NTNU
Norwegian University of Science and Technology
Department of Marine Technology

M.Sc.THESIS

Title:	Delivered:
Choke condition and performance monitoring	**14^{th} June 2010**
	Availability: Unlimited
Student: Jørgen Hagemo Sæther	**Number of pages in total:** 105

Abstract:

Sand production is a common complex problem in the oil and gas industry, and choke valves is typically suffering for this in form of erosive damage. The degree of erosive damage is decided by many different factors where the flow rate velocity and the sand rate are the most important ones.

Much effort has been spent on ways of reducing the choke erosion to be able to maintain the oil and gas production at an optimal level with attention to increased profit, safety and availability. Use of Computational Fluid Dynamics (CFD) has been essential in this work by simulating flow through the choke valve for optimizing the choke design, choosing the optimal erosion resistant material, coming up with improved erosion-related models, and optimal operational procedures of the choke.

Producing with Acceptable Sand Rate (ASR), which means allowing a certain degree of sand erosion in chokes, have proven to be a successful way of maintaining the oil and gas production at an optimal level. To satisfy ASR-production, demands are made on an optimal use of condition and performance monitoring equipment and tools. The use of the condition and performance monitoring tool INSIGHT (from ABB) has in general proven to be successful for satisfying the ASR-production on different Statoil fields, including Statfjord which is in this thesis the area of focus regarding the use of INSIGHT. Important condition monitoring data such as sand rate, flow rate and pressure necessary to say something about the choke erosion status in INSIGHT must be as good as possible, because the quality of the results are limited by quality of the input data.

In this thesis, INSIGHT has been presented, discussed and tested to be able to come up with possible limitations and improvements with special attention to condition monitoring (input) data used in INSIGHT.

Keyword:

sand erosion, choke valve,
condition and performance monitoring

Advisor:

Erling Lunde, Statoil

Address:
NTNU
Department of Marine Technology
N-7491 Trondheim

Location
Marinteknisk Senter
O. Nielsens vei 10

Tel. +47 73 595501
Fax +47 73 595697

NTNU
Norwegian University of
Science and Technology

Faculty of Engineering Science and Technology
Department of Marine Technology

MASTER THESIS
for
M.Sc. student Jørgen Hagemo Sæther
Department of Marine Technology
Spring 2010

Choke condition and performance monitoring.

The MSc. thesis will be concerned with methods for condition monitoring of chokes, especially with regard to wear due to sand. Focus should be on models for describing, and methods for detecting, erosion problems in choke valves.

The candidate should base his work on the current practice for choke monitoring in Statoil. In particular, consider the choke erosion tool Insight (from ABB) and discuss limitations and possible improvements.

The main tasks in this thesis should be to:

1. Describe the state-of-the-art of sand erosion models, with application to choke valves.
2. Describe the state-of-the-art of sand measurement equipment and techniques.
3. Investigate different approaches to condition and performance monitoring.
4. Test and verify different methods on choke data from a Statoil plant (Statfjord) using Insight, EFDD, or other tools.

During the period for this master thesis work the candidate need to have close cooperation with the Statoil.

The thesis must be written like a research report, with an abstract, conclusions, contents list, reference list, etc.

During preparation of the thesis it is important that the candidate emphasizes easily understood and well written text. For ease of reading, the thesis should contain adequate references at appropriate places to related text, tables and figures. On evaluation, a lot of weight is put on thorough preparation of results, their clear presentation in the form of tables and/or graphs, and on comprehensive discussion.

Three copies of the thesis are required. One of these should the candidate deliver to Statoil.

Starting date: 18th January 2010
Completion date: 14th June 2010
Handed in

Tom Anders Thorstensen

Trondheim 18th February 2010.

Tom Anders Thorstensen
Associated Professor II

Preface

This thesis represents the course "TMR 4905-Marine Systems, Master Thesis" within Operational technology. It is valued 30 study points and is the finalization of the Master degree study.

Much time has been dedicated to gather necessary information from different sources like presentations, reports, internet, and not least from people related to this theme. Considering the use of the condition and performance monitoring tool INSIGHT, much time has also been spent to get a reasonable comprehension of it.

Some changes to the area of focus and limitations of the scope during the thesis period have been made since the initial phase. Considering the chapters with background information and necessary theory about choke valves, subsea choke valves have been chosen to take a closer look at since they had more interesting information available and that I have been focusing on these in my Pre project.

Some chapters and themes would have been interesting to include further and go deeper into, but due to lack of information, not enough time to gather the information and the fact that some information is confidential for some companies, this has not been possible. For instance; the calculation methods used in INSIGHT would have been interesting to go deeper into details, but due to the facts mentioned above, this have not been possible.

Sources are marked with a footnote in the different chapter headlines and marked with its respective number in a [ ]. The source list can be found in chapter 10.

For an overview of the most used abbreviations, see page ix.

Thanks to the teaching supervisor Erling Lunde at Statoil, Rotvoll. I will also like to thank Knut Hovda and Åse Unander at ABB for help and guidance regarding use of the condition and performance monitoring tool INSIGHT, and production director at Statfjord C Unit, Aud Sævareid for help related to Statfjord.

Trondheim, 14th June 2010

Jørgen H. Sæther

Summary

The Statfjord field consists of the three production platform Statfjord A, -B and-C where the three subsea fields (Statfjord North, -East and Sygna) are linked up to Statfjord C. The field started production in 1979 and is likely to remain production until 2019.

Increasing sanding tendencies has become an important issue for the production process at Statfjord, because with increased sand production comes increased erosion potential in important equipment such as choke valves which is absolutely not desirable due to potential loss in profit and safety. Sand production can vary from well to well, making the potential amount of sand erosion for each and every choke vary.

Different types of choke valves exist but the principle is the same, which is to regulate (choke) the flow with adjustment of the choke opening. At the Statfjord field, MOV chokes are used on topside wells, while cage types are used on subsea wells.

The flow coefficient-Cv is an important parameter saying something about the choke's performance. It defines the flow capacity of the choke, which means it relates the flow rate through the choke to the choke opening and the pressure differential over the choke. By comparing the theoretical Cv-value (given by the choke vendor) with an actual Cv-value @ a given choke opening, erosion in the choke could be detected because an eroded choke will have an increase in the actual Cv-value compared to the theoretical value representing a non-eroded choke. Different models of finding the actual Cv value exists, but a so-called Elf model is often preferred.

Much investigation is done on erosion damage and how to reduce the erosion potential in chokes as much as possible. Simulating flow through a choke valve using Computational Fluid Dynamics (CFD) to improve erosion models, finding the optimal choke design and -choke operation has been beneficial. The use of wolfram carbide has proven to be the optimal erosion resistant material to be used in chokes.

Different erosion models have been developed through time to be able to say something about the amount of sand erosion based upon different parameters which influences the erosion potential. The flow velocity seems to be the most important factor regarding choke erosion.

Measuring the amount of produced sand is important to be able to say something about the erosion potential. Improvements and further development of existing sand measuring technologies and equipment will make the sand monitoring process even more exact. This will in the next round give an even better "picture" of the erosion potential in choke valves.

The use of Condition Monitoring (CM) in general is beneficial in many ways. In the oil- and gas industry time is money, and a safety breach could cause serious damage on people and the environment. Therefore, use of CM in best possible way to detect deviations and unwanted situations at an early stage is with no doubt beneficial.

INSIGHT (from ABB) is a condition and performance monitoring-tool regarding sand erosion in chokes and bends. It has been used by Statoil for almost a decade, making it a well proven tool with much history and experiences. It monitors the choke status and performance regarding erosion, and comes up with recommendations to reduce erosion potential and increase the production. Erosion monitoring with use of erosion models, sand monitoring and Cv-value calculations are the three main ways of detecting erosion in INSIGHT. An erosion calculator can manually calculate erosion rates and other parameters based on given input data. This is a helpful tool in INSIGHT to see how different input data influences the erosion results.

The integration of INSIGHT at the Statfjord field in 2003 made it possible to produce with an Acceptable Sand Rate (ASR) strategy instead of Maximum Sand Free Rate (MSFR), which means allowing sand erosion under controlled manners to be able to optimize the production. During 2004, 1,9 mill.bbl (barrels of oil) was added to the production, proving that this has been successful.

There is always room for improvements, and that is why INSIGHT is now and then upgraded to become even better and more accurate. More accuracy in the CM process means increased profit due to less failures and improved optimal production. As an example; INSIGHT uses fixed ("worst case") sand rates instead of actual sand rate data, which means that the accuracy in the erosion calculation process has an improving potential. An increase of 1314% was found when using "worst case" sand rate on 0,75[gram/s] instead of sand rate data for a given well at Statfjord C during a certain historical period. This refers to a difference in the choke erosion rate on 0,004871[mm/yr] which is not much as a value, but it is a difference after all.

It would be of interest to go further with some of the possible improvements such as the fact that INSIGHT uses "worst case" instead of actual sand rate data since they exist and are available. It would also be interesting with a further investigation of the different erosion models and calculation methods used in INSIGHT, such as the important Cv-calculation models. For making the CM process as easy as possible and to avoid numbers of errors and complications, the use as less CM tools as possible could be a solution. A thought is to integrate the main functions of INSIGHT into the state-of-the-art CM-tool EFDD.

The INSIGHT development team at ABB has been cooperative and helpful with attention to identifying limitations and possible improvements regarding INSIGHT. They will take the discussed issues into account in later software updates.

Contents

Figure list

Abbreviations

ASR	-	Acceptable Sand Rate
CFD	-	Computational Fluid Dynamics
CM	-	Condition Monitoring
DSP	-	Digital Signal Processing
EFD	-	Early Fault Detection
EFDD	-	Early Fault and Disturbance Detection
FCM	-	Flow Control Module
MOV	-	Multi Orifice Valve
MSFR	-	Maximum Sand Free Rate
PDA	-	Plant Disturbance Analysis
P&ID	-	Process and Instrumentation Diagram
ROV	-	Remote Operated Vehicle
WC	-	Tungsten Carbide

1 Introduction

1.1 Background

This master thesis has four main tasks which in the best possible way, considering available information and time, has been given answers and point of wives to. These tasks are given in the master thesis description (the page after the front page).

INSIGHT is a condition (and performance) monitoring tool which is used to alert and give an early warning to the users about the choke valve condition, considering sand erosion. It has been in use at the Statfjord field since 2003, which means that much historical data and experience exists here.

A close cooperation with Statoil and some people from the development team at ABB, which has developed INSIGHT, is necessary to be able to work with INSIGHT and collect most of the important information needed, since much of the background theory and information are not normally available for others than the people involved.

1.2 Further

Sand production is a major limiting factor for optimal oil and gas production, especially when considering the declining in reservoirs. This concerns old fields such as Statfjord which is first of all the area of focus in this master thesis. This is one major reason for why an increased focus on sand production and the consequences that can have, such as increased erosion potential of choke valves, has appeared the last decade at Statfjord. Another major reason is; using INSIGHT as a condition monitoring tool on such important equipment as the choke valves will achieve optimal production and reduced down time, which again pays off as increased profit.

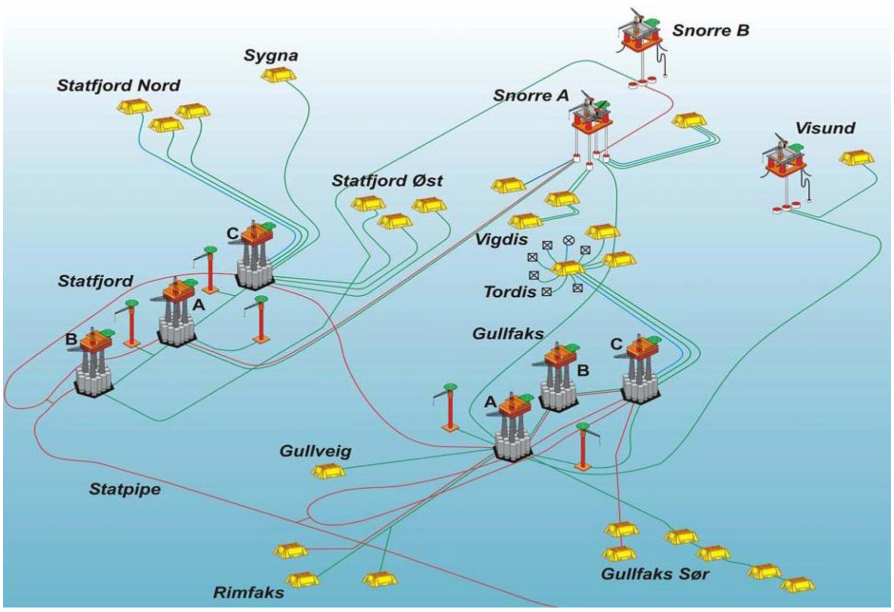
Considering the motivating information above, it is of interest to discuss limitations and possible improvements regarding INSIGHT based upon the four main tasks given in the master thesis description, and the experiences Statfjord has with use of INSIGHT.

2 The Statfjord field

2.1 General[1]

The Statfjord field is a part of the Tampen area (see picture below), and is the largest oil discovery in the North Sea. It consists of the Statfjord A, -B and -C production platforms. It was discovered in 1974 and Statfjord A started production in 1979. Statfjord B and –C started production respectively in 1982 and in 1985. The field is likely to remain production until 2019.

The hydrocarbon reservoir formations on Statfjord lie at depths of 2 500-3 000 meters. They consist of sandstones, with the oil and gas held in pores between the individual sand grains.



2-1: Tampen area in the North Sea

1 [1]

2.2 Subsea[2]

2.2.1 General

The Statfjord subsea equipment is mostly delivered by FMC Technologies, and the Xmas tree design is vertical.

2.2.2 Statfjord North

Statfjord North was discovered in 1977 and began production in 1995. It has been developed with three subsea templates (D, E and F) which are tied back and remotely operated from Statfjord C. The D-template is for water injection, while E and F handle production.

2.2.3 Statfjord East

Statfjord East was also discovered in 1977 and began production in 1994. Like Statfjord North, this field has been developed with three subsea templates (K, L and M) which are tied back and remotely operated from Statfjord C. The K-template is for water injection while L and M handle production.

2.2.4 Sygna

The last and latest subsea field related to Statfjord is Sygna. Sygna was discovered in 1996 and began production in 2000. Sygna has been developed with a subsea template (N) which are tied back and remotely operated from Statfjord C.

2.3 Sand production[3]

The Tampen area in the North Sea where the Statfjord field lies is known for large volumes of water and increasing sanding tendencies considering the production process. Yearly sand production on each platform is estimated to be 50 to 100 tonnes. On individual wells, sand production can be as high as 5 tonnes/year. About 2/3 of the around 90 active production wells are currently limited by sand production.

[2] [1]
[3] [5]

3 Subsea choke valves

3.1 General[4]

The main principle of a subsea choke valve is just the same as for topside choke valves, but subsea it regulates the main flow from its respective well into a common manifold. Typically it is up to 4 wells for each manifold.

There are two main types of choke valves and that is the axial style and the angle style. Subsea chokes are normally of angle style, so therefore this style is further discussed. There exist many different types of subsea choke valves considering all the different suppliers. Some major and important vendors are:

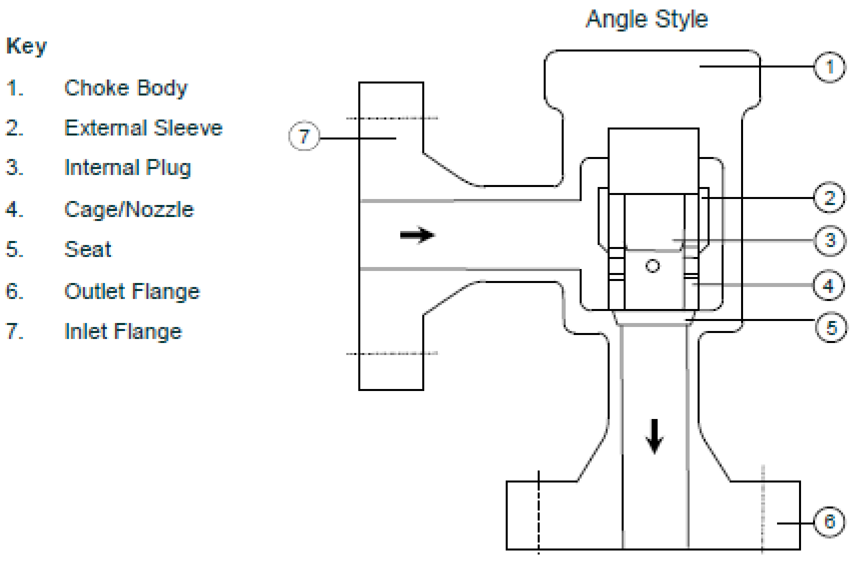
- FMC Technologies
- Kent Introl
- Master Flo
- CAMERON

As mentioned above there exists many different types of subsea choke valves (angle style), and it is especially the type of trim components which is the main difference. The type of material used for these trim components is Tungsten Carbide (WC) because it is the most optimal material to use with attention to potential erosion damage. The main types of trim components are:

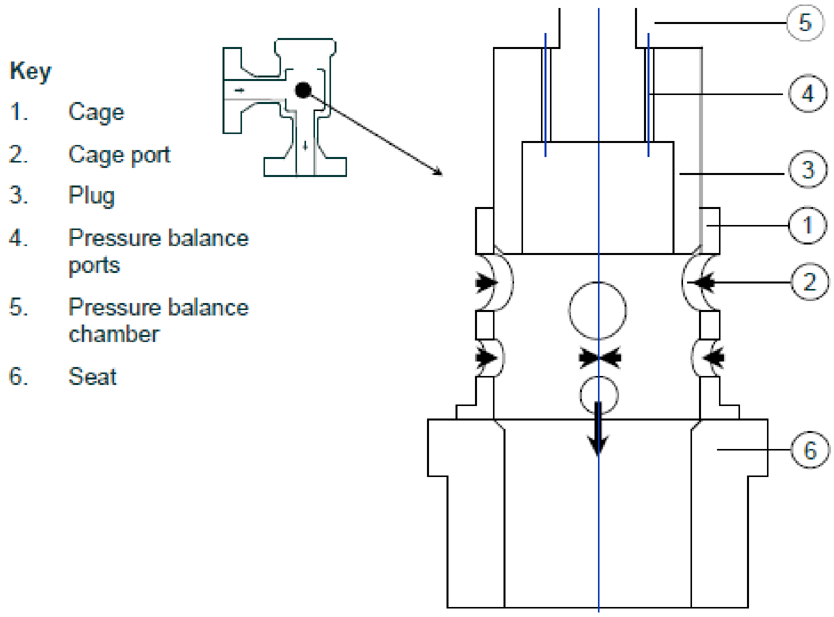
- Cage
- Needle
- Multi Orifice (MOV)

Figure 3-1 and 3-2 on the next page shows a simple sketch of one of the angle style chokes and its trim assembly. This one has a single stage cage with an internal plug. For an overview of other typical used subsea chokes, see attachment A.

[4] [10],[20]

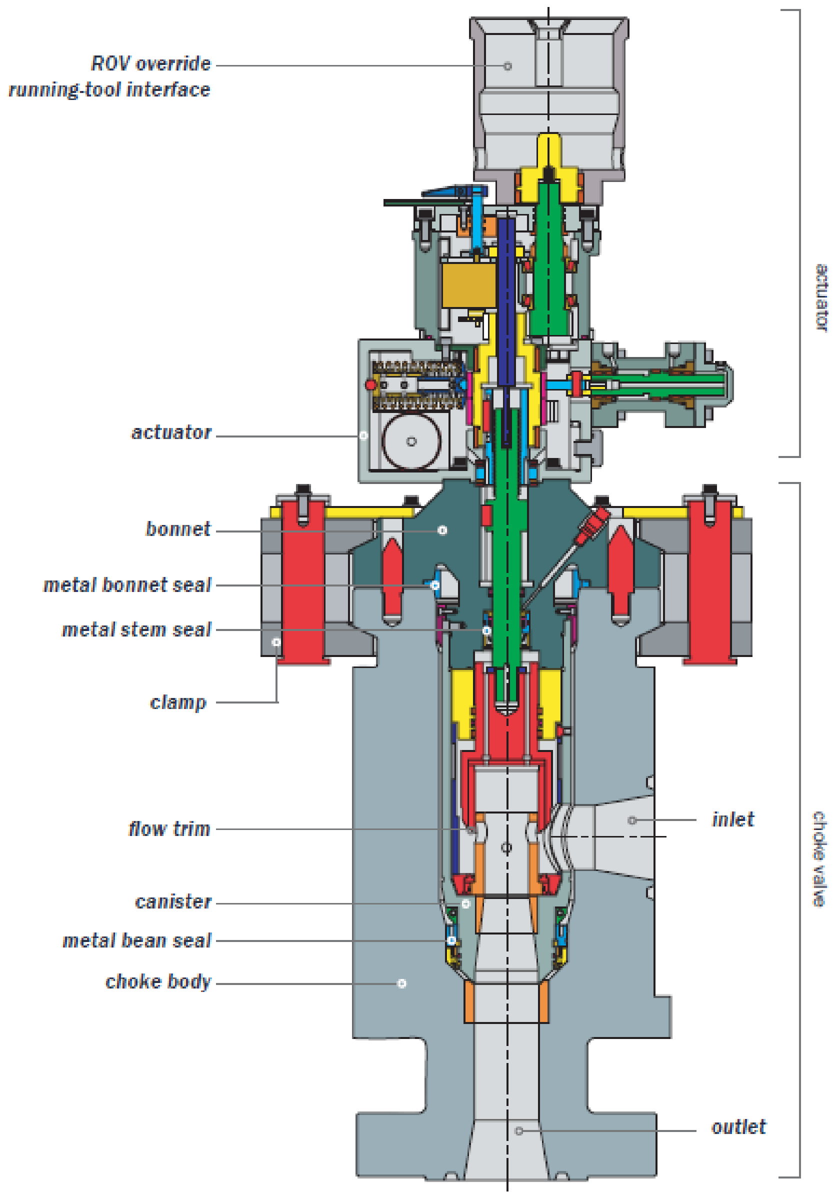


3-1: Angle style choke valve



3-2: The trim assembly for the choke with single stage cage and internal plug

Figure 3-3 below shows a subsea choke valve from Master Flo. The upper part is the "control unit" which is operated by an ROV or from topside and adjusts (chokes) the flow through the valve (seen at the bottom).



3-3: A subsea choke valve

3.2 Subsea choke valves used on Statfjord[5]

"Master Flo P4" is used on the wells at Statfjord North, while "Master Flo P4" and "Master Flo P5" is used on Statfjord East. The difference is the size and therefore the capacity, while the design and type of trim components is the same. The type of trim components on these is single stage cage with external sleeve.

At Sygna the type of choke valve is "Kent Introl 4"". It has a single stage cage with internal plug.

The type of material used in all these chokes mentioned above is Tungsten Carbide, which is the most typically used one.

3.3 Flow coefficient-Cv

3.3.1 General[6]

The Cv is decided and limited by the configuration of the cage and the disk, which are the primary restrictions in the choke.

The flow coefficient-Cv plays an important role when it comes to the choke performance, because it defines the flow capacity of the choke which means it relates the flow rate through the choke to the choke opening and the pressure differential across the choke. Therefore, it also plays an important role considering condition monitoring which is further explained in chapter 7.

The flow capacity is important when it comes to choosing the right choke, because most wells have different flow characteristics.

