lost wire	2L
2c.2: Run coil, spool off wire untill reel can be reached	2c.2-1	Failure of winch	2L
	2c.2-2	Wire vipping/cutting working personel	2M
	2c.2-3	Wire gets stuck	2L
2c.3: Run coil, connecting wire and coil	2c.3-1	Squeesing of hand/fingers in conection mechanism	3NL
	2c.3-2	Faling object/personel	2M
2c.4: Run coil, retrive coil	2c.4-1	Coil is lost when pulled uppvards (failure or wrong use of winch)	2L
	2c.4-2	Coil is lost when pulled uppvards (failure of conection point wire-coil)	2L
	2c.4-3	Coil/wire get stuck	2L
	2c.4-4	Failure of support structure/components on the reel	3NL

Table A8.64 Summation of step 2d hazardous events part 1

WBS element	Risk ID	Hazardous Event	Reduced Risk
2d.1: Pull wire through injector assembly	2d.1-1	Rope not pre-installed or pulled out	2L
	2d.1-2	Stuck wire/rope	2L
	2d.1-3	Lost wire	2L
2d.2: Spool off wire and pull against reel	2d.2-1	Failure of winch	2L
	2d.2-2	Wire vipping/cutting working personel	2M
	2d.2-3	Wire gets stuck	2L
2d.3: Connect wire and coil	2d.3-1	Squeesing of hand/fingers in conection mechanism	3NL
	2d.3-2	Faling object/personel	2M
2d.4:Retrive coil/guide pipe	2d.4-1	Coil is lost when pulled upwards (winch failure/missuse)	3L
	2d.4-2	Coil is lost when pulled upwards (failure of connection point)	3L
	2d.4-3	Guide pipe lock stuck inside feeder or bend restrictor	2L
	2d.4-4	Failure of guide pipe lock	2L
2d.5: Install saddle support	2d.5-1	Squeezing of hand/fingers in connection mechanism	3L
	2d.5-2	Faling object (s)	3L

Table A8.65 Summation of step 2d hazardous events part 2

WBS element	Risk ID	Hazardous Event	Reduced Risk
2d.6: Lock guide pipe to bend restrictor	2d.6-1	Damage /reduced fatigue life to part of the coil	3L
	2d.6-2	Coil/wire get stuck	2L
	2d.6-3	Unsynchronized action between injector and winch	2L
	2d.6-4	Failure of lock, coil not released	2L
	2d.6-5	Failure of lock, locking to bend restrictor failed	2L
2d.7: Conect saddle point to tower	2d.7-1	Squeezing of hand/fingers in connection mechanism	3L
	2d.7-2	Faling object (s)	3L
2d.8: Release saddle point from guide pipe	2d.8-1	Squeesing of hand/fingers between in locking mechanism or between locking mechanism and guide pipe	3L
	2d.8-2	Not able to reach/unlock locking mechanism	2L
	2d.8-3	Failure of support arm in tower	3L
	2d.8-4	Failure of link tower-saddle support	3L
2d.9: Spool of entire guide pipe lenght	2d.9-1	Failure of bend restrictor (complete or functional)	3L
	2d.9-2	Failure of support structure/components on the reel (very general hazzard becauce of unclear design)	3L
2d.10: Lock lower guide pipe end to lower bend restrictor	2d.10-1	Guide pipe pulled out of bend restrictor	2L
	2d.10-2	Guide pipe is not locked of automatically as it reaches its position inside the bend restrictor	2L

Table A8.66 Summation hazardous events operation CiC

WBS element	Risk ID	Hazzarous Event	Reduced risk
6.1 CiC: Operation, CiC	6.1 CiC-1	Damaging wear of guide pipe	3L
	6.1 CiC-2	Damage to coil	3M
	6.1 CiC-3	Unsatesfactory heave compensation/finction saddle support-tower conection	3M
	6.1 CiC-4	Failure of bend restrictor (s)	3L

Table A8.67 Summation hazardous events operation TR

WBS element	Risk ID	Hazzarous Event	Reduced risk
6.1TR: Operation	6.1TR-1	Fatigue damage to coil	3L
	6.1TR-2	Fracture of coil because of fatigue damage	4L

Table A8.68 Result risk analysis step 2a

Consequence						
Extreme(5)	5-NL	5-L	5-M	5-H	5-E	
High (4)	4-NL	4-L	4-M	4-H	4-E	
Moderate (3)	3-NL	3-L 2a.2-1, 2a.3-1, 2a.3-2, 2a.3-3, 2a.3-5, 2a.4-1, 2a.5-1, 2a.5-2, 2a.6-1, 2a.7-1, 2a.7-3, 2a.7-4, 2a.7-6, 2a.7-7, 2a.8-1, 2a.9-2, 2a.9-3	3-M 2a.4-2	3-H	3-E	
Low (2)	2-NL	2-L 2a.1-1, 2a.1-3, 2a.3-4, 2a.3-6, 2a.4-3, 2a.6-2, 2a.6-3, 2a.7-2, 2a.7-5, 2a.8-2, 2a.9-1, 2a.9-4	2-M 2a.1-2, 2a.2-2	2-H	2-E	
Neglible (1)	1-NL	1-L	1-M	1-H	1-E	
	Not Likely (NL)	Low (L)	Medium (M)	High (H)	Expexted (E)	Probability