[5] [13]
[6] [10],[24],[C]

Cv is defined as number of US gallons per minute of pure water @ 60°F that will flow through the choke valve @ a pressure drop of 1psi with reference to the choke inlet and outlet flange. In the metric system Cv is often called Kv. There exist different models and methods for calculating and estimating the Cv. A basic and often used method is presented below:

$\mathbf{Cv = 1,167 * \frac{Q}{\sqrt{\frac{\Delta P}{\rho}}}}$, where $\mathrm{Cv = 1{,}167 * Kv}$

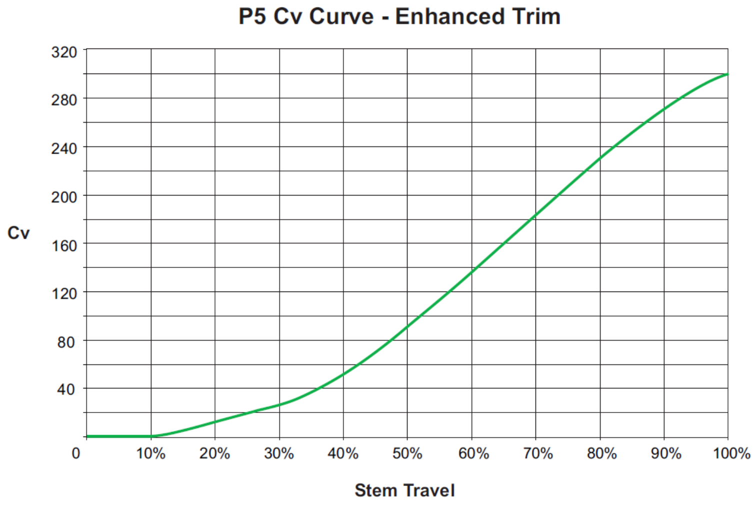
Q: flow rate $[\frac{m^3}{h}]$

ΔP: pressure drop over choke [bar]

ρ: specific gravity of the medium $[\frac{kg}{m^3}]$

3.3.2 The theoretical Cv-value[7]

The theoretical (and optimal) Cv-value is given in tables developed by the choke vendor for the specific choke based on simulations such as use of a simple water flow circuit where accurate measurements of the flow rate and the upstream and downstream pressure are taken. The figure below shows a typical (theoretical) Cv-curve given by a choke vendor. This curve is for the "Master Flo P5" choke valve.



3-4: Theoretical Cv-curve

[7] [10],[20],[24]

3.3.3 The actual Cv-value[8]

There exist more than one way of calculating the actual Cv-value, but the main principles are the same. In this thesis the method used in INSIGHT (by ABB) is discussed. More about INSIGHT in chapter 7.5.

The actual Cv-value during operation is estimated based on (assumed) production rates for oil, gas and water, and temperature- and pressure data from sensors. The flow rate (Q) and the specific gravity of the medium (ρ) is decided at the actual pressure and temperature with help of a so called PVT-model which in simple words "helps" the multiphase meter to find the actual flow rate(Q) by calculating the specific gravity of the medium (ρ).

A flow scheme showing the typical placement of these sensors and the multiphase meter is shown in attachment B. An illustration of the choke valve and the different sensors is shown in attachment C.

3.3.4 Possible improvements of Cv value estimation[9]

As the technology develops and more investigation is done, new and improved models for estimating the Cv values appears. Faster and more advanced computer technology can simulate and calculate more variables, data sets and so on.

The Elf model used in INSIGHT (see chapter 7.5.4) was developed in the early 90's and had off course not the same possible technology as recently developed models, even if the model accounts for critical flow which is an very complex phenomenon.

The Hydro model is such a "modern" model which has proven to be more accurate than the Elf model and others. This can be seen in attachment M where the plots for predicted vs. measured mass flow rate are shown for those two models.

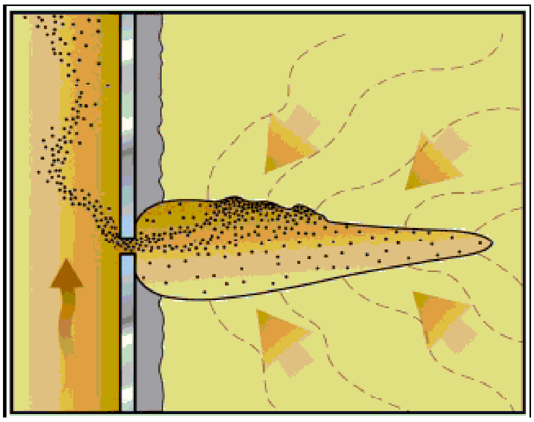
[8] [C]
[9] [31]

4 Sand production and erosion

4.1 Sand production[10]

Sand grains in an undisturbed reservoir are held together by cohesion and friction between the grains. Sand production (as we know it) appears in the very moment when stresses around the wellbore get bigger than the rock strength. Then the sand grains will lose the contact and go from solid rock to sand. Once the sand is detached, it follows the fluid stream through the perforations and into the well. During its transport along with the fluid stream, the sand grains- and fragments are subjected to effects from gravity and hydrodynamic forces. This is just a brief and easy way of explaining sand production which is a complex theme.

The picture below shows in a simple way how the sand goes from solids to particles that follow the well stream.



4-1: Sand production

In the real world this complex theme is a huge potential problem for the oil- and gas production companies. Some examples of what effect sand production can have on this production are presented below:

- It may affect the functionality of regularity equipment such as valves.
- Sand fill in separators, storage tanks and transportation vessel may cause process problems and this may lead to costly shut downs and removal operations.

[10] [4],[5],[7],[19]

The potential amount of sand production may wary a lot from reservoir to reservoir. A way of categorizing this potential is presented in table 4-2 below:

Strong reservoir	No sand production expected, even with pressure on over 300 bar.
Medium strong reservoir	Sand production can be expected between 100 and 200 bar, depending on the stress range.
Weak reservoir	Sand production is expected from day one.

4-2: The potential amount of sand production

Two main factors causing increased sand production is:

1. Declining reservoir pressure
2. Increasing amounts of water

4.2 Sand erosion

4.2.1 General[11]

Erosion (or erosive wear) can be defined as the loss of original material due to solid particle impact on the material surface. With attention to sand erosion, these solid particles are sand grains. This means that the kinetic energy of the moving sand particles is transferred to the material surface causing abrasive material removal. This material is typically some kind of steel.

The figure 4-3 on the next page shows the sand erosion potential vs. the flow velocity, which is the most important parameter considering sand erosion.

[11] [2],[7],[8],[11]

	Wells with extremely low erosion potential	Velocities 0- 5m/s
	Wells with low erosion potential	Velocities 5 -10m/s
	Wells with medium erosion potential	Velocities 10 – 20m/s
	Wells with high erosion potential	Velocities 20- 35m/s
	Wells with extremely high erosion potential	Velocities > 35m/s

4-3: Sand erosion potential vs. velocity

Sand production and erosion is two very complex themes and problems, especially for the oil- and gas industry. As described in 4.1, the sand production is not constant. Adding that complexity together with the fact that the respective amounts of oil and gas are flowing with changing pressure and velocity makes it even more complex and unpredictable. The result can be unpredicted premature failures with inflated operation costs and increased safety problems. That is one major reason why corrective maintenance from time to time has to be carried through on important and sensitive equipment such as choke valves.

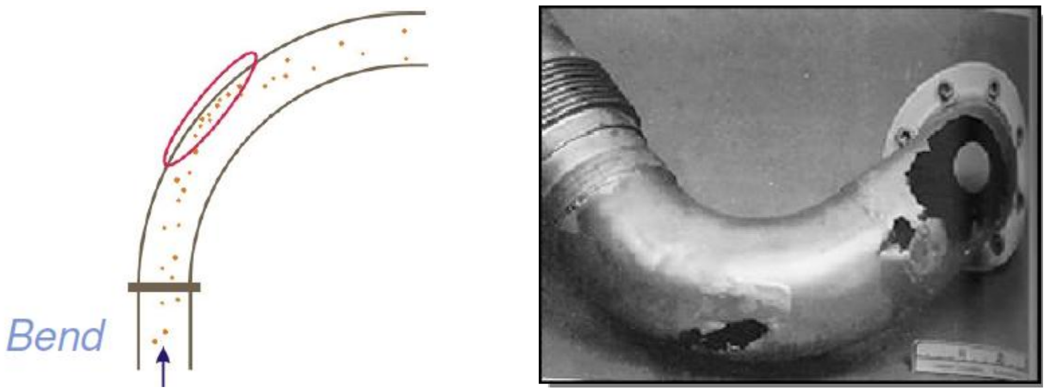
Based on a lot of experience through the times together with research, models for predicting and assess erosive wear have been carried out. More about these models in chapter 5.

4.2.2 Degree of damage[12]

The severity of erosion and what kind of damage it inflicts upon typical "oil- and gas related" equipment such as tubing, flow lines and chokes are strictly linked with the sand transport process and depends on first of all the sand fragment velocity (as mentioned in the last chapter) and the sand rate, but also factors such as:

- Fluid properties
- Flow rate
- Sand grain size
- Type of material

The figure below shows typically what kind of damage sand erosion can cause on equipment such as pipe bends which is a frequent used part in the oil- and gas industry. The sand grains flows along with the well stream with a certain quantity and velocity (left), and hits the pipe material at a certain angle (right). The result is obvious and shows erosion damage.



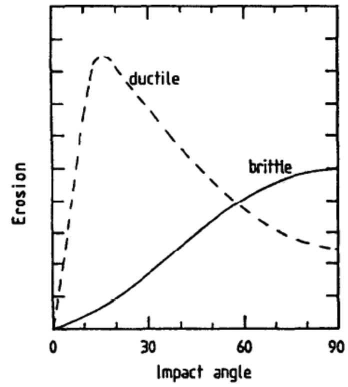
4-4: Sand erosion in a bend

[12] [2],[7]

4.2.3 Sand erosion vs. different materials[13]

A lot of erosion modelling and material testing has been performed trough times for the purpose of finding the optimal material/alloy for the respective equipment and conditions.

The "behaviour" for typical brittle- and ductile materials are shown in figure 4-5 below. Ductile materials normally attain maximum erosion attacks for impact angles in the range 15^0-30^0, while brittle materials normally attain maximum erosion attacks for normal angle (90^0).



4-5: Typical erosion behaviour of ductile and brittle materials as a function of impact angle

In a test of the erosion resistance for 28 different materials relevant for present- and future use in offshore valves/chokes, the most resistant were found to be solid Tungsten Carbide (TC) material, and two very hard ceramics, Silicon Nitride (Si_3N_4) and Boron Carbide (B_4C). Only one coating, a detonation gun deposition (Degun) tungsten carbide (WC) layer was found to give significantly improved erosion characteristics as compared with the reference material, carbon steel.

As another result, the erosion rate shows a strong dependence of the impact velocity, while the impact angles showed a low dependence.

Erosive exposed equipment such as valves can consist of over 10 different material- and coating systems combined to give optimum performance and protection. This has allowed a certain control of erosion.

[13] [2],[3],[11]

4.2.4 Erosion mechanisms[14]

Cutting and deformation are the two types of erosion mechanisms. For low impact angles (typically 0^0-40^0) with hard particles on ductile targets, cutting is likely to happen when the shear stresses of the impact exceed the shear strength of the target. Deformation is likely to happen at higher angles (typically 30^0-90^0) where a stress field is generated near the contact inducing plastically deformed sub-layers (typically sub-surface) where the stress exceeds the yield strength of the target material. This leads to erosion by delamination and micro-cracking.

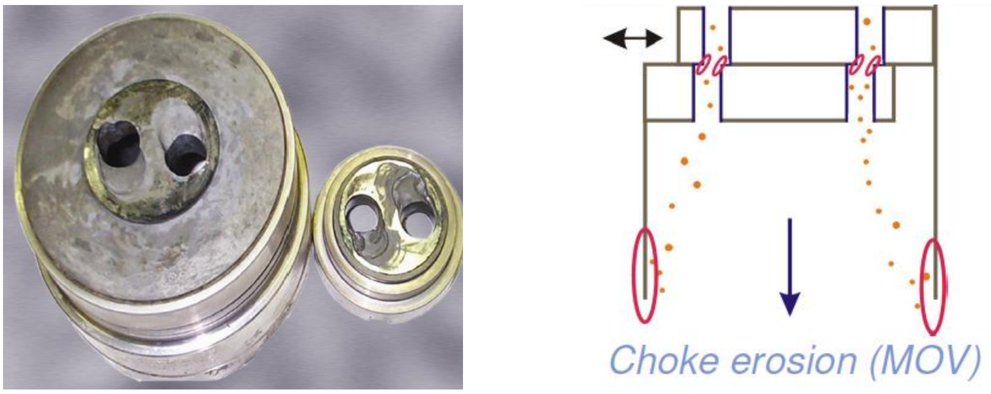
4.3 Sand erosion in choke valves

4.3.1 General[15]

Sand erosion is in general a major problem when it comes to choke valves (both subsea and topside). That is for instance why much time has been spent on research, and tests have been run such as the one mentioned in chapter 4.2.3 for achieving reduced down time caused by problems such as sand erosion. Such premature failures lead to inflated operation costs and increased safety- and containment problems.

Attachment F shows an overview over the most experienced failures to choke valves where sand erosion is a major cause. The overview also shows other causes to experienced failures and their typical root causes.

Figure 4-6 below shows a typical example of a choke valve (MOV) which has been exposed to sand erosion. The figure shows clearly how the sand wears down the choke trim area.



4-6: Example on sand erosion of a MOV choke

---

[14] [11]
[15] [9],[11]

Figure 4-7 below also shows result of sand erosion in a choke, but for a cage trim.
It illustrates severe attack of the once circular cage ports caused by sand impingement and erosion to the inner surfaces due to the misaligned hydrocarbon jets generated by eroded trim port geometries.

4-7: Example on an eroded cage

4.3.2 The sensitivity and criticality of sand erosion[16]

First of all it is the choke body and the trim components which are most sensitive to failures and thereby most critical to erosion.

Erosion to the choke trim components is a concern considering controllability of the choke and may accelerate the erosion process in the choke body outlet ultimately leading to loss of containment. The criticality depends on the tolerable erosion rates which are dependent of the choke design.

Failures due to severe erosion of the choke gallery are not frequently experienced, even though significant erosion here has been reported in several occasions.

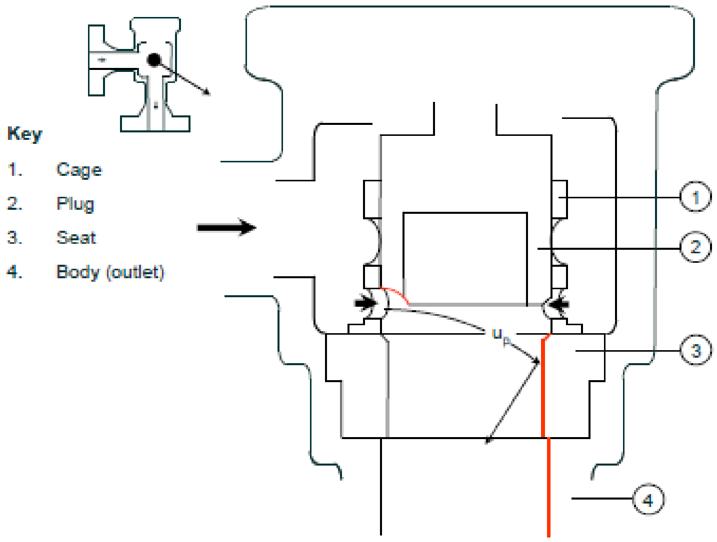
[16] [10]

Chokes with lower opening tend to erode faster in general. This is due to the following arguments:

- Low choke openings normally causes high pressure drop across the choke.
- High pressure drop combined with low fluid density causes high particle velocity through the cage ports.
- Deeper erosion grooves can potentially appear because the particles are focused on a small surface area.

If focusing on safety, it is the choke outlet which is the most critical part considering erosion. This is due to the potential erosion escalation if erosion of the trim components occurs. The safety issue is that this kind of erosion will normally impair the controllability and sealing performance at closed position.

The potential escalation effects are shown in the figure below; where higher flow rates trough the eroded plug/sleeve nose and biased flow inside the cage will occur.



4-8: Potential erosion escalation effects

4.4 Avoiding sand erosion in best possible way

4.4.1 General

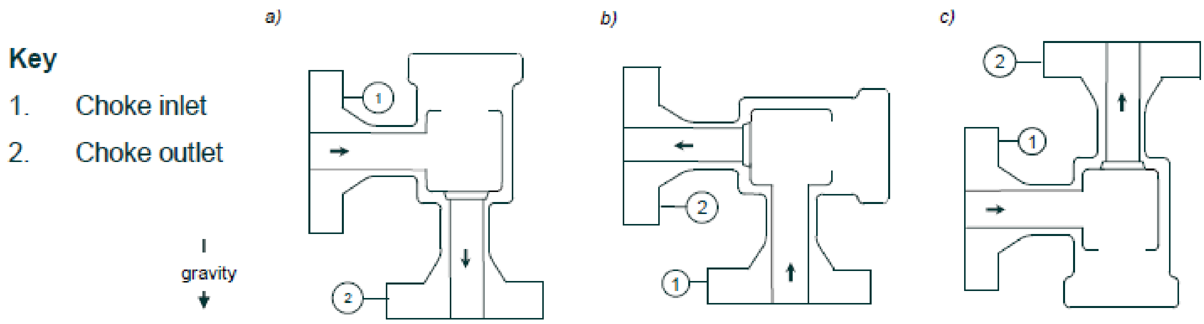
The ideal is to have no sand production at all, because then there will not be any sand erosion. This is very difficult to achieve when producing, but there exist some recommendations for minimizing the sand production based on different studies and experiences.

Condition monitoring of choke operation and the production process plays an important role in avoiding sand erosion in best possible way, which is further described in chapter 7.

Here it is focused on the operation and selection of chokes for avoiding sand erosion in best possible way. There are many issues to take into account for choke selection, so the main issues are presented here.

4.4.2 Selection and operation of chokes[17]

Figure 4-9 shows the different types of choke orientation. Orientation a) is normally recommended subsea. This is due to top access, and that b) may potentially have the problem with detecting all the sand when the choke is closed for inspection because it may potentially drop into the upstream pipe. When production is resumed, the sand may be produced back to the choke and cause erosion. C) is not recommended due to high potential of sand settling on trim components.



4-9: Choke orientation

[17] [10],[13],[26]

Chokes with cage and external sleeve are mostly recommended considering reduction of erosion potential (see attachment A for details). This is mainly due to that the sealing surface is located on the outside of the cage where the particle velocities are lower relative to the inside of the cage. It has a reduced effective gallery flow area at reduced choke opening which can increase the risk of erosion, but as mentioned in chapter 4.3.2, failures due to gallery erosion are not frequently experienced.

The optimal choice of a cage- choke with respect to erosion is a choke with choke opening greater than 15%, due to the potential erosion problems that can occur with low choke openings. For a MOV-choke, a choke with choke opening greater than 45% or 60% depending on the bean size is recommended.

In general, the operating conditions may either be based on historical data or production forecast considering normal operation in potential erosive conditions. Classifications of the erosion criticality for the different choke parts should be considered when selecting choke for “normal” operation, together with the vendor’s recommendations and procedures. This is especially important for the choke outlet and the trim components since these parts are known to be most critical considering erosion.

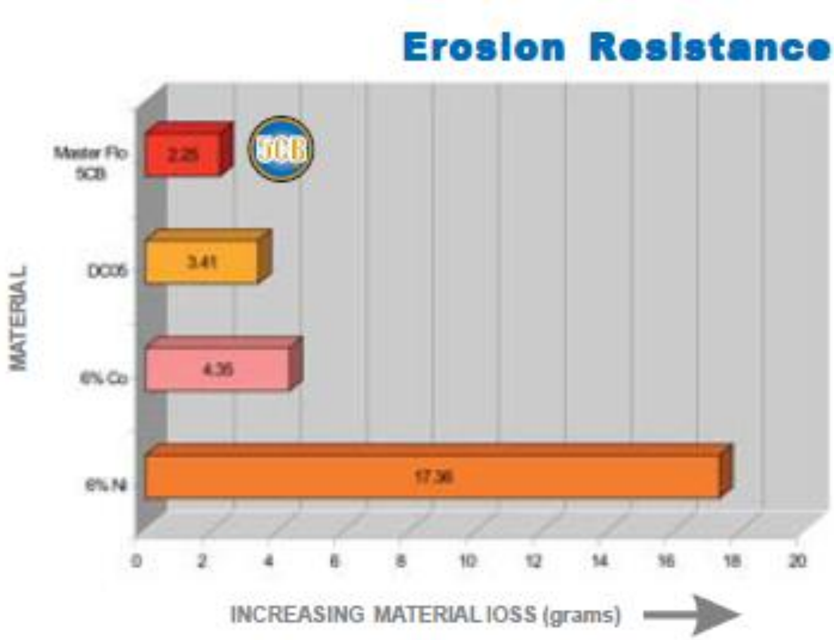
4.4.3 Type of material[18]

As mentioned earlier, Tungsten Carbide is the most used material for choke trim components due to its qualities for avoiding erosive wear better than for instance regular steel. It has to be mentioned that a cost-benefit analysis could be necessary when choosing the optimal material for a choke valve because stronger materials such as diamond could probably be a better choice for avoiding erosive wear, but then again the costs would most likely be too high.

“Master Flo” has developed a type of choke valve that they call the “E-Series”. This is a type of choke valve with improved erosion resistance compared to a “regular” Tungsten Carbide valve. The material is called 5CB and is a 5% Composite-Binder Tungsten Carbide. As it is shown in figure 4-10 on the next page, this material has much higher erosion resistance compared to other types of Tungsten Carbides.

An improved type of material like the 5CB is not only improving the erosion resistance, but also important factors such as corrosion and fracture toughness.

[18] [20]



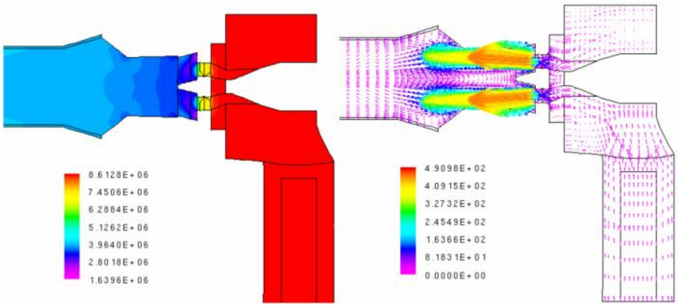
4-10: Erosion resistance of some different Tungsten Carbides

4.4.4 Computational Fluid Dynamics[19]

Computational Fluid Dynamics (CFD) is a powerful mathematical tool which is used in many areas, included choke valves. It simulates the flow through the choke which makes it possible to analyze and see how the flow behaves inside it and therefore predicting the erosion potential and develop erosion models (see chapter 5). Further, the results of such a simulation can be used to optimize the choke design and the predicting the lifetime with respect to erosion. This optimization and prediction can be done by changing choke opening, type of material, the choke geometry, amount of sand, velocity and so on. In addition to lifetime estimation, optimization of operation, inspection-, maintenance- and replacement intervals, CFD has also a huge benefit.

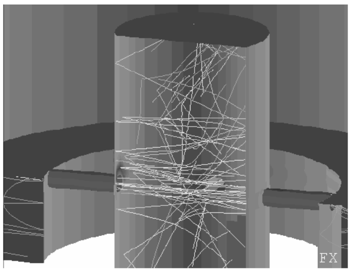
[19] [12],[27]

Some examples of a CFD simulation are shown in figure 4-11, 4-12 and 4-13 below. The use of colors to show the results of the simulation is a very useful method as shown in figure 4-11. This is a simulation of a MOV choke.

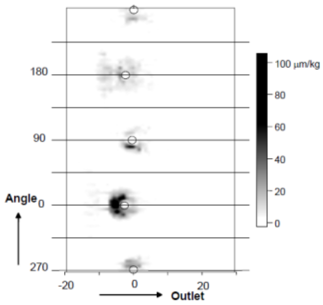


4-11: A CFD simulation showing the pressure contours to the left and the velocity vectors to the right

On figure 4-12 and 4-13 below, a simulation of erosion process in a cage is shown. Here the result is obviously that the amount of erosion is high around the cage holes.



4-12: A CFD simulation of the particle path inside the cage



4-13: The deviation of the erosion rate of a folded out inner cage based on the CFD simulation from the figure above

5 Sand erosion models

5.1 General[20]

Based on research, different experimental investigations and results, models for assessing the sand erosion has been developed. There exist different models for different equipment such as choke valves, pipe bends, reducers and more, but here the erosion models with a connection to choke valves are presented. DNV has played an important role in developing such models.

Exact values of erosion are difficult to achieve with the models due to the complexity of erosion, but it can be estimated with good accuracy. The models are often intended to give conservative estimate of the erosion attacks in order to avoid excessive erosion of the actual system during operation.

5.2 Erosive wear and erosion rate[21]

This is the fundamental and general erosion model which other models concerning different equipment such as choke valves, pipe bends and so on are based upon. Different variants and approaches have been developed from this model, but they are pretty much the same. The differences are first of all due to different values of the coefficients and different denominations. One version and its respective values for two different materials are chosen to be explained further on the next page.

[20] [2]
[21] [12]

The term erosive wear means the same as the term erosion, but is in some relations better to use. Erosion rate is the “amount” of lost original material due to erosive wear given in [mm/yr]. This general model is further explained below:

$$\mathbf{E_L} \approx \frac{\mathbf{K} * \mathbf{u^n} * \dot{\mathbf{m}}_\mathbf{p} * \mathbf{F}(\boldsymbol{\alpha})}{\mathbf{A} * \boldsymbol{\rho}_\mathbf{w}}$$

E_L: Erosion rate $[mm/yr]$

$\dot{m}_p$: Mass flow of particle (sand) that hit the area A [kg/s]

K: Material constant $[(m/s)^{-n}]$

n: Velocity exponent dependent of the wall material [-]

u^n: Impact velocity [m/s]

$F(\alpha)$: A number between 0 and 1 given by a functional relationship dependant of the wall material and the impact angle α (see figure 5-2) [-]

A: The size of the area exposed to erosion $[m^2]$

ρ_w: Wall material density $[\frac{kg}{m^3}]$

The erosion rate in some small sub-area is found by the summation over all particles that hit within the defined area:

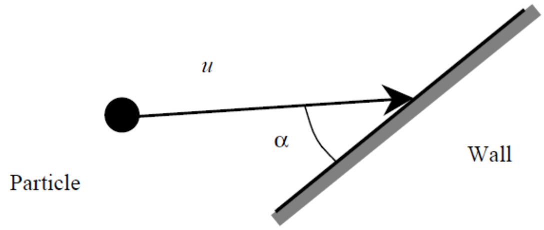
$$\mathbf{R} \approx \frac{\mathbf{K}}{\mathbf{A} * \boldsymbol{\rho}_\mathbf{w} * \mathbf{M}} * \sum_{\mathbf{i=1}}^{\mathbf{nhit}} \mathbf{u_i^n} * \mathbf{F}(\boldsymbol{\alpha}_\mathbf{i})$$

R: Erosion rate [μm/kg total sand feed]

M: Total number of sand particles (total sand feed)

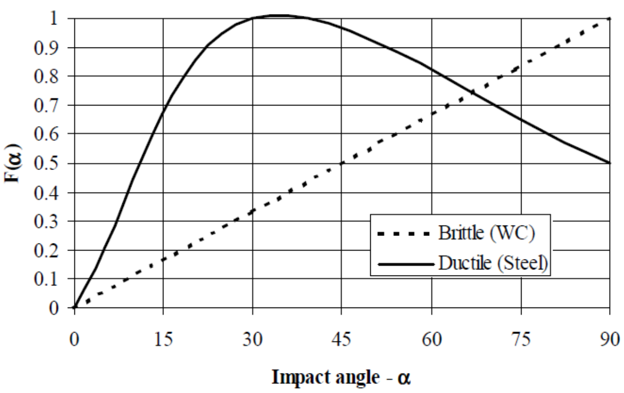
nhit: total number of hits in the sub-area

These models are based on the situation shown in figure 5-1 below, where u is the velocity and α is the sand particle impact.



5-1: Definition of flow parameters in fundamental erosion model

Further is the $F(\alpha)$ dependent of the wall material and the impact angle α. This is shown in the figure 5-2 below.



5-2: Type of material vs. impact angle

The respective values of K, n and ρ_w for the two typically used materials shown in figure 5-2 are listed in the table below.

Material	K	n	ρ_w
Steel grade	$2.0 \cdot 10^{-9}$	2.6	7 800 kg/m³
Tungsten carbide (WC)	$1.1 \cdot 10^{-10}$	2.3	15 250 kg/m³

5-3: Table with the respective values of K, n and ρ_w for the two typically used materials Steel and Tungsten carbide

5.3 Choke valves

5.3.1 General

There exists different choke erosion models, and since topside- and subsea chokes are based on the same principle these models are valid for both.

These models are based on assumptions and simulations so they will never be 100% exact, but they will with no doubt give a good estimate of the erosion rate.

5.3.2 Overall volumetric erosion per impact[22]

Based upon the two erosion mechanisms mentioned in chapter 4.2.4, the following erosion model giving the overall volumetric erosion per impact:

$$\mathbf{V_u} = \left\{\frac{100}{2\sqrt{29}} * r_p^3 * \left(\frac{U_p}{C_k}\right)^n * \sin 2\alpha\sqrt{\sin\alpha}\right\} + \left\{\frac{M_p*(U_p*\sin\alpha - D_k)^2}{2E_f}\right\}$$

V_u is the overall volumetric erosion per impact, and is (as shown in the model) the summation of cutting- and deformation erosion where the first term represents the cutting and the second term represents the deformation. The other parameters are described below:

$$\mathbf{C_k} = \sqrt{\frac{3\sigma {R_f}^{0,6}}{\rho_p}}$$

$$\mathbf{D_k} = \frac{\pi^2}{2\sqrt{10}} * (1,59Y)^{2,5} * \left(\frac{R_f}{\rho_t}\right)^{0,5} * \left[\frac{1-q_p^2}{E_p} + \frac{1-q_t^2}{E_t}\right]^2$$

22 [11]

r_p: The particle radius

U_p: The particle velocity

α: The particle impingement angle

M_p: The particle mass

E_f: The deformation erosion factor

R_f: The roundness factor of the particle

σ: The plastic flow stress for the target

Y: The yield stress of the target

q: The Poisson's ratios for the particle (p) and the target (t)

E: The modulus of elasticity for the particle (p) and the target (t)

Simpler models assume that:

$\mathbf{V_u = f(N, E_k, \alpha)}$

N: Number of particles actually eroding the surface

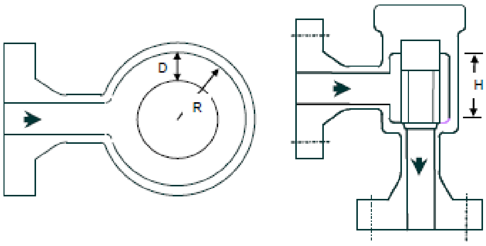
E_k: The kinetic energy of the particle

α: The particle impingement angle

5.3.3 Erosion rate of choke gallery[23]

This is an erosion model for the choke gallery for an angle type of choke valve (see figure below) where R is the radius of the gallery, D is the gap between the cage and the choke body, and H is the height of the gallery. It is closely linked to the general erosion rate formula described in chapter 5.2.

Its limitations are that the model does not account for detailed geometry of the choke gallery, and considers the gallery free of obstructions.



5-4: Angle type choke valve

The erosion model is as followed:

$$\mathbf{E = \frac{K * F(\alpha) * \sin(\alpha) * u_p^n}{\rho_t * A_g} * G * C_1 * 10^6}$$

E: erosion rate [mm/ton]

K, F(α) and n: as described in chapter 5.2

α: characteristic impact angle which is given by $\tan^{-1}\frac{1}{\sqrt{2*R}}$

ρ_t: mass density of target material $[\frac{kg}{m^3}]$

A_g: Effective gallery area $[m^2]$

u_p^n: the particle velocity which is $\frac{3}{4} * \frac{\text{actual flow rate}}{A_g}$ [m/s]

C_1: Choke geometry factor which is set to be 1,25 [-]

---

[23] [10]

G: particle size correction factor which is further described as followed:

$$G = \begin{cases} \frac{\gamma}{\gamma_c} \text{ if } \gamma < \gamma_c \\ 1 \text{ if } \gamma \geq \gamma_c \end{cases}$$

were $\gamma = \frac{d}{D}$

d: particle diameter [m]

$$\gamma_c = \begin{cases} \frac{1}{\beta[1{,}88 * \ln(A) - 6{,}04]} & , \gamma_c < 0{,}1 \\ 0{,}1 & , \gamma_c > 0{,}1 \ \wedge \ \gamma_c \leq 0 \end{cases}$$

were $A = Re * \frac{\tan \alpha}{\beta}$ and $\beta = \frac{\rho_p}{\rho_m}$

Re: Reynolds number [-]

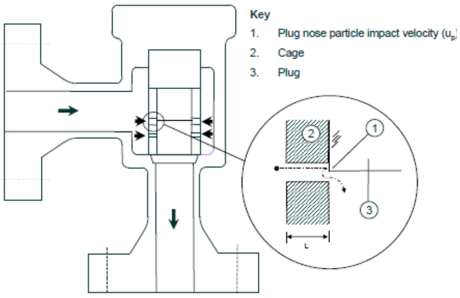
ρ_p: mass density of solid particles [$\frac{kg}{m^3}$]

ρ_m: mass density of the fluid mixture [$\frac{kg}{m^3}$]

5.3.4 Erosion rate of plug/sleeve nose[24]

This erosion model gives the erosion rate for the cage chokes with internal plug or external sleeve. How the particles hit the plug and thereby starts eroding the plug is illustrated in the figure below.

Its limitations are that the model does not distinguish between variations in cage port configurations, and that the erosive solids (sand particles) are equally distributed through the available flow area in the cage.



5-5: Erosion of plug

The erosion model is as followed:

$$\mathbf{E} = \frac{\mathbf{K} * \mathbf{u}_\mathbf{p}^\mathbf{n} * \mathbf{F}(\boldsymbol{\alpha})}{\boldsymbol{\rho}_\mathbf{t} * (\mathbf{C} * \mathbf{C}_\mathbf{v})} * \mathbf{10^6}$$

E: erosion rate [mm/ton]

$F(\alpha)$, n and ρ_t: as described in chapter 5.3.3.

C_v: Actual flow coefficient for given choke opening [-]

C: conversion factor from C_v to effective bean area in cage which is set to be $1{,}9 * 10^{-5}$ [m^2]

u_p: particle impact velocity which can be approximated by:

$$u_p = f_p * \left[\frac{2 * \Delta P}{\rho_m}\right]^{1/2} \ [m/s]$$

f_p: factor describing particle velocity relative to fluid velocity which is set to be 1 (conservatively) for single stage cages [-]

ρ_m: fluid density at choke inlet [$\frac{kg}{m^3}$]

ΔP: pressure drop over choke

[24] [10]

5.3.5 Maximum erosion rate in the outlet spool of an MOV choke[25]

This erosion model is based upon 23 Computational Fluid Dynamics (CFD) cases where the valve opening, pressure drop, bean size, outlet spool and particle size were varied while two jets containing sand particles were directed toward the walls when the choke was not fully open. The compilation of the data resulted in the erosion model shown below, which can be used to determine the maximum erosion rate in the outlet spool.

$$\mathbf{E = K * \left(\frac{\Delta p}{p_i}\right)^m * \left(\frac{choke\ opening}{100}\right)^n}$$

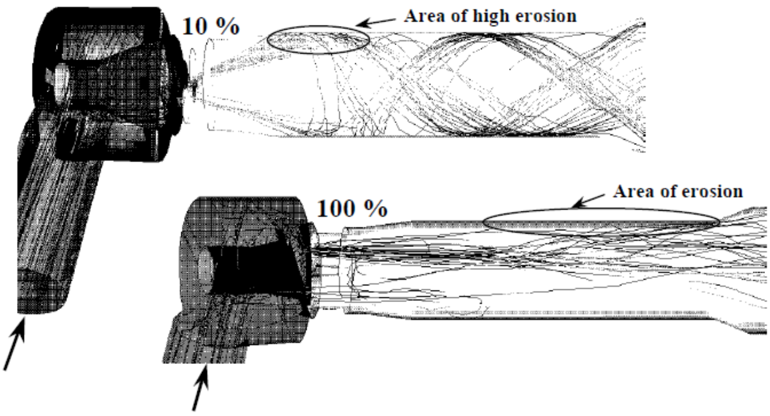
E: erosion rate.

K, n and m: constants depending on location of the maximum point, the lining material, the outlet spool and bean size.

Δp: pressure drop over the choke valve.

p_i: inlet pressure to the choke valve.

Examples from a CFD case are shown in the figure below. Here it is shown the location of high erosion at 10% opening, and less erosion at 100% opening.



5-6: CFD analysis of a MOV valve with 10% and 100% choke opening

[25] [26]

5.3.6 Accumulated erosion of choke gallery and plug/sleeve nose[26]

This model is equal for both the choke gallery and the plug/sleeve nose. It is based upon the erosion models described in chapter 5.3.3 and 5.3.4 where the respective erosion rate calculated there is putted into the following equation to get the accumulated erosion:

$$\mathbf{E_{ac}(t), E_{psn}(t) = \int E(t) * m_s * t\, dt}$$

E_{ac}: accumulated gallery erosion [mm]

E_{psn}: accumulated plug/sleeve nose erosion [mm]

E: calculated erosion rate of the choke gallery or the plug/sleeve nose [mm/ton]

m_s: solids production rate [ton/time]

t: time [time]

[26] [10]

5.3.7 Erosion allowance[27]

How much erosion that is tolerated or allowed in a choke valve before it is recommended to change the choke can vary, but one recommendation is as followed:

$$\boldsymbol{\xi_g = \frac{E_g}{E_p} * \frac{X_p}{X_g}}$$

ξ_g: consumption of choke gallery erosion allowance relative to consumption of erosion allowance for the upstream piping. [-]

E_g:erosion rate for the choke body or the choke inlet [mm/ton]

E_p: erosion rate for upstream piping [mm/yr]. It may be found by using models similar to the ones described for choke valves.

X_p: erosion allowance for upstream piping [mm]. This parameter is normally set to 1[mm] because it is a reference value.

X_g: erosion allowance of the choke gallery or inlet [mm]

The value of this model is that it says something about the selection of choke valves with attention to erosion potential and replacement. The choke replacement frequency relative to the reference upstream piping may be expressed as$\frac{1}{\xi_g}$.

[27] [10]

6 Sand measurement equipment and techniques

6.1 General

In this chapter the main focus is on the subsea related equipment and techniques.

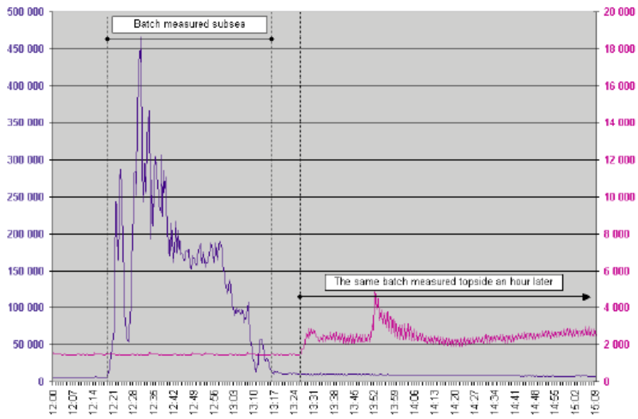
Considering that the availability is limited subsea compared to topside installations, the amount of possibilities within sand measurement are less, but the subsea technology development has the latest years come far. A proof is that more and more equipment are placed and planned subsea. Some major reasons for this are:

- The computer technology with all its possibilities has come far in a relatively short time.
- Increasing speed and amount of data which can be received and sent subsea.

6.2 Placement of equipment[28]

A typical issue is should the sand measurement equipment related to subsea installations be installed subsea or topside, which is cheaper and the operators has easy access to the equipment such as sensors.

For a subsea well it would be the best to have sand monitoring system subsea because then the sand signal will be picked up earlier and more strongly than it would be topside. An example of this can be seen below. Here the signal from the subsea sand monitor (left) indicates a strong and more obvious signal than the topside monitor (right). A major reason for this is because when sand particles travel over a longer distance, the sand particles will be dispersed over the total flow line distance.



6-1: the difference in the sand monitoring signal subsea and topside

[28] [17]

Other reasons of why placing sand monitoring equipment subsea for subsea wells are that the operator will have the sand production information available earlier than if it was placed topside, and if several wells are operating with the same line, the operator will meet difficulties knowing what well is producing sand without shutting it down.

6.3 Sand erosion probes

6.3.1 General[29]

Figure 6-2 below shows a sand erosion probe developed by ROXAR installed in a pipeline and how they typically look like.

An erosion probe in optimal condition will provide information about the long term accumulated erosion development.

The sand erosion probes provide direct measurement with accuracy better than +/- 5 nanometre of sand erosion by feeding them with a constant current. The probe is based on the electrical resistance principle, where metal loss on the element is measured as increased electrical resistance in a sensing element. This loss of metal happens due to sand particles hitting the probes during transportation with the flow. Sand production rates can be quantified by combining measured metal loss rates with average sand particle size and flow data. The sand erosion probe is unaffected by mechanical, electro-mechanical or flow-induced noise.

To compensate for temperature changes, which influence the resistance of the element material, a reference element is included at the back of the probe body. This element is exposed to the same temperature, but is shielded from the erosive sand particles. The corrosion resistant sensing elements are cast in a high quality ceramic into the probe body which is made in stainless steel to ensure that the probe has the necessary mechanical strength and corrosion resistance.

6-2: A sand erosion probe with 4 probe elements installed in a pipeline (left) and how the look (right)

29 [14],[15],[16]

Behind this state-of-the-art technology there is a model which is based upon the fact that if the sand injection rates are kept at a constant level, the erosion probe gives a complete linear response with a constant wear rate. As the sand injection rate increases or decreases, the slope of the metal loss curve will change accordingly.

The model below shows the erosion probe response as a function of the relevant flow parameters. Several hundred tests were performed to establish this model, and based on the results the model was established as followed:

$$\mathbf{R} = \mathbf{K} * \mathbf{S} * \mathbf{D} * \mathbf{V}[\mathbf{G}(\mathbf{water}, \mathbf{oil}, \mathbf{gas})]$$

R: Thickness reduction of sensing elements

K: Constant

S: Sand rate

D: Average particle size

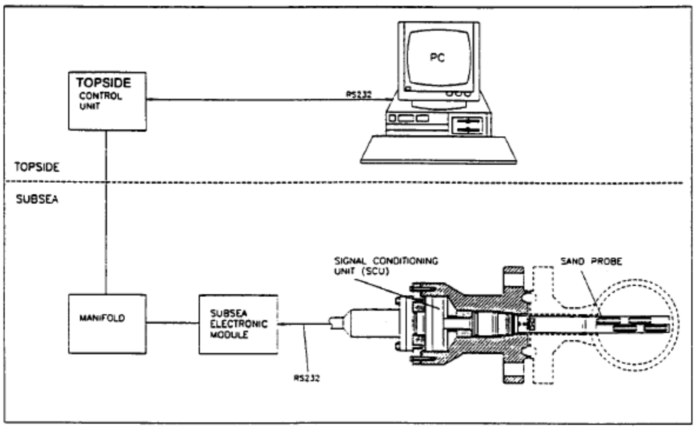
V: Mixture velocity

G: Function including fractions of oil, gas and water

The model is a basic relationship between the erosion measured on the erosion probes elements and the sand content when the process parameters are known. The most important parameter is the mixture velocity, V, because it gives the effective sand grain impact on the erosion probe elements.

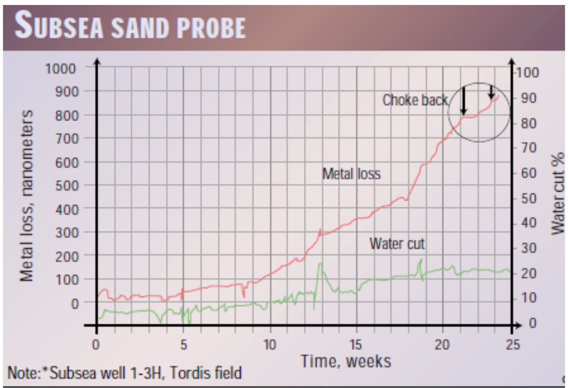
6.3.2 Subsea[30]

The subsea erosion probes have to be installed as on-line system. The erosion probes are normally placed downstream of the choke valve. The “data” from the probes is sent to the subsea control module on the X-mas tree, then transmitted and sent via the manifold topside where storing and reading by the operators takes place. Figure 6-3 below shows a simple schematic of this process.



6-3: The data flow from subsea to topside

Figure 6-4 below shows the readable data from a subsea erosion probe. Here it is shown clearly an increasing sand production trend which makes the metal loss curve increase due to erosion.



6-4: Readable data from a subsea erosion probe

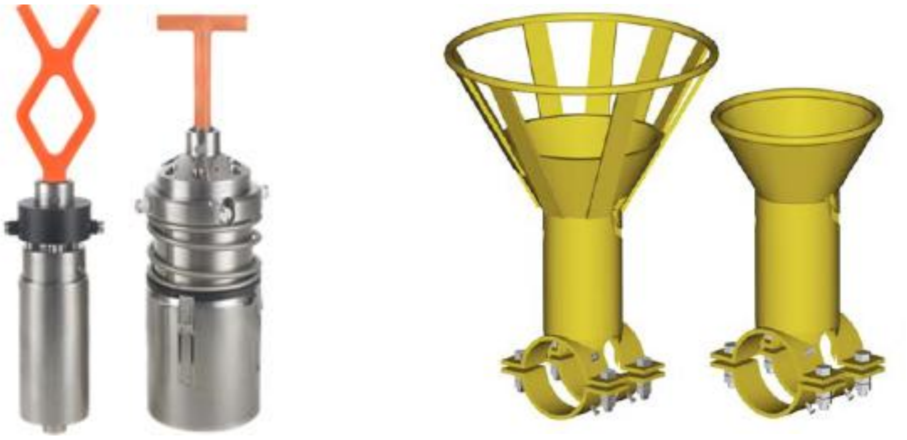
Erosion probes are not (until recently) ROV retrievable which means that the element thickness should be selected according to the planned/expected service intervals for the given subsea system.

---

30 [14],[15]

6.4 Subsea sand particle monitor[31]

Figure 6-5 shows a picture of subsea sand particle monitors developed by ClampOn, and their funnels which protects them when they are installed on a subsea pipeline. The orange handles are operated by ROVs.



6-5: Subsea sand particle monitors (left) and their funnels (right)

This is an passive acoustic intelligent sensor which means that it picks up the ultrasonic pulse which sand particles generates when they impact the inside of the pipe wall. The sensor is typically placed two pipe diameters after a bend where the impacts are largest.

Acoustic sensors are recommended to be used for day to day sand production monitoring. They also detect sand production at an earlier stage that erosion probes, making them more "popular" in use.

The signals are processed internally by a DSP-06 engine (see the next chapter) and filtered before being sent to the topside control system for monitoring and evaluation.

One practical advantage is that these sensors are so-called non-intrusive which means that they are easy to (after) mount, and can easily be calibrated with DSP-06 after mounting it.

[31] [17]

6.4.1 DSP-06[32]

DSP stands for Digital Signal Processing and is a processing technique. The DSP-06 is an improvement of earlier DSP-solutions which is developed and used in these monitors from ClampOn.
The unique about them is that the DSP-process is used internal in the equipment so that the distance from measurement to processing is very short for the signal. This gives a good signal-to-noise (s/n)-ratio and has therefore managed to reduce unwanted noise substantial compared to a "traditionally" DSP. Figure 6-6 below shows this difference in the signal where the red curve represents a sensor with "traditional" DSP where (in worst case) the sand production signal may drown in the background noise. The blue curve represents this monitoring technology with DSP-06 which clearly gives better indications on that sand production is present.

DSP-06 also uses digital filters which allows the measurements to be processed parallel and therefore can be used to several tasks. By changing the configurations in the sensor software it can be used as for instance a PIG-detector, leak detector and so on without changing its physical properties.