Table A8.69 Result risk analysis step 2b

Consequence						
Extreme(5)	5-NL	5-L	5-M	5-H	5-E	
High (4)	4-NL	4-L 2b.9-2	4-M	4-H	4-E	
Moderate (3)	3-NL	3-L 2b.2-1, 2b.3-1, 2b.3-2, 2b.3-3, 2b.4-1, 2b.5-1, 2b.5-2, 2b.6-1, 2b.6-3, 2b.7-2, 2b.7-3, 2b.8-2, 2b.8-3, 2b.8-4, 2b.9-3, 2b.9-4, 2b.10-3, 2b.10-	3-M 2b.4-2, 2b.10-1	3-H 2b.10-2	3-E	
Low (2)	2-NL	2-L 2b.1-1, 2b.1-3, 2b.3-4, 2b.6-2, 2b.7-1, 2b.8-1, 2b.8-5, 2b.9-1	2-M 2b.1-2	2-H	2-E	
Neglible (1)	1-NL	1-L	1-M	1-H	1-E	
	Not Likely (NL)	Low (L)	Medium (M)	High (H)	Expexted (E)	Probability

Table A8.70 Result risk analysis step 2c

Consequence						
Extreme(5)	5-NL	5-L	5-M	5-H	5-E	
High (4)	4-NL	4-L	4-M	4-H	4-E	
Moderate (3)	3-NL 2c.3-1, 2c.4-4	3-L	3-M	3-H	3-E	
Low (2)	2-NL	2-L 2c.1-1, 2c.1-2, 2c.1-3, 2c.2-1, 2c.2-3, 2c.4-1, 2c.4-2, 2c.4-3,	2-M 2c.2-2, 2c.3-2	2-H	2-E	
Neglible (1)	1-NL	1-L	1-M	1-H	1-E	
	Not Likely (NL)	Low (L)	Medium (M)	High (H)	Expexted (E)	Probability

Table A8.71 Result risk analysis step 2d

Consequence						
Extreme(5)	5-NL	5-L	5-M	5-H	5-E	
High (4)	4-NL	4-L 2b.9-2	4-M	4-H	4-E	
Moderate (3)	3-NL 2d.3-1	3-L 2d.4-1, 2d.4-2, 2d.5-1, 2d.5-2, 2d.6-1, 2d.7-1, 2d.7-2, 2d.8-1, 2d.8-3, 2b.8-4, 2b.9-1, 2b.9-2	3-M	3-H	3-E	
Low (2)	2-NL	2-L 2d.1-1, 2d.1-2, 2d.1-3, 2d.2-1, 2d.2-3, 2d.4-3, 2d.4-4, 2d.6-2, 2d.6-3, 2d.6-4, 2d.6-5, 2b.8-2, 2d.10-1, 2d.10-2	2-M 2d.2-2, 2d.3-2	2-H	2-E	
Neglible (1)	1-NL	1-L	1-M	1-H	1-E	
	Not Likely (NL)	Low (L)	Medium (M)	High (H)	Expexted	Probability

Table A8.72 Result risk analysis operation

Consequence						
Extreme(5)	5-NL	5-L	5-M	5-H	5-E	
High (4)	4-NL	4-L 6.1TR-2	4-M	4-H	4-E	
Moderate (3)	3-NL	3-L 6.1 CiC-4 6.1TR-1	3-M 6.1 CiC-1, 6.1 CiC-2, 6.1 CiC-3	3-H	3-E	
Low (2)	2-NL	2-L	2-M	2-H	2-E	
Neglible (1)	1-NL	1-L	1-M	1-H	1-E	
	Not Likely (NL)	Low (L)	Medium (M)	High (H)	Expexted (E)	Probability

11.6 List of Tables and Figures

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11.6.9 To the Appendix

11.7 Abbreviations and List of Symbols

ACTF: advanced coiled tubing tension frame

ALARP: low as reasonably possible

A_w: water line

BCC: body centered cubic structure

BOB: blowout preventer

CiC: coil in coil

COF: coefficient of friction

CT: coil tubing

DHSV: down hole safety valve

E: modulus of elasticity/ young's modulus

ETA: event tree analysis

FCC: face centered cubic

FMECA: failure modes, effects and criticality analysis

FTA: fault tree analysis

HAZOP: hazard and operability analysis

HB: Brinell hardness

H_s: significant wave height

HR: Rockwell hardness

HSE: health, safety and environment

HV: Vickers hardness

k: stiffness

LCC: life cycle cost

M_a: added mas

M_t: total mass

M_v: vessel mass

OD: outer diameter

PEEK: polyetheretherketone

PM: Pierson-Moskowitz

PTFE: polytetrafluorethylene/teflon

RAMS: risk and reliability, availability, maintainability and servability

ROVs: remote operated vehicles

SJA: safe job analysis

S-N: stress-number of cycles

SWIFT: structured what-if technique

T_e: Eigen period

T_g: glass transition temperature

T_m: melting temperature

TR: traditional rig up

URR: ultimate recoverable reserves

UTIM: universal tubing integrity monitor
WBS: work breakdown structure

ϵ: strain
σ_u: maximum stress level that can be applied before failure
σ_y: elastic limit
ω: wave frequency
ω_e: Eigen frequency