6-6: The difference between good (s/n)-ratio (blue curve) and pure (s/n)-ratio (red curve)

[32] [B]

6.5 Sand trap[33]

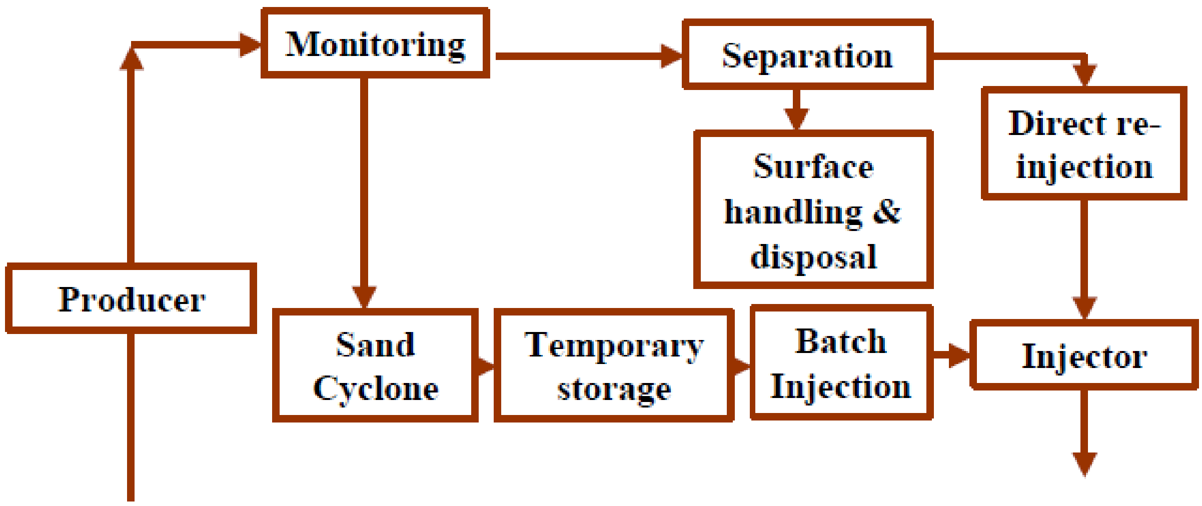
This is a volumetric, non-real-time method of monitoring the amount of sand. These traps are usually mounted on tees or bends to capture sand. The amount is measured by disassembling the sand trap. Such methods have not proven effective and experience indicates a recovery of only 1-10% of the total amount of produced sand.

6.6 Sand cyclone[34]

Applying an in-line sand cyclone is a new method used on some North Sea platforms. Here sand is effectively separated from the flow and stored in a tank. Load cells or other devices on the tank allow a measure of sand accumulation in real time.

Due to the increased amount of injected water and the production of (often) more water than hydrocarbons, subsea reinjection and separation systems have been developed. This also means that produced sand will be re-injected which gives the issue of sand separation. The figure below illustrates two principal options for subsea sand separation.

1. Separation from the oil and stored in a temporary storage tank or directly re-injected.
2. Send the sand topside with the oil.



6-7: Two options for separation of sand subsea.

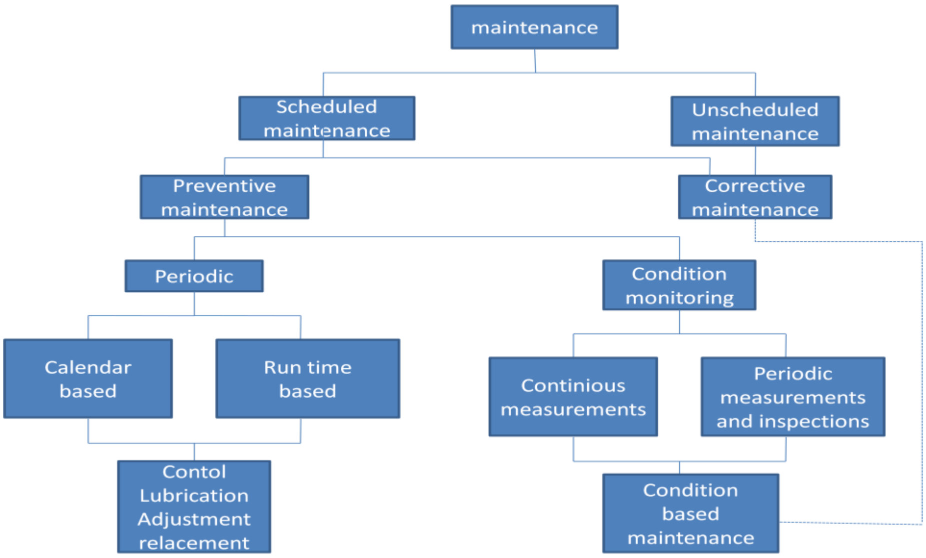
[33] [7]
[34] [7]

7 Approaches to condition and performance monitoring

7.1 Background[35]

7.1.1 General

Condition monitoring (CM) is the process of monitoring one or more parameters of condition for an item or system to detect deviations that might be the result of an initiating failure. By detecting a failure at an early stage, maintenance can be planned and scheduled and CM is hence an important part of preventive maintenance and predictive maintenance as shown figure 7-1 below:

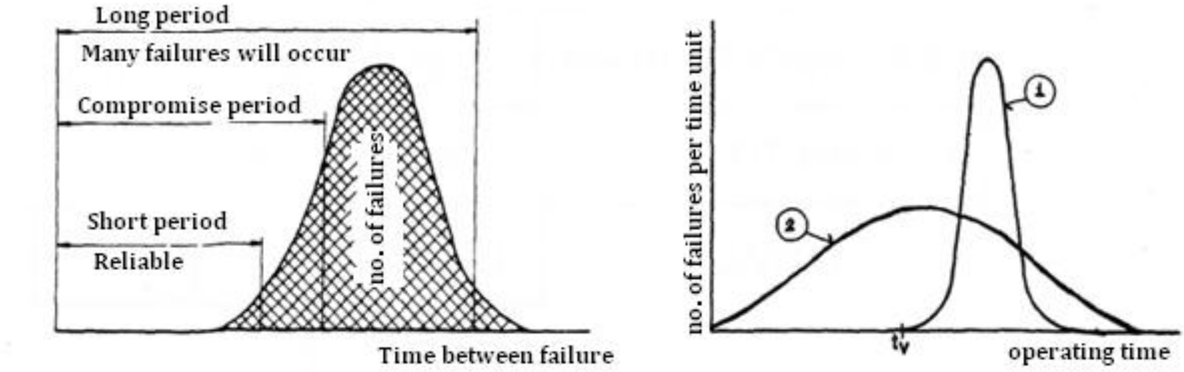


7-1: Maintenance deviation

CM does not predict failure; it only helps predicting the time to failure. Nevertheless, a deviation from a reference value (e.g. temperature or vibration behaviour) must occur to identify impeding failures. These limits will either come from quantitative or qualitative methods, data-driven methods or experience alone. This will be further discussed later on.

Normally CM is preferable for components which have an unclear failure distribution, hence, an optimal interval for maintenance is difficult to achieve. This is illustrated in figure 7-2 where graph 2 on the right figure is the kind of failure deviation actual for use of CM.

35 [25]



7-2: Maintenance interval and failure deviation

7.1.2 Benefits of CM

There are several benefits achieved by applying CM to a process or system, both economical, environmental, health- and safety matters are influenced in a positive direction. All of these benefits come from the possibility to detect deviations in the process at an early stage before they escalade and major failures occurs.

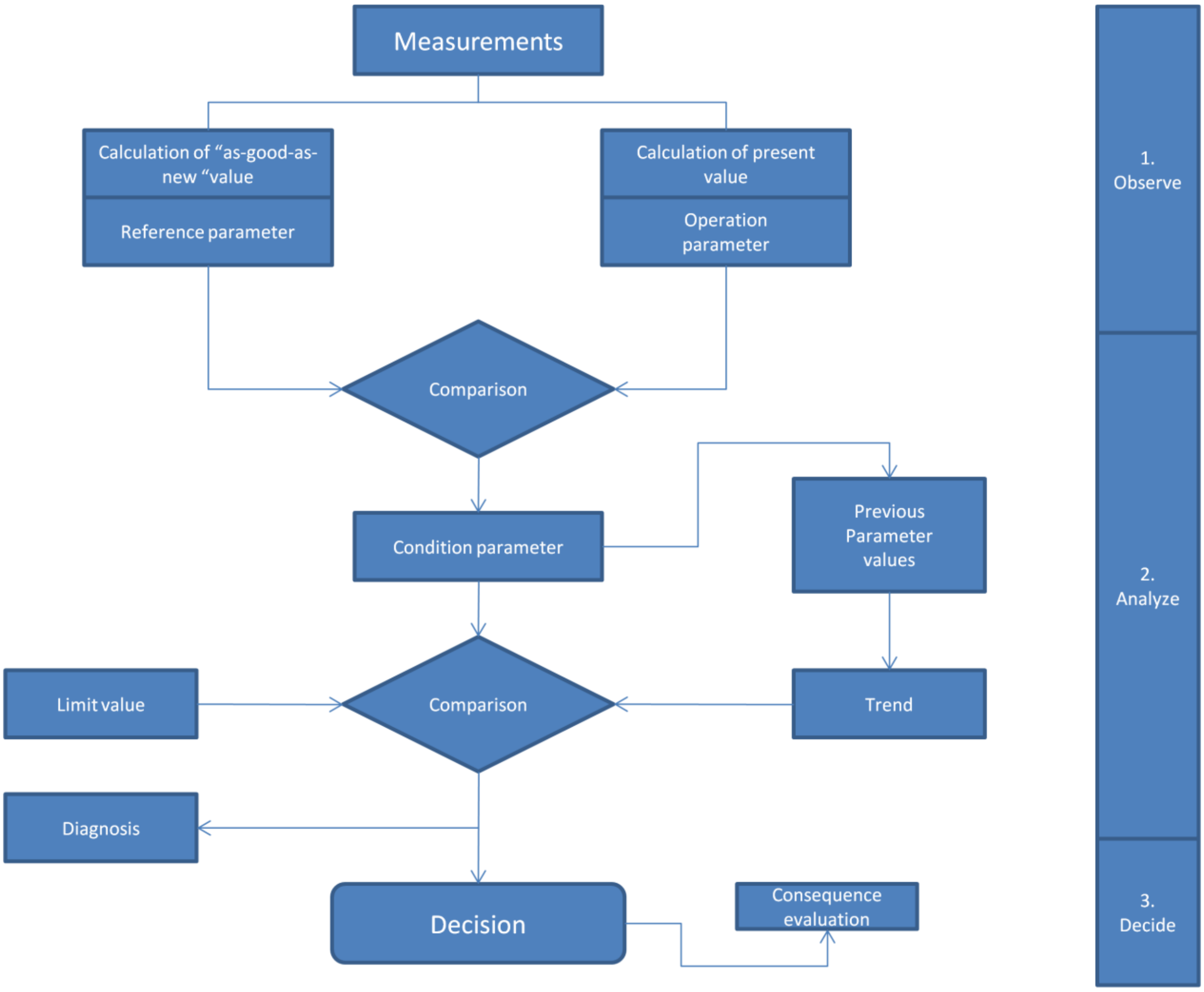
The detection of a problem before an actual fault is fully developed allows for more efficient maintenance planning. This introduces the possibility to perform planned maintenance actions, which is typically more cost efficient than the unscheduled maintenance needed when equipment is allowed to run until it fails. Spare parts could be ordered and delivered in a normal manner rather than rushing to get it after the original part is broken. This “warning” at an early stage will also help prevent unscheduled shutdowns which are extremely costly for most modern systems these days, especially in the oil and gas industry.

The possibility to act before the equipment brakes down will help prevent accidents and spills which can lead to environmental catastrophes and human injuries, both of which are costly and bad for the company’s reputation.

As a result of these factors the system can, with efficient condition monitoring, diagnosing and preventive maintenance achieve better operational stability, better production rates and higher profits.

7.1.3 The core of CM

The CM process consists of three core processes; observation, analyzing, and decision-making as shown in the figure 7-3 below:



7-3: The three core processes of CM

The first step observation can be performed in several ways, both manually and automatically, online and offline. Every method gives some kind of indication of condition. However, there are considerable differences between the methods. The main difference is the time from detection to failure.

The second step analyzing analyzes the result of the observation by comparing the observed condition parameter with the reference (normal condition) parameter.

The condition parameter is given as:

$$\textbf{Condition parameter} = \frac{\textbf{Reference value} - \textbf{Actual value}}{\textbf{Reference value}} * \textbf{100}\%$$

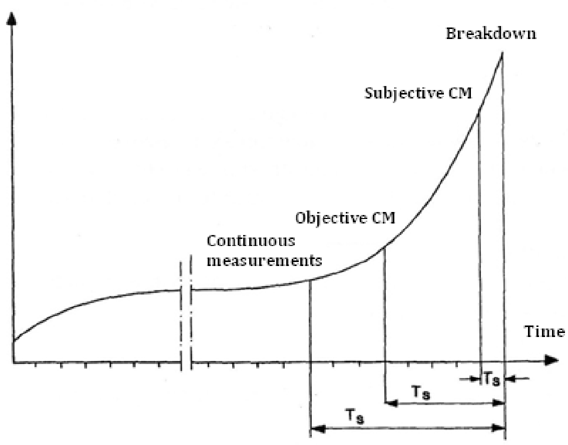
Where the difference between the reference value and the actual value says something about the condition at the actual point (actual value).

The third step decision making decides on the background of the analyze which possible maintenance action should be done.

When it comes to how often measures of condition should be done, and choosing type of method, it depends on:

- Criticality (health/safety, environment, economy)
- Common damages and consequences
- That there exists a suitable method for the given failure
- Condition progressiveness and control frequency

The figure below shows that the "simplest" method for CM gives shorter pre warning time which is a very critical parameter in industries such as the oil and gas industry due to normally huge down-time costs.



7-4: Different types of CM

Roughly CM can be divided into the following areas of use:

- Thermodynamic CM
  - Control of efficiency, coating, temperatures etc.
- Vibration control
  - Controlling the changes in vibration signals which develops over time and say something about the condition of the vibrating system(e.g. machinery)
- Oil analysis
  - Look for wear particles and pollution in hydraulic- and lubricating oils. Size and composition of the particles are important information about the condition
- Acoustic issue
  - A very high frequent vibration appears when a crack or a corrosion crack is starting to grow
- Corrosion measuring
  - Measure the level of corrosion with special corrosion-feelers and the voltage level etc.
- Special inspection aids
  - X-ray, ultrasound, magnetic powder e.g. for crack detection
  - Fibre optics
  - Thermography
  - Ultrasound microphone for leak detection

7.1.4 Limitation of CM

It is important to have in mind that not every component is ageing. A component may be as good as new even after several years. Replacing such a component could actually degrade our system. This is so because different components have different failure modes. These modes are important to have in mind when choosing maintenance strategy, such as CM. If a component suddenly fails, CM would not serve any predictive function.

In addition there exist some main parameters which need to be covered in order of using CM:

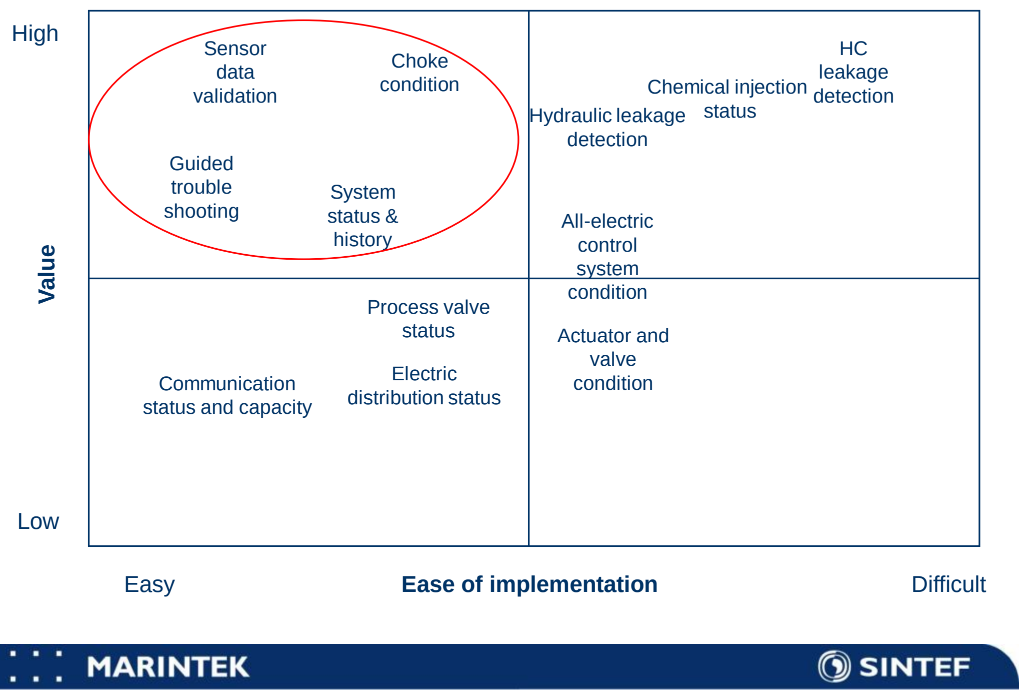
- The failure evolves slow enough to be able to do a maintenance action/intervention before breakdown
- There exists a adequate control method

7.2 Challenges and potential[36]

7.2.1 General

In the early nineties, subsea production systems were equipped relatively simple with one or two pressure and temperature sensors to gather information from individual wells, and the complexity of the systems was not the same as it has been developed into today. The problem was that since the CM methods was mostly dependent upon direct human access, the surveillance methods were becoming more and more outdated simultaneously as the subsea systems and equipment became more and more complex.

In the figure below is a general overview of the challenges (and potential) regarding integration/improving CM with attention to the degree of implementation difficulty vs. how high the value/profit is. As it is shown here, choke valve condition and sensor data validation is themes which has a high value and is reasonable easy to implement. This is one major reason and a motivational factor of why study the possibilities around choke CM.



7-5: Challenges (and potential) regarding integration/improving CM subsea

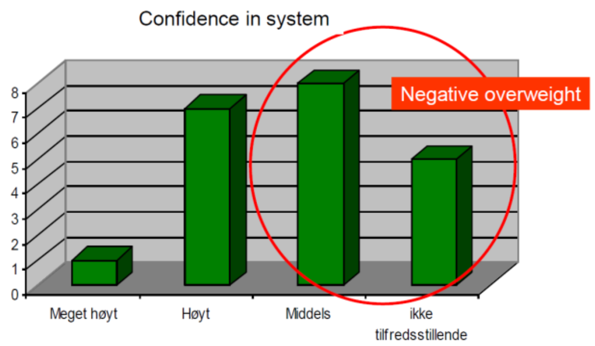
---

36 [21],[37]

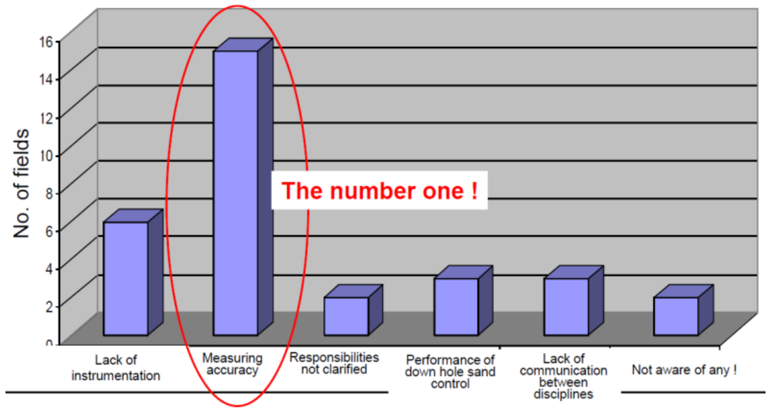
7.2.2 Sand monitoring[37]

It is unfortunately a "tradition" that sand monitoring is often neglected, even if sand monitoring systems is installed and sand rate data is available.

The monitoring process of sand production and sand erosion has the challenges of poor confidence and –measuring accuracy as shown in the figures below. This has probably a lot in common with the development of the complexity of the subsea systems, together with the lack of understanding and competence among the "users".



7-6: Confidence of sand-and erosion monitoring system



7-7: Uncertainties related to sand- and erosion monitoring

37 [22],[28]

7.3 Sand management

7.3.1 General[38]

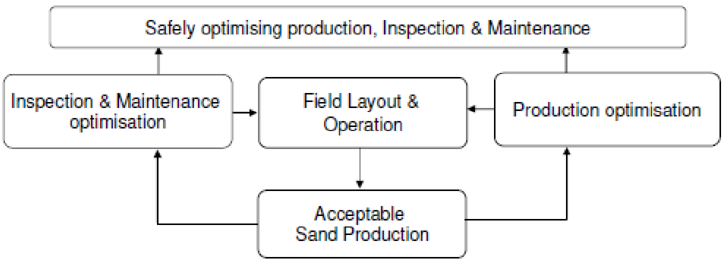
Sand management means in short managing the sand production and thereafter the potential erosion damage in best possible way without having to reduce the production considerably. This means that CM equipment and techniques has to be integrated as reasonable as possible.

Until around the year 2000, Statfjord had been operated by the criterion of Maximum Sand Free Rate (MSFR) which has “held back” a lot of potential production and therefore profit. The increasing sanding tendencies in the production process described in chapter 2.3 is one major reason of why Statfjord has for many years followed up the sand production with integrating a sand management strategy.

The sand management strategy has introduced daily production with an Acceptable Sand Rate (ASR) which is the major success factor in sand management.

7.3.2 Acceptable Sand Rate[39]

The main implications of the Acceptable Sand Rate (ASR) strategy are illustrated in the figure below:



7-8: The main implications of the ASR strategy

Operating the daily production process with ASR is a strategy of managing the sand production in best possible way with attention to cost-benefit and safety, which all in all are the most important factors. ASR means that sand is allowed to be produced in controlled manner, so that the production is optimized.

An ASR strategy demands a certain control over the sand production due to the fact that ASR allowing for a certain level of erosion as long as the safety is kept in focus. The erosion control is monitored by tools such as INSIGHT which is presented in chapter 7.5.

[38] [5]
[39] [29]

7.4 Inspection of a subsea choke valve

7.4.1 General

As opposed to condition monitoring using erosion probes and other remote equipment where the subsea choke valve is exposed for minimum physical interruptions, inspection of a subsea choke valve can often mean that the production must be shut down for a period. Shutting down the production is extremely critical due to the costs an inspection activity has, and not least the major loss in production profit.

The possibilities are limited and the challenges are high considering a subsea choke valve inspection compared to a topside choke valve inspection job.

7.4.2 Typical used inspection methods[40]

For retrievable subsea chokes, visual inspection with ROV camera when the chokes are subsea, or laser scanning when the chokes are pulled topside are inspection techniques that have been used with success for the choke body.

If the subsea choke are pulled topside, an opening for also inspecting the choke gallery and the choke internals appears because this is required to be done topside due to the need for splitting the choke to see inside.

[40] [10]

7.5 INSIGHT

7.5.1 General[41]

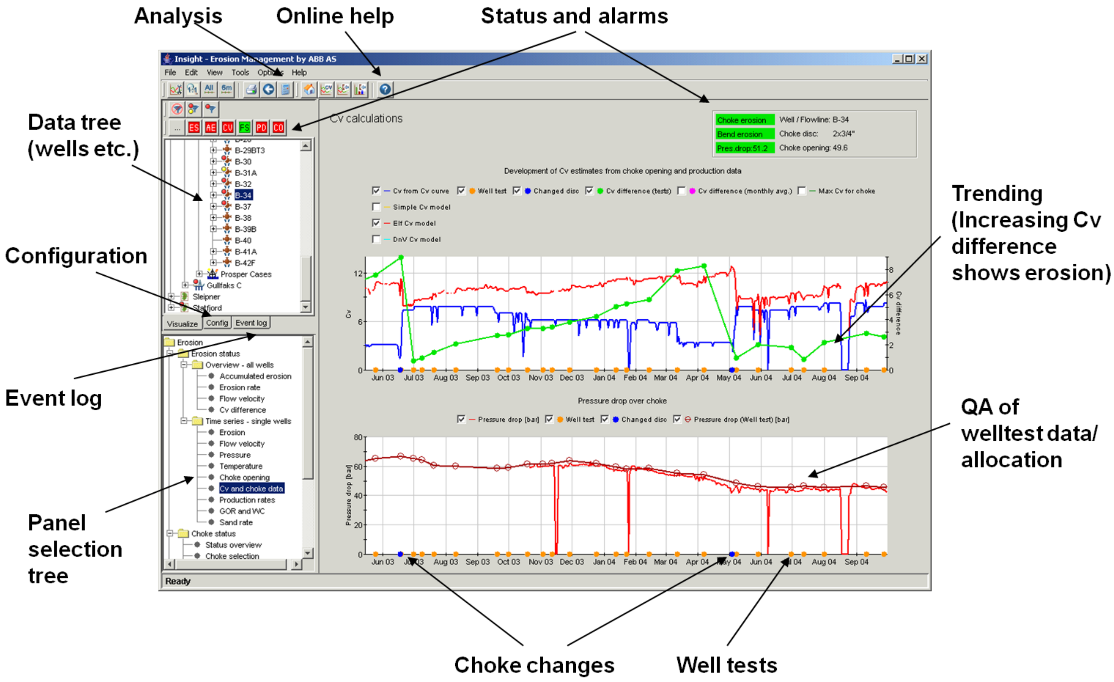
INSIGHT is a CM-tool developed by ABB and used by Statoil at the Gullfaks field since 2001, and at the Statfjord field since 2003. It is therefore a well tested CM-tool with a lot of history from a total of about 240 wells. As mentioned earlier, INSIGHT is in use to "satisfy" the ASR strategy.

INSIGHT is a commercial tool under continues development, and has since the start in 2001 gradually become better and better. This means that new versions with better functionalities have replaced older ones with functionalities that needed an update.

7.5.2 How it works[42]

Based on welltest data and/or production data, INSIGHT calculates and visualizes erosion at chokes and bends. These calculations are done automatically every day, also called online calculations.

The picture below explains the main functions of INSIGHT in use, and shows some example plots of calculated data:



7-9: Main functions in INSIGHT

[41] [13]
[42] [1],[13]

The statuses and alarms are easy to supervise. This is because they have a “traffic light”-function which means that the respective status (erosion speed, pressure drop and so on) is marked with either a red, yellow or green light, where red is “critical”, green is “ok” and yellow is somewhere in between. The table below shows the different statuses and which criteria available for “red”, “yellow” and “green” “traffic light”.

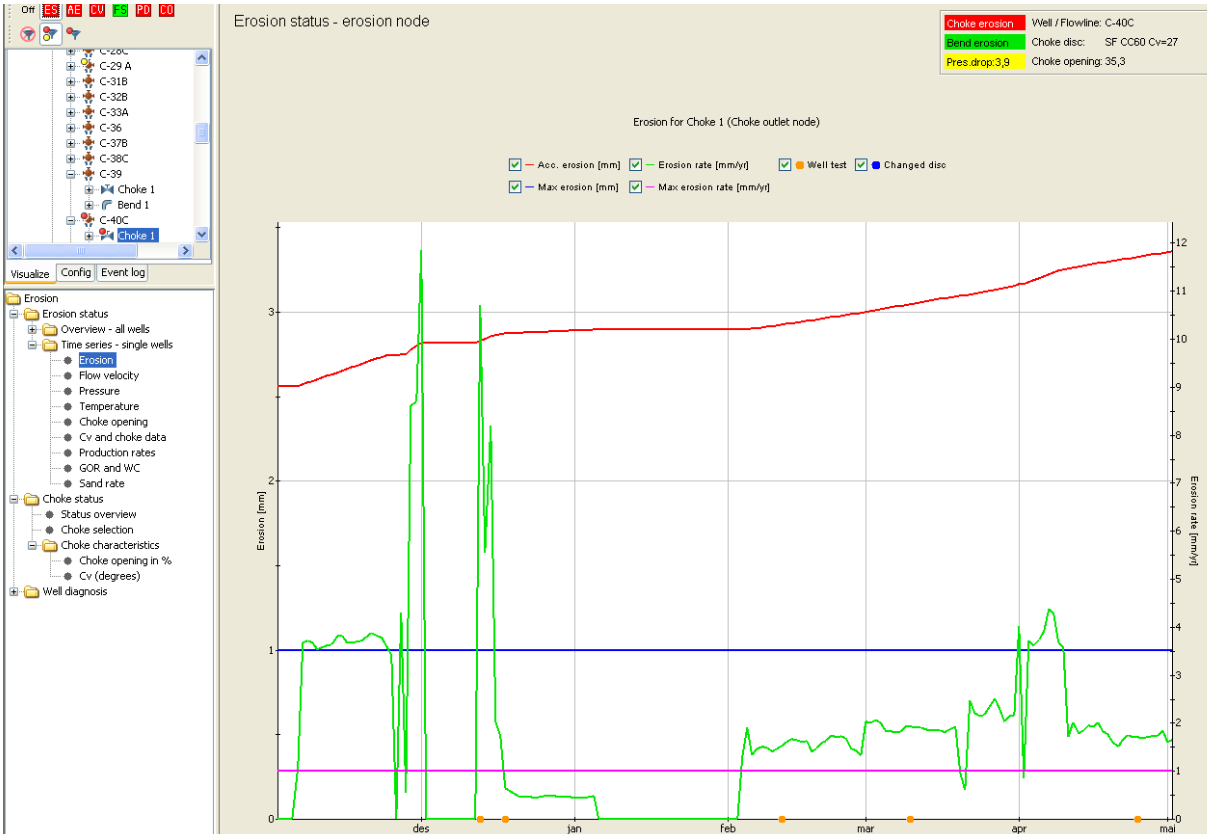
Status	**Red**	**Yellow**	**Green**
Erosion Speed	greater than 1.0 mm/year	greater than 0.1 mm/year and less than 1.0 mm/year	less than 0.1 mm/year
Accumulated Erosion	greater than 1.0 mm	greater than 0.1 mm and less than 1.0 mm	less than 0.1 mm
CV difference	greater than 7	greater than 4 and less than 7	less than 4
Pressure Drop	less than 2 bar	greater than 2 bar and less than 5 bar	greater than 5 bar

7-10: The different statuses and criteria

7.5.3 Erosion detection[43]

INSIGHT can detect erosion in three independent ways:

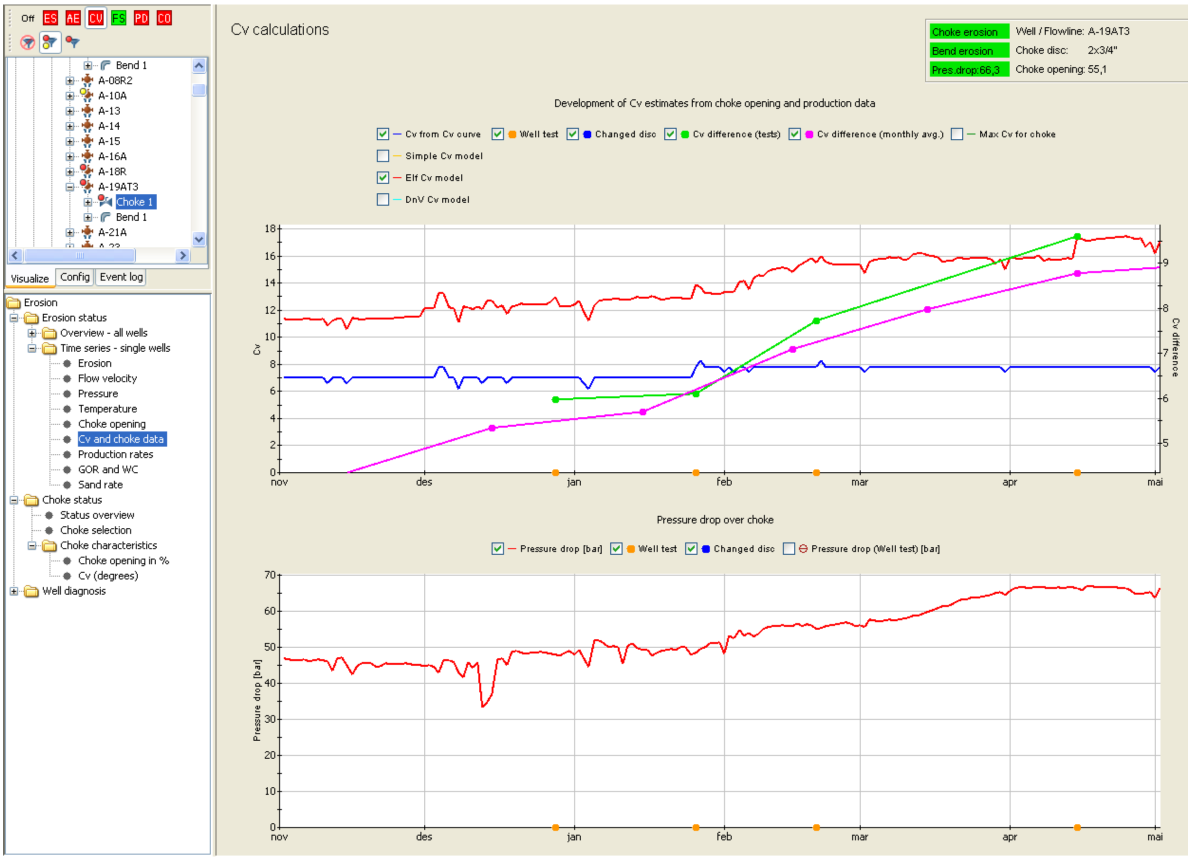
1. Choke erosion model developed by DNV with use of fixed sand rates as input where worst case is assumed. It calculates the choke outlet erosion. This model is described in chapter 5.3.4. The figure below shows a clearly indication of choke erosion. This is marked with a red “traffic light”. The erosion rate (green curve) is clearly above the max erosion rate (pink curve). At the same time the accumulated erosion (red curve) is above the max erosion (blue curve), and is increasing.



7-11: Red “traffic light” indicating that choke erosion is present

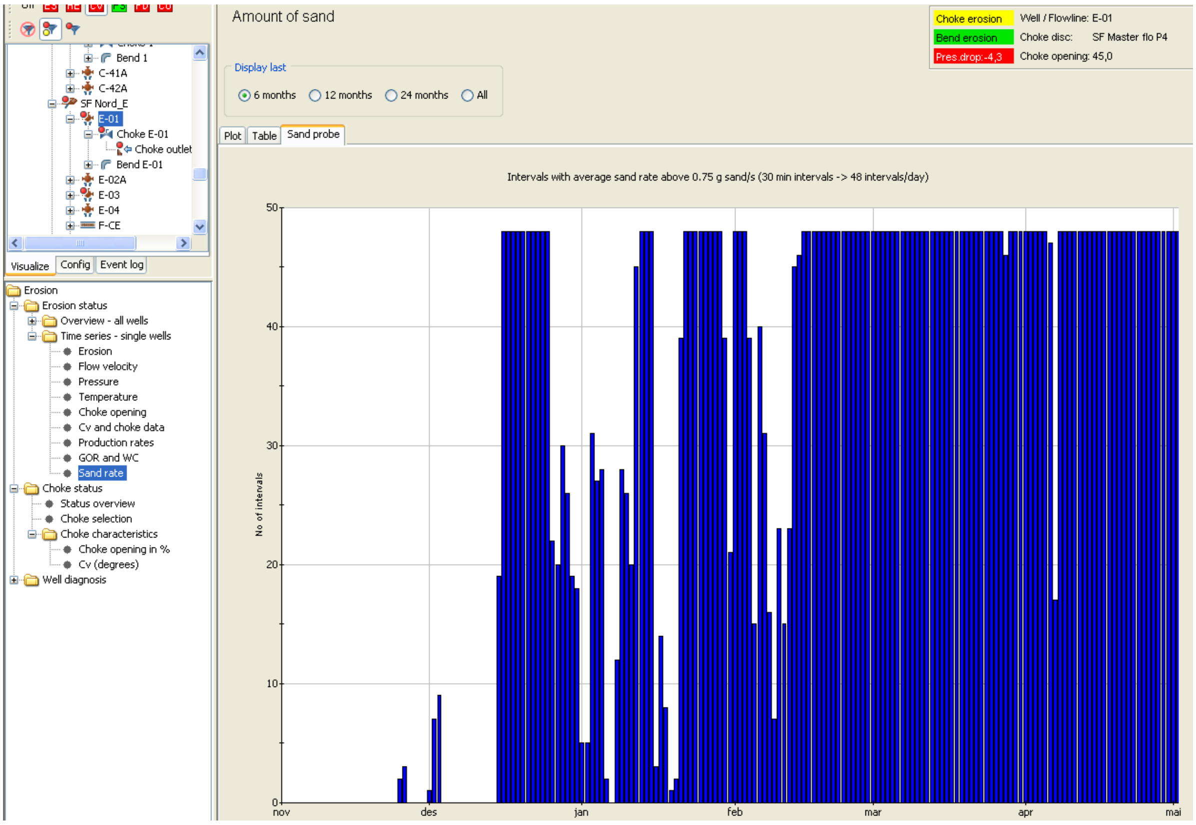
[43] [13],[D]

2. Calculations of the actual Cv-values for the chokes based on some Cv-models, and comparing these up against the theoretical Cv-values of a non-eroded choke from the choke characteristics given by the choke vendor, as described in chapter 3.3. This Cv-calculation (and thereafter possible Cv-differences) "monitors" the choke erosion. An example is shown in the figure below, where the Cv-difference curves (green and pink), representing the "gap" between the Cv-curves (red and the blue line). This increasing "gap" can indicate erosion (depending on the reliability of the data). A red "traffic light" in the data tree appears when the Cv-difference is higher than 7. This is further described in chapter 7.5.6.



7-12:Cv trend for the actual choke

3. Sand rate measurements which shows intervals with an average sand rate above 0,75[g sand/s] (30 min intervals-> 48 intervals/day)



7-13: Sand rate measurements

7.5.4 Cv-calculations[44]

How in general the Cv-calculation is done in INSIGHT is explained in chapter 3.3.

INSIGHT uses a few different models to estimate the actual Cv value based on the production data. All the models can be used in INSIGHT at the same time to see the difference. The one that gives the best result is the Elf-model.

The Elf model handles both critical and subcritical flow for multiphase mixtures and it gives therefore a more reliable result which makes it the most used model. This so-called Elf model is based upon the principle that equations which describe isentropic flow of multiphase mixtures through chokes can be deduced from the general energy equation, and are valid for both critical and subcritical flow.

7.5.5 Erosion calculator[45]

The erosion calculator is a tool in INSIGHT that is useful to do erosion calculations independent of the actual production data and the operation of a specific choke valve.

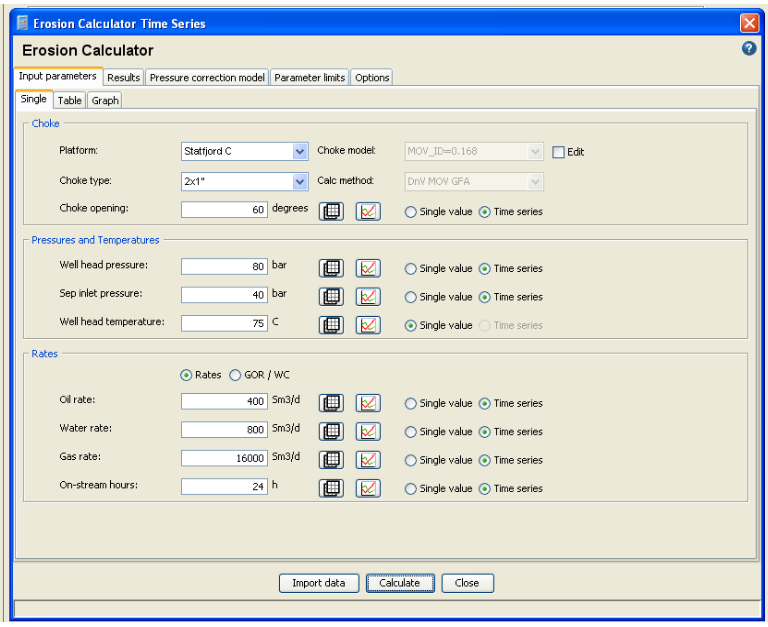
The input window is shown in figure 7-14 on the next page. Input data can be single input values or time series data imported for a certain time lag for a given field and well. The sand rate, well head temperature and the pipe diameter are the parameters that have not the opportunity to import data so these inputs must be typed manually and will be constant for the whole time period. But if data are available, these can be putted into an input table for the same time period as the rest of the time series data, and then the calculation results will be more accurate (depending on the data quality).

The calculator operates with two different types of calculation methods. These are:

- DnV MOV GFA
- DnV Guidelines

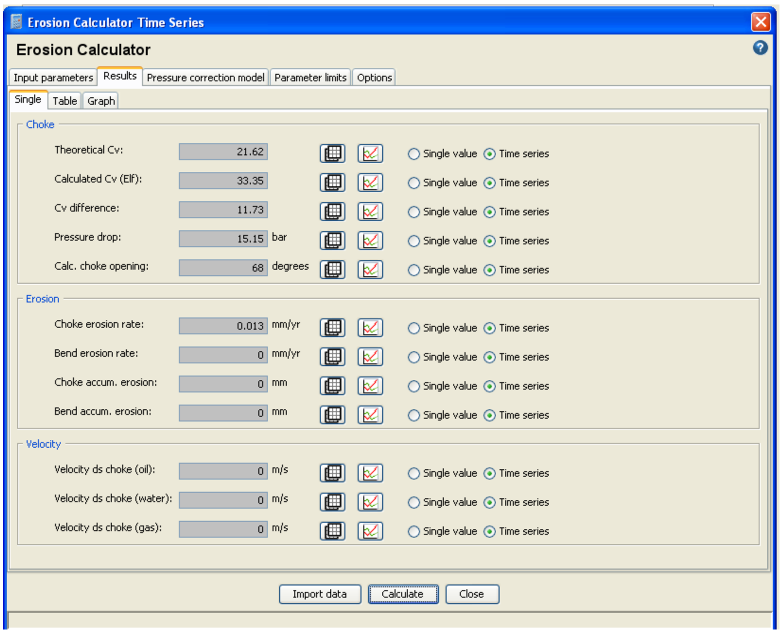
DnV MOV GFA is used for MOV chokes (typically topside), while the DnV Guidelines is used for the chokes with cage-types (typically subsea).

[44] [13],[30]
[45] [13]



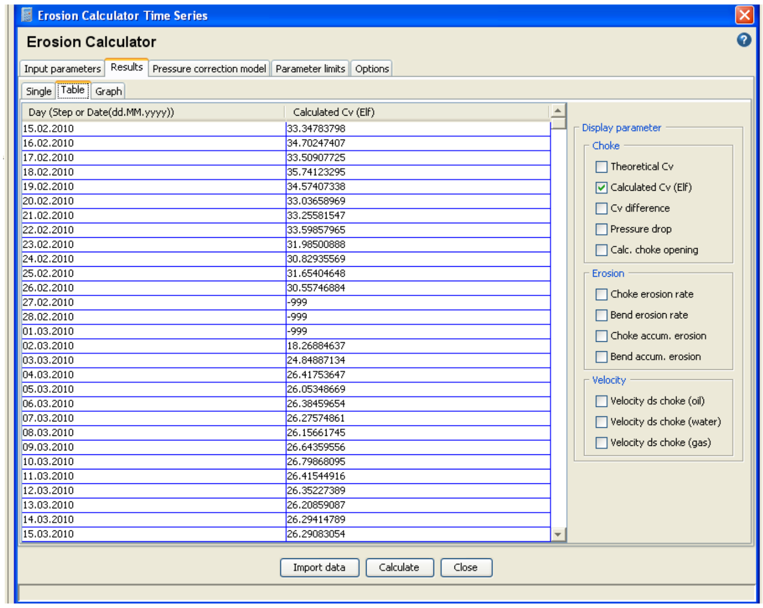
7-14: Input window for the erosion calculator

The output window and results from this input values is shown below. Here, only the result for the single input values or the values for the first day in the time period is shown.



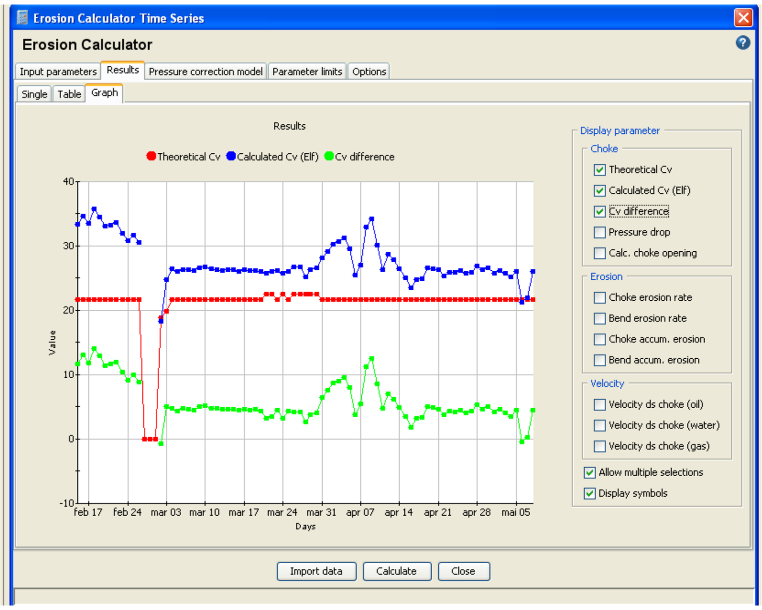
7-15: Output window for the erosion calculator

The results for the different parameters for the respective time period can be seen in tables such as the one shown below:



7-16: Calculation results shown in tables

These values can also be presented in graphs and compared to other output parameters. An example of this is shown below. Here the theoretical Cv, the calculated Cv and the Cv difference is presented together in one plot.



7-17: Calculation results shown as graphs

7.5.6 Evaluation and recommendation of choke operation[46]

Based on the status for a given choke, INSIGHT comes up with a recommendation basically telling the user if the choke is OK or that it should be changed with a smaller/larger choke.

The criteria defined in INSIGHT are as followed:

- Choke selection OK:
    - Erosion rate is less than 0.1 mm/year
- Consider smaller choke:
    - Erosion rate is between 0.1 and 0.5 mm/year.
    - The recommendation is based on the erosion rate only, and the choke opening degree is not taken into account.
    - For chokes with choke opening less than 60%, one can reduce erosion by changing to a smaller choke, which can be run with a greater opening.
- Use larger choke:
    - Erosion rate exceeds 0.5 mm/year.
- Potential gain in production by changing to a larger choke:
    - If erosion is not a problem, the choke is already almost full open, and the pressure drop across the choke is still considerable, the choke in use is probably too small. One can increase the production by changing to a larger choke.

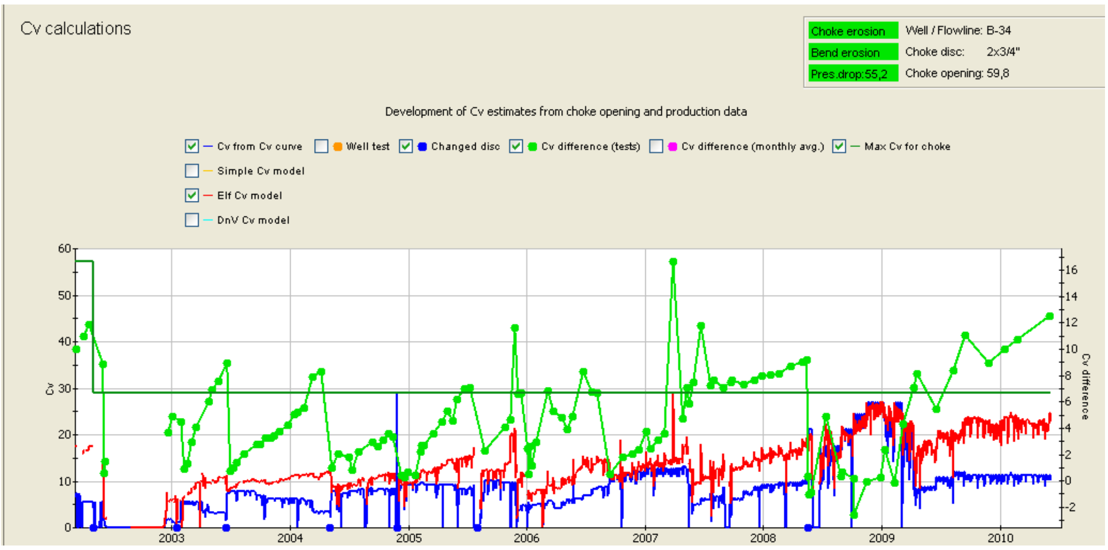
Due to the high influence on choke erosion results, the total flow velocity downstream choke should not exceed 10 [m/s].

The erosion allowance for the erosion rate and the accumulated erosion in INSIGHT can vary from well to well and from choke to choke. The values determined in INSIGHT are typically 0,1 or 1,0 for both accumulated erosion [mm] and erosion rate [mm/year].

When it comes to the Cv-value which seems to be the best indicator on choke erosion, a difference between theoretical and calculated Cv-value should not exceed 7. If it does, it is time to change the choke. This value is set based on first of all earlier experiences.

[46] [13],[C],[D]

Underneath is an example from Cv-calculations in INSIGHT showing the benefit of using Cv-trends as an early warning on choke erosion before a critical level is reached. Here, data from several years back in time is taken into account with the intention to show that the Cv-difference curve has a “saw-tooth” because of the choke changes (blue dots). In this case, a choke (disk) change (for a topside well) has been performed once every year when the Cv-difference has passed the “max Cv for choke”-line.



7-18: Cv-calculations

7.5.7 Weaknesses and limitations[47]

The quality of the input data decides the quality of the results, which means that with inaccurate input data from Prosty[48] will in the next round give inaccurate erosion results in INSIGHT. It has been experienced that the Prosty data quality can vary. For instance; uncertainties in the gas rate-data can often have a huge influence on the results in INSIGHT.

As mentioned in chapter 7.5.5, the values of well head temperature and sand rate have to be single value inputs in the erosion calculator (if not time series data is available from other sources), since Prosty, which INSIGHT takes the input data from, only uses fixed values for these (varying from field to field). This means that the accuracy of the erosion calculations (both in the erosion calculator and in INSIGHT in general) is weakened. It has to be mentioned that the well head temperature are normally not varying that much, and is not that "important" for the erosion results as the sand rate.

There is not enough thrust to the sand rate data/measurements due to problems with disturbances in the data. That is the major reason why Statoil has originally requested the conservative strategy of using "worst case" sand rates in INSIGHT, even if there exists sand rate data from sand detectors in Prosty. This confirms what is described in chapter 7.2.2 about sand monitoring. The positive aspect of using "worst case" (fixed) sand rate is that the erosion rate results can be used to classify wells (with the same sand rate) by their sensitivity regarding to erosion, given a certain sand rate, and that they are conservative.

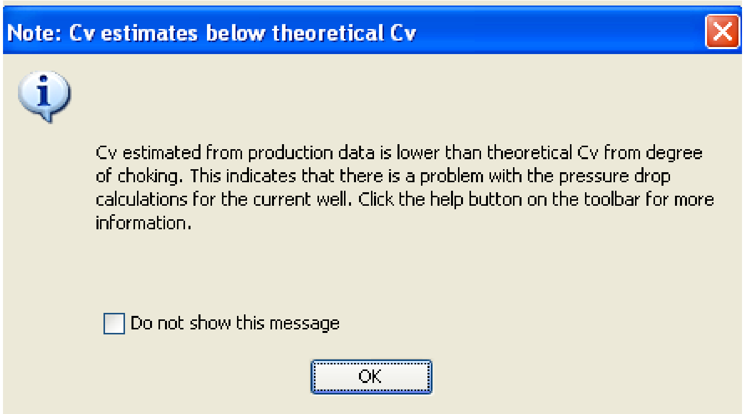
Considering the well head temperatures, fixed values for subsea wells are given in Prosty which is then integrated into INSIGHT. For the topside wells, the temperatures are defined in INSIGHT as a fixed value for each field since no Prosty data are available.

The topside choke changes are registered manually in Prosty which INSIGHT automatically reads data from, so there is a certain risk that some changes have not been included in Prosty and therefore also not in INSIGHT, even if the curves can indicate (clearly) so. At figure 7-18 it can be seen that for instance between 2006 and 2007 there probably should have been a blue dot indicating a choke change. It should also be mentioned that the present Cv-difference is on about 12, and a choke change should take place again. There is also a certain risk that wrong choke types are included in Prosty which again influences the results in INSIGHT. When it comes to subsea chokes, they are not registered in Prosty when changed, so people controlling INSIGHT must get a message when a subsea choke has been changed.

47 [C],[D],[32]

48 Prosty is a Statoil-database (data source) which INSIGHT reads data from

Sometimes the input values for the Cv-calculations can be wrong. Then the information window shown below appears:



7-19: Information window regarding bad Cv-values

This can indicate that there is a failure with the assumed production data like for instance the pressure measurements or the gas measurements, which again can make it look like there has been erosion but it is the input values which are incorrect. Therefore INSIGHT has build in various quality assurance mechanisms for input data such as visually comparison of production data with well test data, to detect these problems.

If the pressure drop over the choke is small, only small failures in the input values can give relatively large deflections on the calculated Cv-value. This is first of all because the pressure difference over the choke has a large influence on the calculated Cv-value. A thumb rule says that a pressure drop of at least 5-10 bar should be present to ensure reliable Cv results.

Considering subsea chokes at Statfjord, there is a weakness with the pressure drop over the chokes because there are no pressure measurements downstream given in Prosty that INSIGHT can use. INSIGHT adresses this problem by using a Prosper[49] model to calculate the pressure downstream. This means that the values from this Cv calculations are less accurate than for a regular pressure measurement.

Since December 2009 the computer calculating the Prosper values at Statoil has not been in operation due to technical problems, so a default pressure downstream has been used, which means that for this period the Cv values are even more inaccurate.

[49] Prosper is a well performance, design and optimisation program developed by Petroleum Experts

7.6 EFDD

7.6.1 General[50]

Since this master thesis has not made use of EFDD, only a brief presentation will be made with focus on how it is operated and how it works, and not focusing on the advanced algorithms and so on that EFDD is based upon.

Early Fault and Disturbance Detection (EFDD) is a condition monitoring software developed to do exactly what the name implies. That is to detect faults and disturbances in systems before they develop into more critical conditions and eventually cause the system to fail. The goal of the system is to achieve reduced downtime, optimized production and improved maintenance strategies.

The development project of EFDD is one of the results from the TAIL IO collaboration (2006-2008) which consisted of Statoil and the companies ABB, IBM, SKF and Aker. EFDD is developed (and are still under development) by Statoil and ABB where Statoil is the end user and ABB will end up with the ownership of the finished product.

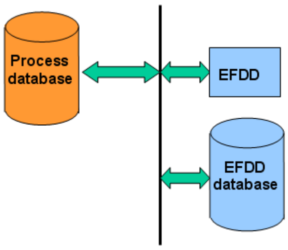
7.6.2 How it works[51]

Everything the EFDD tool can do is based on data. This means that all analysis operations require a data input. Data and datasets are values that somehow describe the process or system state, like different sensor readings. Mostly, the data will be organized in one or more time series that characterizes how the process develops over time.
However, EFDD may also analyze more general data sequences that are not pure time sequences. The only requirement is that data are organized so that a sample describes a "snapshot" in time, space, or other.

[50] [A],[33]
[51] [A],[33],[34],[35],[36]

The system has three main components as shown in the figure 7-20 underneath:

1. The process database
    - Where we get the input data from. We may also load data from file.
2. The EFDD program
    - A stand-alone application used for system configuring and data analysis.
3. The EFDD database
    - Where we save all EFDD parameters and analysis results.



7-20: The three main components of EFDD

The system can be run in two modes:

- Interactive mode – for detailed configuring and analysis, also including a simplified monitoring user interface.
- Automated mode – for scheduled analysis of online data.

The everyday operation of the EFDD system include users such as those responsible for planning of maintenance for the specific system, and those responsible for plant operation. These people require high-level and relevant information about the plant condition and a way to drill down to the desired level of details. The actual day-to-day use of the system is intended to be automatic and unsupervised.

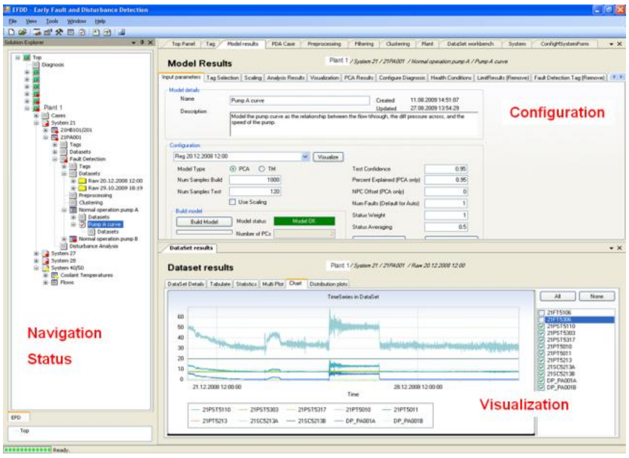
EFDD is based on two main modules. These are:

- EFD – Early Fault Detection
- PDA – Plant Disturbance Analysis

Explained in simple words; EFD is as the title says-detecting a failure at an early stage to reduce the risk of potential danger with an given failure and so on. PDA is used to automatically detect disturbances and determine the root cause of a failure.

Both of these makes the use of sensitive algorithms which may give a fault indication much earlier than if observing the effect of a fault that has developed to something serious. The data flow within these two modules is shown in attachment G.

Underneath is a figure showing the three main windows in EFDD:



7-21: The three main windows in EFDD

These three are:

- The Navigation status window
    - Plant
        - Here the choice of which plant to study is taken. This could for instance be an offshore platform.
    - System
        - This is a part of the chosen plant representing the area of interest for the given study. This could be a group of equipment such as the heat exchangers for the respective offshore platform, or it could be a process with a dedicated purpose like the separation process.
    - Sub-system
        - A sub-system is a part of the system, since a system could be very large. It is here the respective tags and their data are defined and uploaded.

- The configuration window
    - Here analyses using the different chosen data can be done. Models can be built including different tags and their data. "Virtual tags" can also be made here, creating new tags based on different data using mathematics to get the information needed. This could be a pressure difference, subtracting one pressure tag from another. Treatment such as filtering and manipulating the data can also be performed here.
- The visualization window
    - Here the data (from the configuration) can be studied as different curves. It is possible to cluster different data to look for a "pattern" like for instance same frequency spectra.

7.6.3 Possibilities and limitations considering choke erosion monitoring[52]

EFDD is a kind of "future-oriented" condition monitoring tool where one of the main objectives is to integrate data/information from many different systems and equipment making it easier to monitor. This is obvious because one tool is easier to handle and control than several for each and every system, such as INSIGHT for choke erosion monitoring. Therefore, a futuristic possibility is to integrate the data/information used in INSIGHT into EFDD with the same or preferably even better condition monitoring capacity.

If, and how the "INSIGHT-properties" can be integrated in EFDD is not clear today and is difficult to know exactly, but some reasonable suggestions and thoughts around this can be done. Based on what are the best and most reliable condition monitoring possibilities that INSIGHT has, these suggestions are:

- Use of "virtual tag" to calculate Cv-values and erosion rates
    - Here, an integration of the necessary formulas and data can be done to get the actual Cv-value for a given choke and the compare it against the Cv-curve (theoretical Cv-value).
    - Using "virtual tag" to get the erosion rate for the chokes and compare these up against recommended values and so on.
- Sand rate measurements
    - Use the data from the sand detectors to see the sand production over time and then get an indication of the potential sand erosion of the respective choke valve.

[52] [D]

Both EFDD and INSIGHT are being developed by the same development team in the department 'Integrated Operations' within the Oil, Gas and Petrochemical unit in ABB, and they confirm that data integration and presentation are a part of the strategies for both products. However, specialized tools such as INSIGHT has quite a lot of specialized functionality (not described in this thesis) compared to general tools such as EFDD, so they will both play an important part in offering a complete suite of tools for analysis and decision support.

7.7 Main benefits of using CM with attention to choke erosion[53]

As described in the beginning of this chapter, condition monitoring is with no doubt beneficial. Considering the criticality and of an eroded choke valve with attention to safety and the potential loss of profit during down time, condition monitoring is not less relevant for this topic.

Having the possibility to see the different production- and sensor data and choke status together with a “recipe” on optimal operation of a choke valve is a huge benefit with attention to avoid sand erosion in a best possible way.

As an example of the benefits with the use of ASR instead of using MSFR in form of increased production at the Statfjord field, it can be mentioned that during 2004 (with INSIGHT in use), 1.9 mill.bbl (barrels of oil) was added. This says something about the huge benefits of using condition monitoring tools such as INSIGHT to be able to operate with ASR even if the confidence of the sensor data and other factors are not optimal (but acceptable).

Considering that more can be done to get an even better optimal CM of the choke valve operation specially and the production process generally due to not optimal (use of) sensor data and so on motivates for more research and opens possibilities for lower operational costs, and increased safety and –profit.

As a practical example of benefits with use of condition monitoring tools such as INSIGHT it can be mentioned that the price of a subsea intervention for replacing a choke valve is high. Knowing at an early stage which chokes (at the same field) that soon have to be changed can save both a lot time and a lot of costs due to possible co-ordination of intervention work.

[53] [8],[19]

8 Testing and verifying the erosion calculator in INSIGHT

8.1 General

The erosion calculator is described in chapter 7.5.5.

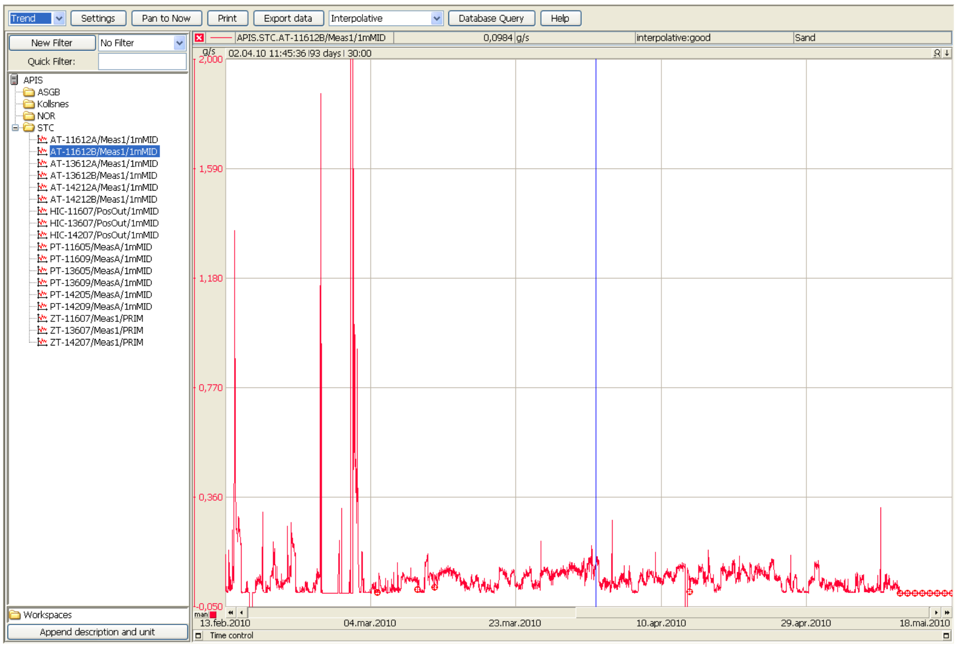
It is of main interest to use the erosion calculator to see the sensitivity of the choke erosion results and compare them, by changing different input data and constant values.

As mentioned earlier, well head temperature and sand rate are the input parameters that manually have to be included in the erosion calculator as time series (if not a fixed single value shall be used). The pipe diameter is of course constant.

The choice of well(s) to analyze data from is done with recommendations from people from Statfjord C and what APIS and INSIGHT shows of data with "good quality". The relevant tag numbers were found and the respective data (curves) were studied in APIS to see if the data was ok to go further with. For information about APIS, see next chapter.

8.1.1 APIS

APIS is a program which in simple words shows the respective data for chosen tags (for sensors and so on) over a chosen time-series. An example of using APIS is shown below where the tag list is to the left, and the tag chosen to see is the sand rate data to be used in INSIGHT.



8-1: Example of using APIS

8.2 Limitations and area of focus

Many aspects could be interesting to take a closer look at using the erosion calculator since it exist a lot of different wells with different chokes that can be analyzed and verified. Considering the time limit, the complexity of this field and the fact that necessary information for analyzing data for certain areas has not been available, the focus area has to be limited in best possible way.

The idea was in the beginning to focus on a subsea choke valve since this has been the main focus area when it comes to describing choke valves, but this is not critical since a subsea choke valve and a topside choke valve are based upon the same principles considering INSIGHT. Some simple explanations to the lack of information and change in focus area are:

- Problems/weaknesses with INSIGHT as explained in chapter 7.5.7.
- The persons who are sitting on the key-information are not available.
- The key-information is not available for this project and its time limit.
- The relevant/recommended documents and/or tag numbers for the respective sensors and so on cannot be found in the database.

Based on the main limitations mentioned above and the fact that the sand rate has no time-series data integrated in INSIGHT, it is of interest to test choke erosion results by changing sand rate values using “worst case” sand rates vs. time series data.

An evaluation was also done on if an similar analysis should be done with the well head temperature as well because of the use of fixed values also here, but due to the time limit of this master thesis and the fact that temperatures normally do not vary as much as the sand rates are (compared to the assumed values) it was chosen to only focus on the sand rate case. Another important reason is that sand production is a more critical factor concerning sand erosion than temperatures as well.

Another idea was to compare the erosion results for two different choke valves (one subsea and one topside) by using the same input data.

People working with development of INSIGHT is interested to test INSIGHT-functions such as the erosion calculator since it is a tool under (constant) development which means that “bugs”/weaknesses and different errors can appear in the different calculation models and so on. Therefore, this is also interesting to include in the results since it represents possible improvements for INSIGHT.

8.3 Sand rates

Since sand rates are the main area of focus, wells with clearly sand production were of interest. The well chosen to take a closer look at in this case is the C-16 which is a platform-well. This is because well C-36 and C-42, which also was recommended by people from Statfjord C, showed in comparison “poor” sand detector data in APIS. Some subsea wells was also recommended and off course of interest to study, but due to the explanations described earlier, this could not be done.

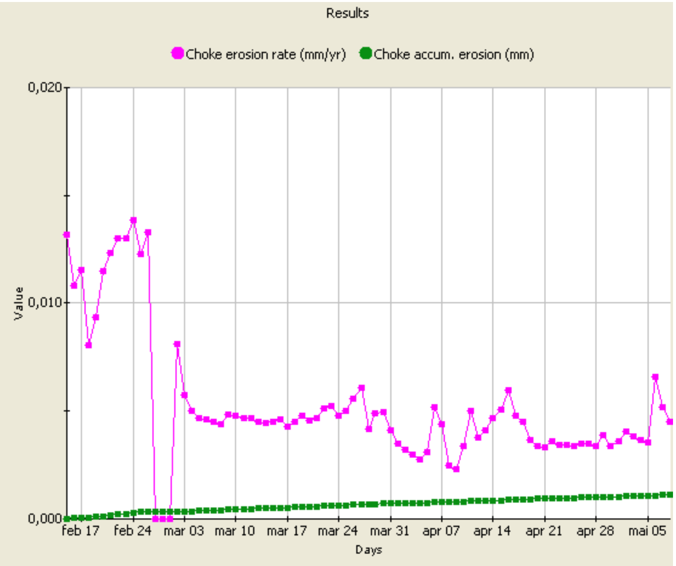
The period chosen for the imported data is from 15.02.2010 to 09.05.2010. The reason for choosing this period is because it is a suitable amount of data, and “peaks” in some curves given in INSIGHT is of interest to include.

Well C-16 has two ClampOn sand detectors placed before the choke valve. The P&ID for well C-16 showing the placement of the choke valve and these sand detectors can be seen in attachment D.

INSIGHT operates with a “worst case” sand production rate which for the wells at Statfjord C is given to be 0,75 [gram/s].

The idea here is to compare the results with and without worst case sand production. Without worst case sand production the sand data is taken from the sand sensors in APIS and integrated into INSIGHT as earlier explained. These data from for the given period can be seen in attachment E.

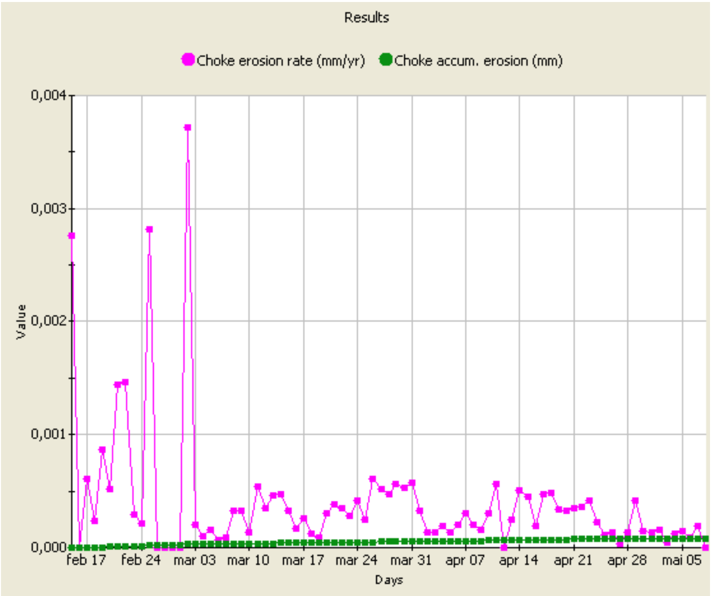
Underneath the choke erosion rate [mm/yr] and the choke accumulated erosion [mm] calculated by the erosion calculator assuming worst-case sand production is presented.



8-2: Erosion results assuming worst case sand production

Even if the values are very low, the curves are showing clearly (as expected) that the erosion rate has an increasing trend throughout the period, and the erosion rate is varying depending on the values of the different parameters such as the velocity, production rates and so on.

The scenario with the sand rate data integrated into INSIGHT is presented below:



8-3: Erosion calculation results with integrated sand rate data

8.3.1 Discussion of result

As for the results with worst case sand rate, the values are low for the scenario with input data, and the accumulated erosion is increasing. The erosion rate curve is varying more here because of the different sand rates from day to day.

For this given period, the average erosion rate with worst case sand production was 0,005272 [mm/yr], while it was 0,000401[mm/yr] with use of sand rate data, which is a difference on 0,004871 [mm/yr]. This corresponds to an increase in the choke erosion rate with 1314%. The value is not high but the relative difference is. Considering the facts that this was just for one well over a small three-month period, and INSIGHT has been in use for almost a decade on several hundreds of wells, this means that the erosion rate differences could (in average) vary even more.

These erosion rate results from the erosion calculator can be seen in attachment H and I.

Another observation (which also was expected) is that the values are lower because the worst case sand rate (0,75[gram/s]) is way above the average sand rate from the data which is about 0,09[gram/s].

8.4 Comparing erosion rates for two different choke types

Here, a comparing of the erosion results for a topside choke and a subsea choke using the same input data was the idea. The topside choke is the same used in the sand rate test (well C-16) which is a 2x1" MOV choke, while the subsea choke is a MasterFlo P4. The topside choke uses the calculation method DnV MOV GFA, while the subsea choke uses DnV Guidelines.

The input data used in both of the calculations and their respective results are shown in attachment J, K and L.

An attempt to change the calculation method for the two chokes was also done.

8.4.1 Discussion of result[54]

With attention to choke erosion rate results, the topside choke got an erosion rate on 0,0021[mm/yr], while the subsea choke got an erosion rate on 4,84[mm/yr]. It was expected a certain difference, but this is a much higher difference in the erosion rates than expected (an increase on about 230476%). According to the development team at ABB, this result has that high difference most likely because the input data are "on the edge" with the area of validity for the DnV MOV GFA method, but also because (as expected) two different types of chokes with use of two different calculation methods will give a certain difference in the results. ABB also points out that currently, the offline erosion calculator in INSIGHT is using a different calculation engine than the online version. Problems seen in the offline use are therefore expected to be limited to the offline case only, and should have no effect on the online erosion monitoring results.

Changing the calculation methods resulted in an error for both cases. For the attempt using the subsea choke with the opposite calculation method ("DnV MOV GFA") gave an error as followed: "Calculation failed". For the attempt using the topside choke with "DnV Guidelines" made the program "freeze" and it had to be restarted. According to the development team at ABB, this happens because the two different models are based on different amount of input data, and therefore they cannot perform the wanted calculation. This is not a critical problem because the two different models are "designed" and meant for their specific choke types. Anyway, a possible solution to this type of "problems" is a sort of programmed interlock which means that calculation with "no-sensible" choice of input data and methods cannot be accomplished.

[54] [D]

9 Main conclusion and further work

9.1 Main conclusion

Sand erosion in general is a problem for the oil- and gas industry, where the Statfjord field is no exception. Hereunder, erosion of choke valves both topside and subsea is critical considering essential factors such as safety and profit. The many root cause of failures of choke valves linked to erosion (as shown in Attachment F) is a clear evidence that supports this statement.

As long as “traditional” oil- and gas production will be present, sand production will occur and cannot be stopped totally. The integration of the CM-tool INSIGHT at Statfjord has since the beginning (in 2003) shown that producing and operating with an ASR instead of MSFR has been successful.

Where there exist forms of limitations and weaknesses, there is room for possible improvements. This also concerns the condition and performance monitoring process of choke valves with attention to erosion. Some important factors discussed in this thesis which illustrates this are:

- New and improved technology within sand monitoring.
- Better (and more exact) erosion models, including calculating models used in INSIGHT, such as the important Cv-calculation.
- Choke valves with state-of-the-art erosion resistant qualities with special attention to shape and type of material.
- Better operational procedures and “follow-up”-routines for the users and others involved in daily operation of INSIGHT.

The quality of the input data decides the quality of the results, which means that improving the accuracy and availability of input data used in INSIGHT will improve the erosion results, and then again give a more accurate overview of the condition and performance of the chokes. Better input data quality from Prosty will give better and more accurate results in INSIGHT. Even though sand rate data exists in Prosty, Statoil decided in the integration phase of INSIGHT that “worst case” sand rates should be used due to problems with disturbances in the data causing a low confidence to these. However, one beneficial reason of using “worst case” sand rate is that INSIGHT will give a conservative calculation result, but the accuracy is anyway weakened compared to use of real sand rate data.

9.2 Further work

Based on the fact that sand rate data available in Prosty is not included in INSIGHT, it would be interesting to investigate this further and see if there is (in 2010) good enough sand rate data and improved thrust to them so they could be (automatically) included in INSIGHT for achieving more precise erosion calculation results.

Considering some of the other factors discussed in chapter 7.5.7 (weaknesses and limitations regarding INSIGHT), pressure- and gas rate data is important parameters for the Cv-calculations. Improving these data reduces the possibility of failures in the Cv-calculation.

Other interesting themes to be mentioned as possible further work is the erosion models, Cv-models and the calculation methods used in INSIGHT. The different erosion models and Cv-calculations could maybe be improved by use of advanced CFD analysis for improving/fine-tuning the existing ones. It was not possible in this thesis, but it would also be interesting to study the two different calculation methods used in the erosion calculator ("DnV MOV GFA" and "DnV Guidelines") by comparing and investigate them for possible limitations and improvements.

Using CM should be as easy as possible for achieving as less complications as possible due to for instance many different information sources to handle that makes more room for errors and uncertainties. Integrating the main functions of INSIGHT in EFDD could be an opportunity to reduce this amount of information sources and make the CM process easier for the users. This will most likely need much investigation and testing.

The INSIGHT development team at ABB has been cooperative in identifying the potential for the different possible improvements, and has responded that they will be addressing the identified issues and release updated software versions handling these issues.

10 Sources

[1] **Statoil**; www.statoil.com [Intranet and Internet]

[2] **DNV**; Recommended practice RP 0501-Erosive wear in piping systems, 2005. [Report]

[3] **K. Haugen, O. Kvernvold, A. Ronold and R. Sandberg**; Sand erosion of wear-resistant materials: Erosion in choke valves. DNV, 2005. [Report]

[4] **H. Nilsen**; Sand erosion in Snorre A. University of Stavanger, 2006. [Master thesis]

[5] **J. Andrews, H. Kjørholt and H. Jøranson**; SPE 94511-Production enhancement from sand management philosophy. A Case Study from Statfjord and Gullfaks. Statoil and SPE, 2005. [Report]

[6] **S. Peri and B. Rogers**; IPTC 11770-Understanding Erosion Prediction: Determining Erosion in a Choke. IPTC, 2007. [Report]

[7] **J. Tronvoll, M. Dusseault, F. Sanfilippo and F. Santarelli**; SPE 71673- The Tools of Sand Management. SPE, 2001. [Report]

[8] **K. Lejon, A. Reme, R. Woster, O. Kvernvold and L. Torbergsen**; Sand Production Management for Snorre B subsea: Development-Lessons learned and actions taken. DNV and Statoil, 2007. [Report]

[9] **K. Hovda and J. Andrews**; Erosion Management for subsea wells at Gullfaks and Statfjord. ABB and Statoil, 2007. [Power point presentation]

[10] **DNV**; Report No: 2009-0373-Guideline for selection and operation of chokes in sandy service. DNV, 2009. [Report]

[11] **R. Wood**; Erosion–corrosion interactions and their effect on marine and offshore materials. Elsevier, 2006. [Report]

[12] **A. Huser, O. Kvernvold and T. Søntvedt**; Erosive Wear in Choke Valves. DNV and Norsk Hydro, 2001. [Report]

[13] **INSIGHT** [Intranet at Statoil]

[14] **N. Braaten and T. Blakset**; SPE 30644-Experience from topside and subsea use of the erosion based sand monitoring system. SPE,1995. [Report]

[15] **N. Braaten, R. Birkeland, S. Lilleland and R. Johansen**; Erosion monitoring manages sand production. Oil & Gas Journal, 1998. [PDF-presentation]

[16] **ROXAR**; www.roxar.com [Internet]

[17] **ClampOn**; www.clampon.no [Internet]

[18] **C. McPhee, C. Farrow and P. McCurdy**; Challenging convention in Sand Control: Southern North Sea examples. SPE, 2007. [Report]

[19] **K. Hovda and K. Lejon**; Effective Sand Erosion Management in Choke and Pipelines. ABB and Statoil, 2007. [Power point presentation]

[20] **MasterFlo**; www.masterflo.com [Internet]

[21] **J. Friedemann, A. Varma, P. Bonissone and N. Iyer**; SPE 112051- Subsea Condition Monitoring: A Path to Increased Availability and Increased Recovery. SPE, 2008. [Report]

[22] **K. Lejon**; Sand Management-Challenges and opportunities. Statoil, 2009. [PDF presentation]

[23] **Italvalv**; www.italvalv.it/tables/ball_valveflowcoeficient.gif [Internet]

[24] **KentIntrol**; www.kentintrol.com/support/testing [Internet]

[25] **M. Rasmussen**; Driftsteknikk GK. NTNU, 2003. [Compendium]

[26] **F. Selfridge, M. Munday, W. Martin, O. Kvernvold and B. Gordon**; ConocoPhillips Sand Management Strategy. DNV,ConocoPhillips,2005. [Report]

[27**] A.Huser, O.Kvernvold**;Prediction of sand erosion in process and pipe components. DNV,1998.

[28**] O. Brakstad, G. Instanes**; SPE123851- Increased earnings: Adding more functions and knowledge into subsea instrumentation to increase production, keeping safety issues in the driver seat! ClampOn, 2009. [Report]

[29] **L. Torbergsen and O. Kvernvold**; Safely optimizing production by introducing the concept of Acceptable Sand Rates (ASR). DNV, 2004. [Report]

[30] **T. Perkins**; Critical and Subcritical Flow of Multiphase Mixtures Through Chokes. SPE, 1993. [Report]

[31] **R. Schûller, S. Munaweera, S. Selmer-Olsen and T. Solbakken**; Critical and Subcritical Oil/Gas/Water Mass Flow Rate Experiments and Predictions for Chokes. SPE, 2006. [Report]

[32] **Petroleum Experts**; www.petex.com [Internet]

[33] **E. Lunde**; Different information sheets and files about EFDD. Statoil, 2009. [Presentations]

[34] **A. Horch, J. Cox and N. Bonavita**; Peak Performance. ABB, 2007. [PDF presentation]

[35] **E. Lunde, K. Hovda and J. Spjøtvold**; SPE 128558-Multi-disciplinary, multi-user process monitoring: Cross-discipline development and cross-company collaboration. SPE, 2010. [Report]

[36] **E. Lunde and E. Meland**; Early Detection and Localization of Equipment Faults in Complex Systems. NTNU and Statoil, 2010. [Report]

[37] **A.Valland**; Condition and performance monitoring. Marintek, 2006.
[Power point presentation]

Conversations:

[A] Erling Lunde (teaching supervisor), Statoil

[B] Tormod Reigstad, ClampOn

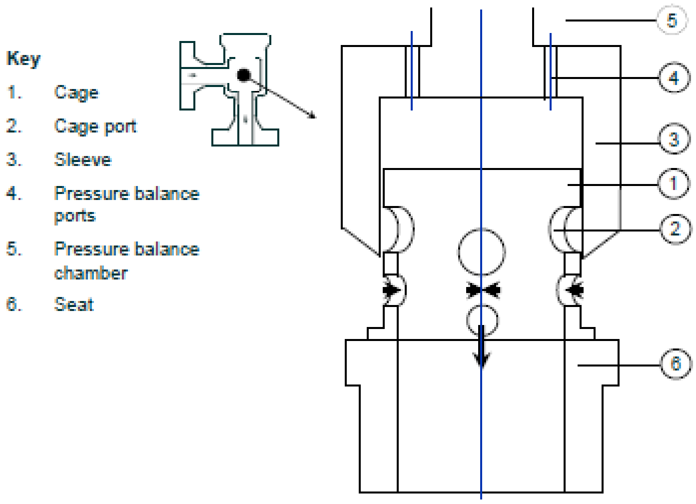
[C] Åse Unander, ABB

[D] Knut Hovda, ABB

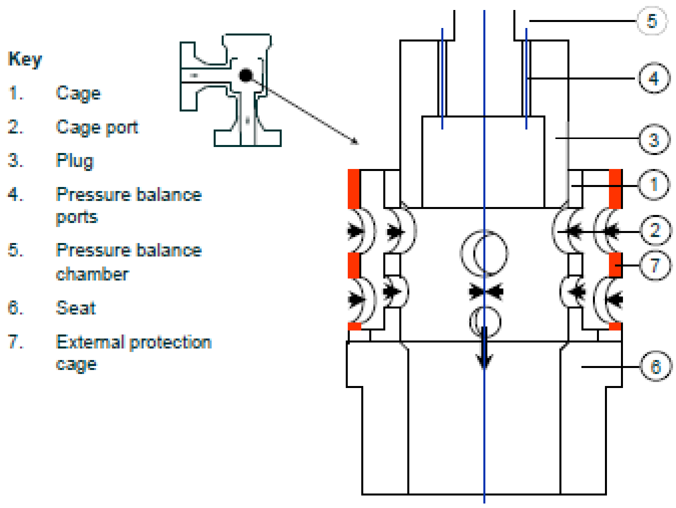
11 Attachments

Attachment A: Typical choke types used subsea

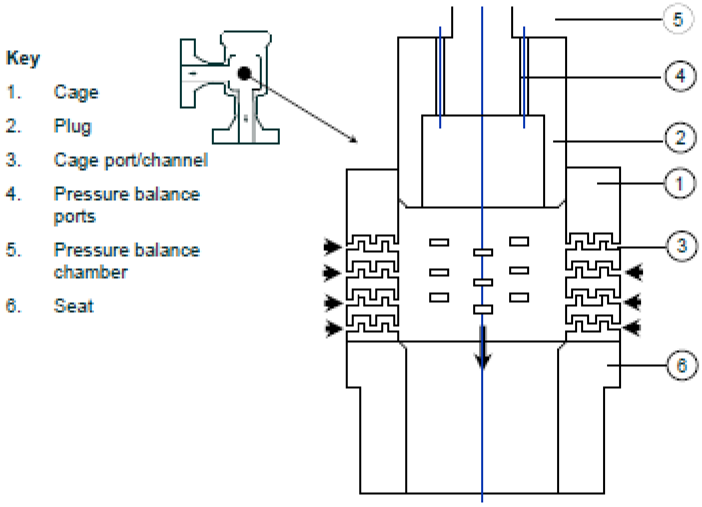
Single stage cage with external sleeve:



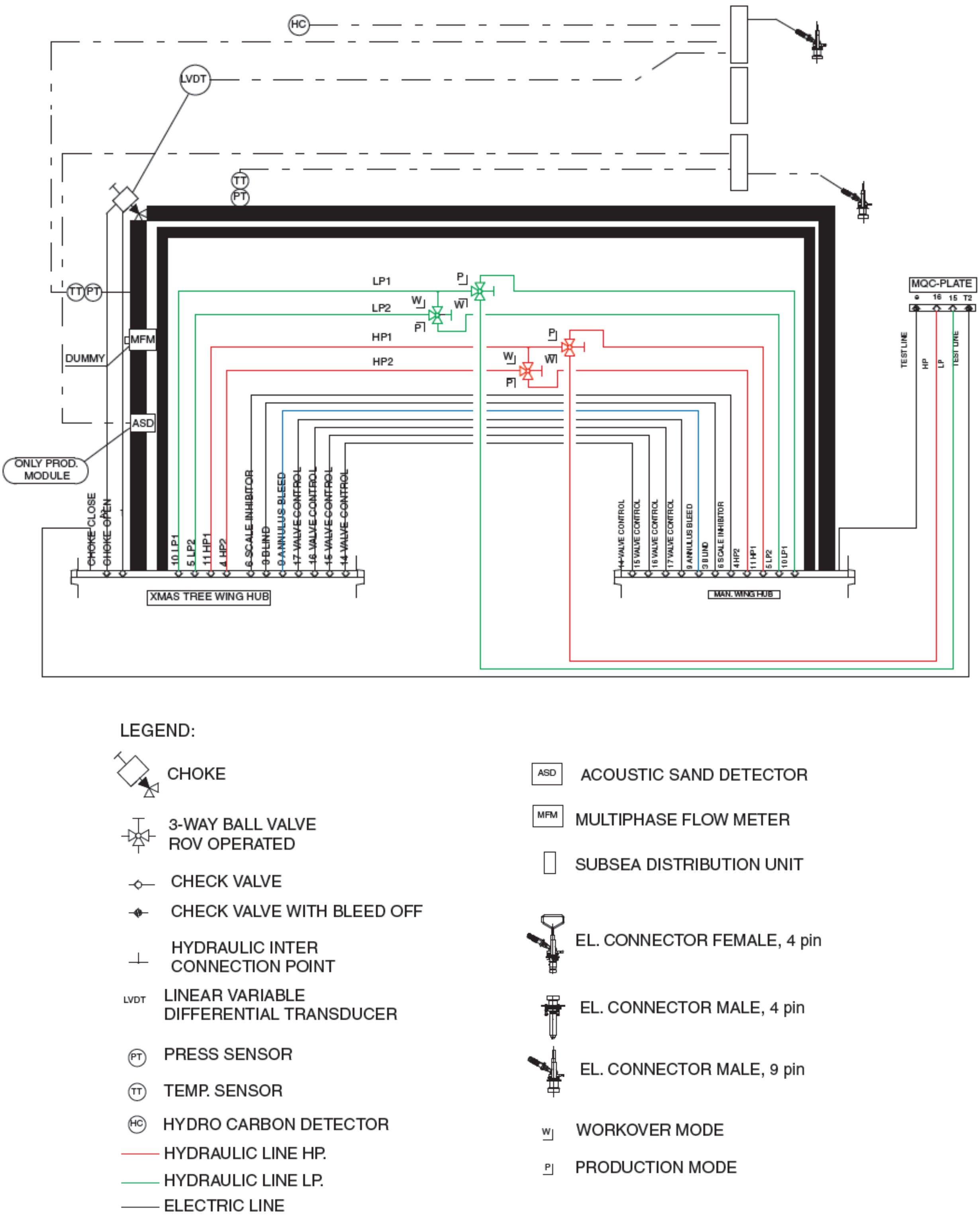
Single stage cage & internal plug with external protection cage:



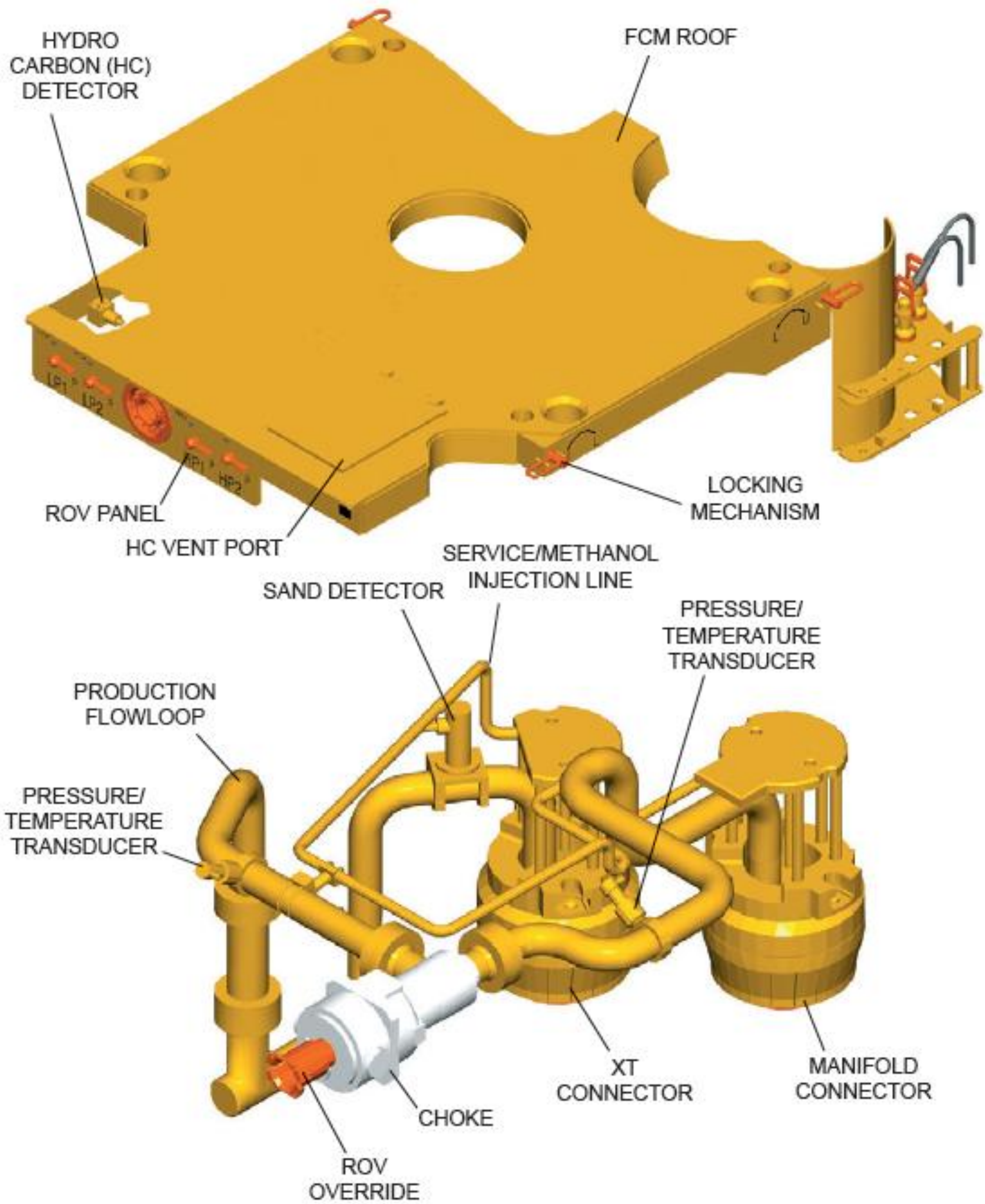
Multistage/Labyrinth cage with internal plug:



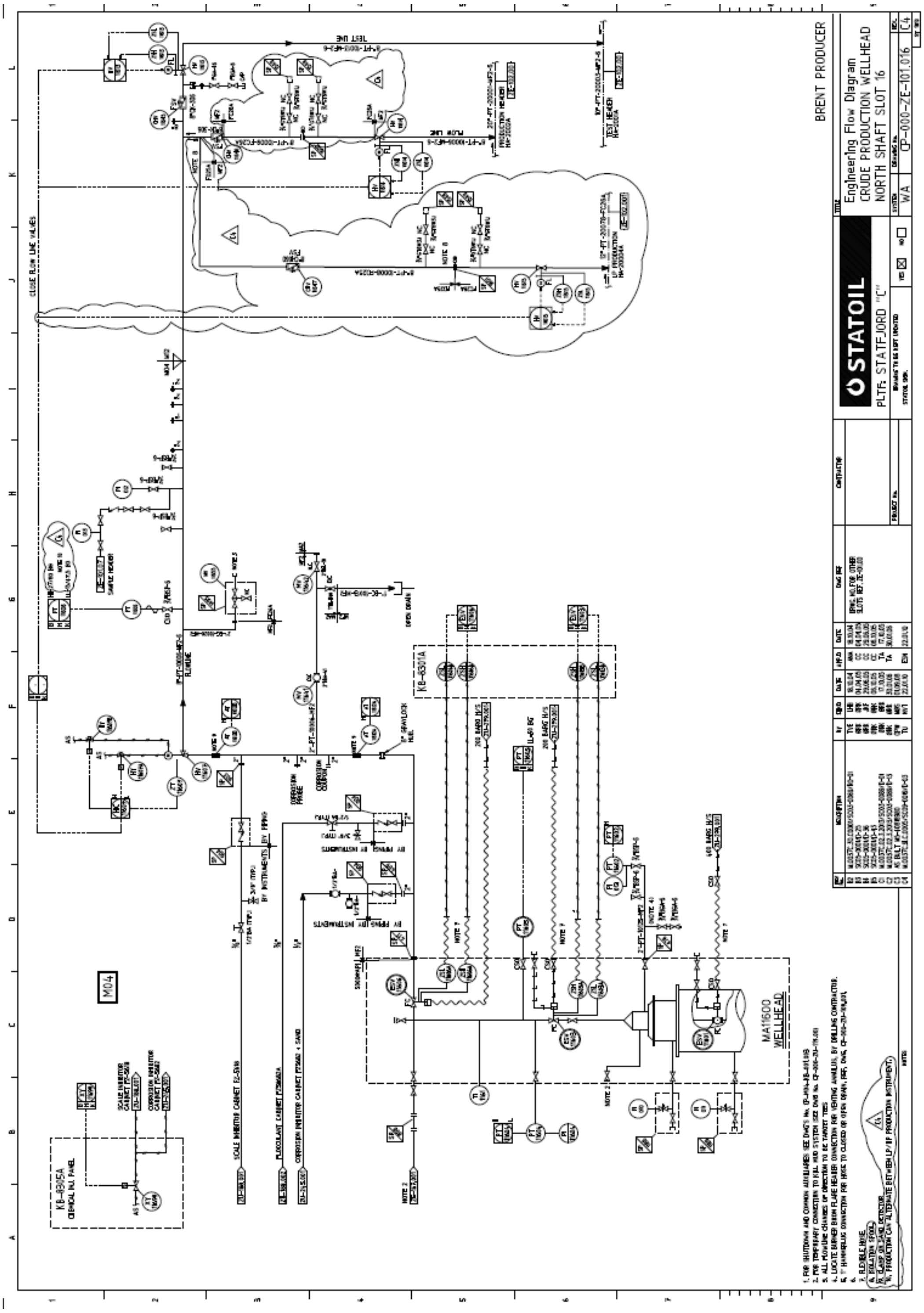
Attachment B: Flow scheme showing the typical instrumentation around a subsea choke valve



Attachment C: Subsea Flow Control Module



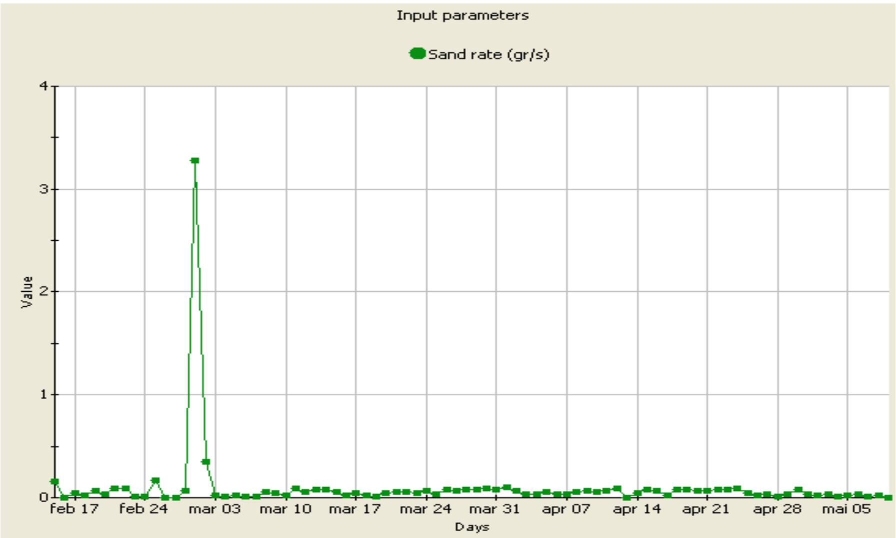
Attachment D: P & ID for well C-16 at Statfjord C



Attachment E: Input sand rate data for well C-16

Date	Sand data from sand probes [gram/s]
15.02.2010	0,1568405549
16.02.2010	-6,4948086848
17.02.2010	0,0398056041
18.02.2010	0,0220001118
19.02.2010	0,0698661182
20.02.2010	0,0336749362
21.02.2010	0,0874746403
22.02.2010	0,0847859916
23.02.2010	0,0166626780
24.02.2010	0,0115443028
25.02.2010	0,1721934249
26.02.2010	0,0000000000
27.02.2010	0,0000000000
28.02.2010	0,0644245061
01.03.2010	3,2739846345
02.03.2010	0,3442634501
03.03.2010	0,0256895082
04.03.2010	0,0144288986
05.03.2010	0,0245862353
06.03.2010	0,0114544680
07.03.2010	0,0158810230
08.03.2010	0,0565122406
09.03.2010	0,0506957361
10.03.2010	0,0206755623
11.03.2010	0,0864299327
12.03.2010	0,0558605029
13.03.2010	0,0771149654
14.03.2010	0,0806293865
15.03.2010	0,0551698894
16.03.2010	0,0280034315
17.03.2010	0,0449012159
18.03.2010	0,0214636584
19.03.2010	0,0136207103
20.03.2010	0,0495786855
21.03.2010	0,0617091808
22.03.2010	0,0512613965
23.03.2010	0,0395425550
24.03.2010	0,0655106495
25.03.2010	0,0369740540
26.03.2010	0,0815454093
27.03.2010	0,0636216766
28.03.2010	0,0769463046
29.03.2010	0,0843499963
30.03.2010	0,0855200843
31.03.2010	0,0798963427
01.04.2010	0,1043644939
02.04.2010	0,0697060391
03.04.2010	0,0326746795
04.04.2010	0,0341414968

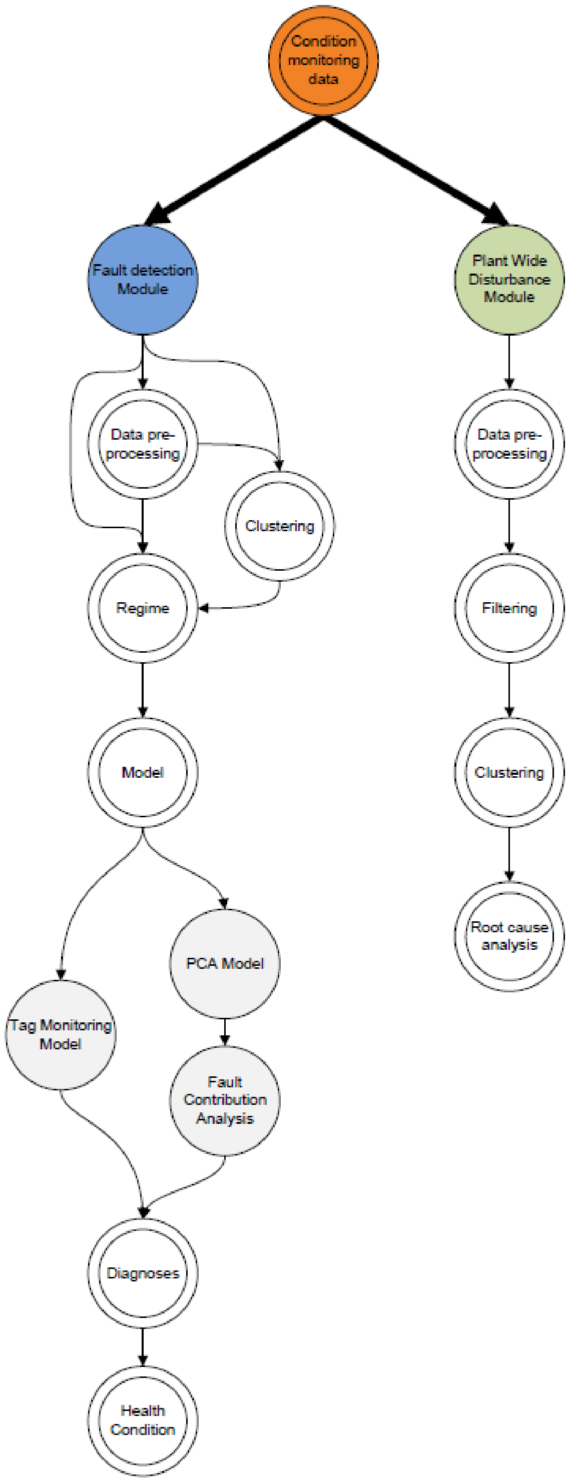
05.04.2010	0,0521492436
06.04.2010	0,0339240582
07.04.2010	0,0296783145
08.04.2010	0,0520670762
09.04.2010	0,0620339372
10.04.2010	0,0511352844
11.04.2010	0,0666423912
12.04.2010	0,0849851393
13.04.2010	-4,2785699675
14.04.2010	0,0462627623
15.04.2010	0,0810471111
16.04.2010	0,0660834909
17.04.2010	0,0245344444
18.04.2010	0,0743220467
19.04.2010	0,0812049714
20.04.2010	0,0704941224
21.04.2010	0,0720272663
22.04.2010	0,0781957483
23.04.2010	0,0745212447
24.04.2010	0,0909848045
25.04.2010	0,0480505249
26.04.2010	0,0252399591
27.04.2010	0,0295449560
28.04.2010	0,0069404689
29.04.2010	0,0288938435
30.04.2010	0,0793155341
01.05.2010	0,0334381506
02.05.2010	0,0279108280
03.05.2010	0,0289864630
04.05.2010	0,0090453852
05.05.2010	0,0264875624
06.05.2010	0,0299687812
07.05.2010	0,0100793638
08.05.2010	0,0273100183
09.05.2010	0,0006036765



Attachment F: Most likely root cause of failure

	Cause of failure									
Experienced Failure	Actuator failure – mechanical failure	Cage/nozzle collapse	Erosion to choke body or flange	Blockage of sleeve / plug due to foreign object stuck in cage (e.g. during or after improper well clean-up)	Erosion to cage port holes	Erosion to plug nose / sleeve nose / seat	Plugging of cage /nozzle	Plugging of pressure balance chamber	Brittle failure of plug nose or cage	Damage by sand to balance seal or dynamic sealing surfaces
a) Choke can not be run to fully open	x	x						x	x	x
b) Choke can not be run to closed position	x	x		x					x	
c) Flow through choke at closed position		x			(x)	x			x	x
d) Lower flow through choke than calculated for given pressure drop							x			
e) Higher flow through choke than calculated for given pressure drop		x			x	x			x	
f) Loss of containment			x			x				
		Too low material fracture toughness, too high actuator load, impact of heavy object	Too small choke body, high bulk rates, low upstream pressure, high sand load	Too small ports in cage	Low choke opening, high pressure drop, low SG, poor TC quality, high sand load	Low choke opening, high pressure drop, low SG, poor TC quality, high sand load	Cage port holes too small	High sand load or high potential for sand to travel up the pressure balance holes	Vibration, thermal shocking, insufficient fracture toughness	
	Root Cause									

Attachment G: The data flow in EFDD



Attachment H: Sand erosion results without sand rate data

Date	Choke erosion rate [mm/yr]
15.02.2010	0,01318071
16.02.2010	0,01081228
17.02.2010	0,01153546
18.02.2010	0,00807674
19.02.2010	0,00937144
20.02.2010	0,01149862
21.02.2010	0,01234809
22.02.2010	0,01299833
23.02.2010	0,01301931
24.02.2010	0,01387523
25.02.2010	0,01228323
26.02.2010	0,01331059
27.02.2010	0
28.02.2010	0
01.03.2010	0
02.03.2010	0,00809177
03.03.2010	0,00577309
04.03.2010	0,00502297
05.03.2010	0,00467085
06.03.2010	0,00463098
07.03.2010	0,00448561
08.03.2010	0,00440865
09.03.2010	0,00482639
10.03.2010	0,00480384
11.03.2010	0,00467457
12.03.2010	0,00470007
13.03.2010	0,00448771
14.03.2010	0,00445075
15.03.2010	0,00448117
16.03.2010	0,0046412
17.03.2010	0,00429872
18.03.2010	0,00451203
19.03.2010	0,0047724
20.03.2010	0,00458933
21.03.2010	0,00465937
22.03.2010	0,00513078
23.03.2010	0,00524123
24.03.2010	0,00480119
25.03.2010	0,00502884
26.03.2010	0,00560466
27.03.2010	0,00610498
28.03.2010	0,00419459
29.03.2010	0,00492171
30.03.2010	0,00493776
31.03.2010	0,00413281
01.04.2010	0,00349801

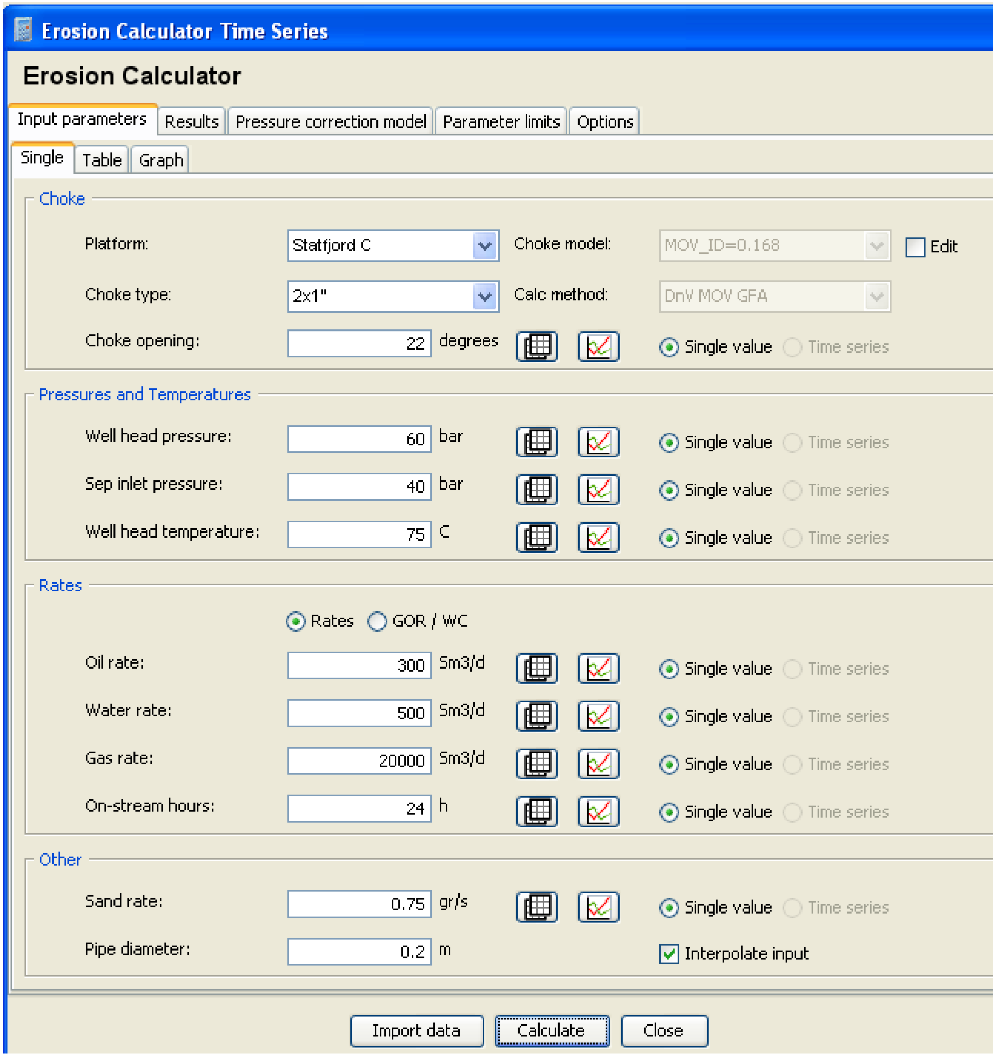
02.04.2010	0,00321656
03.04.2010	0,00299743
04.04.2010	0,00276179
05.04.2010	0,00309992
06.04.2010	0,00517769
07.04.2010	0,0043838
08.04.2010	0,00248535
09.04.2010	0,00230738
10.04.2010	0,00340425
11.04.2010	0,00500443
12.04.2010	0,00377185
13.04.2010	0,00409112
14.04.2010	0,00469294
15.04.2010	0,00505814
16.04.2010	0,00599837
17.04.2010	0,00478159
18.04.2010	0,00451206
19.04.2010	0,00364707
20.04.2010	0,00335402
21.04.2010	0,00333338
22.04.2010	0,00358734
23.04.2010	0,00345354
24.04.2010	0,00344873
25.04.2010	0,00339561
26.04.2010	0,00348491
27.04.2010	0,00349927
28.04.2010	0,00340379
29.04.2010	0,0039111
30.04.2010	0,00335359
01.05.2010	0,00361081
02.05.2010	0,00407979
03.05.2010	0,00383876
04.05.2010	0,00365273
05.05.2010	0,0035706
06.05.2010	0,00660469
07.05.2010	0,00520054
08.05.2010	0,00452402

Attachment I: Sand erosion results with sand rate data

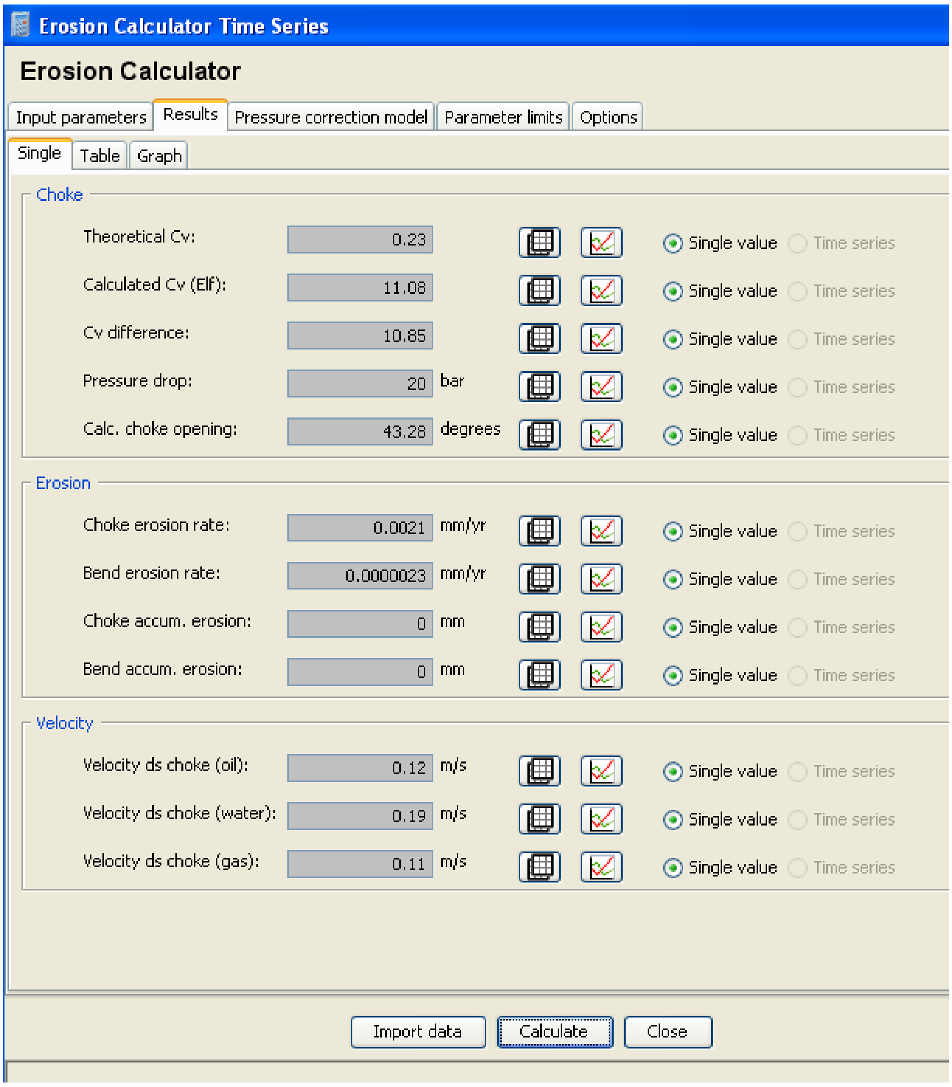
Date	Choke erosion rate [mm/yr]
15.02.2010	0,00275636
16.02.2010	0
17.02.2010	0,00061223
18.02.2010	0,00023692
19.02.2010	0,00087299
20.02.2010	0,00051629
21.02.2010	0,00144019
22.02.2010	0,00146943
23.02.2010	0,00028925
24.02.2010	0,00021357
25.02.2010	0,00282012
26.02.2010	0
27.02.2010	0
28.02.2010	0
01.03.2010	0
02.03.2010	0,00371427
03.03.2010	0,00019774
04.03.2010	0,00009663
05.03.2010	0,00015312
06.03.2010	0,00007073
07.03.2010	0,00009498
08.03.2010	0,00033219
09.03.2010	0,00032624
10.03.2010	0,00013243
11.03.2010	0,0005387
12.03.2010	0,00035006
13.03.2010	0,00046143
14.03.2010	0,00047848
15.03.2010	0,00032963
16.03.2010	0,00017329
17.03.2010	0,00025736
18.03.2010	0,00012913
19.03.2010	0,00008667
20.03.2010	0,00030338
21.03.2010	0,00038337
22.03.2010	0,00035068
23.03.2010	0,00027634
24.03.2010	0,00041937
25.03.2010	0,00024792
26.03.2010	0,00060938
27.03.2010	0,00051788
28.03.2010	0,00047175
29.03.2010	0,00056121
30.03.2010	0,00052601
31.03.2010	0,00057509
01.04.2010	0,00032511

02.04.2010	0,00014013
03.04.2010	0,00013645
04.04.2010	0,00019203
05.04.2010	0,00014022
06.04.2010	0,00020489
07.04.2010	0,00030434
08.04.2010	0,00020557
09.04.2010	0,00015732
10.04.2010	0,00030249
11.04.2010	0,00056707
12.04.2010	0
13.04.2010	0,00025236
14.04.2010	0,00050713
15.04.2010	0,00044568
16.04.2010	0,00019622
17.04.2010	0,00047384
18.04.2010	0,00048854
19.04.2010	0,0003428
20.04.2010	0,00032211
21.04.2010	0,00034754
22.04.2010	0,00035644
23.04.2010	0,00041896
24.04.2010	0,00022095
25.04.2010	0,00011427
26.04.2010	0,00013728
27.04.2010	0,00003238
28.04.2010	0,00013113
29.04.2010	0,00041361
30.04.2010	0,00014952
01.05.2010	0,00013437
02.05.2010	0,00015768
03.05.2010	0,0000463
04.05.2010	0,000129
05.05.2010	0,00014268
06.05.2010	0,00008876
07.05.2010	0,00018937
08.05.2010	0,00000364

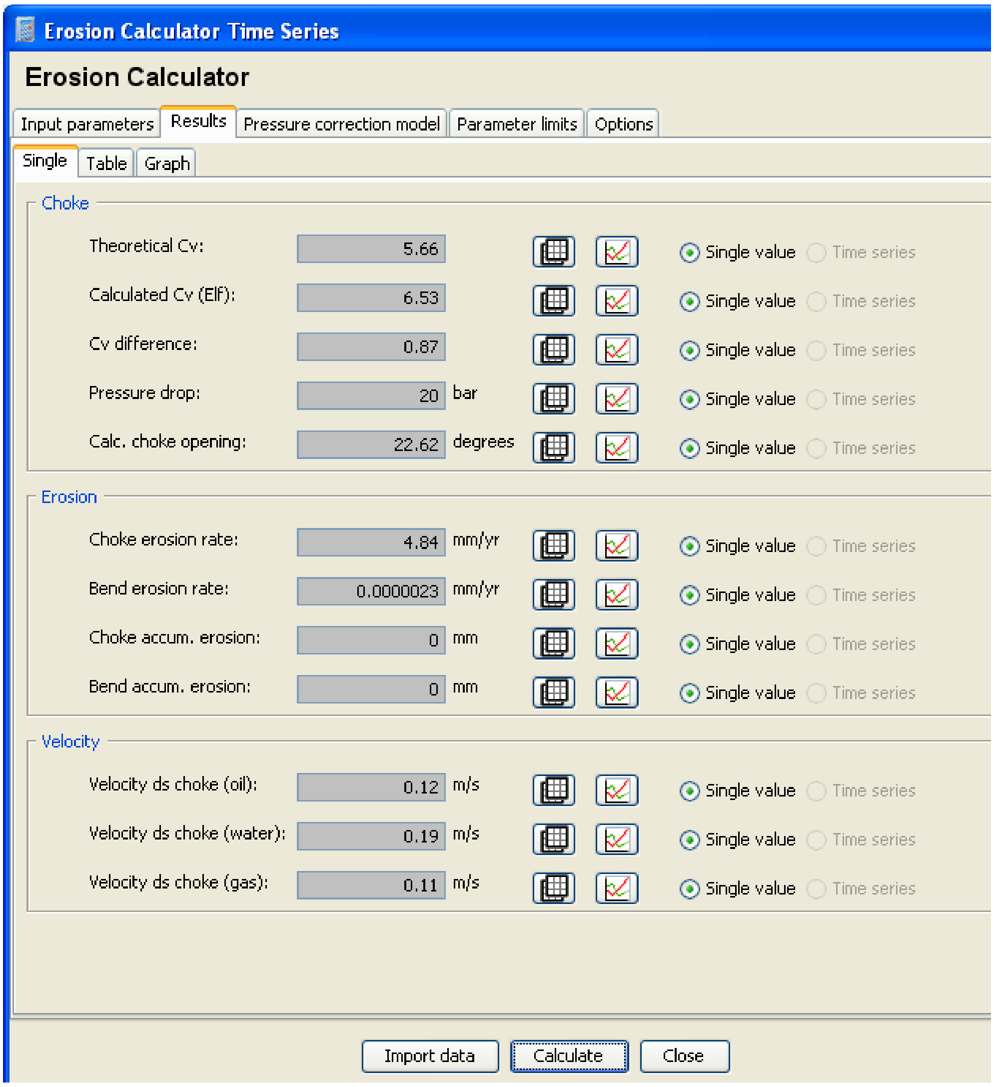
Attachment J: Input data for choke comparing



Attachment K: Results for the topside choke



Attachment L: Results for the subsea choke



Attachment M: Predicted vs. measured mass flow rate for the Hydro model (at the top) and the Elf model (at the bottom)