A study of how functional test intervals are affected by increased diagnostic coverage by use of valve diagnostic system

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Norsk tittel:	Hvordan vil en økt «diagnostic coverage» ved hjelp av diagnosesystem for ventiler påvirke funksjonstestintervall?
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Preface

This report is a bachelor thesis in the study program Industrial Engineering at department of Mechanical- and Marine engineering (IMM) at Western Norway University of Applied Sciences (WNUAS). It is written by Carina Berstad, Markus Bratten Gjøvåg and Mathias Riple in cooperation with MRC Global.

We would like to thank MRC Global and our contact person, Simon Jeeves, for the opportunity to work with them and for the good cooperation throughout the project. A special thanks to our excellent supervisor at WNUAS, Professor Maneesh Singh, for guidance and inspiration through the whole bachelor process.

Abstract

This bachelor thesis has calculated the diagnostic coverage by use of a Valve Diagnostic System (VDS), and further discussed how increased diagnostic coverage affects functional test interval for a ball valve.

Initially, the bachelor thesis describes how the development within the oil and gas industry historically has been targeting on using corrective and scheduled maintenance strategies, rather than using condition and performance monitoring applications as a tool to plan and prioritize maintenance.

Necessary tools and theories that have been used during the thesis are presented as well as different data collection methodologies, such as qualitative-, quantitative-, primary- and secondary data.

The analysis is starting by identifying all possible failure modes for both the different main components of a ball valve and as a unit. Further, there are identified links between all failure modes and corresponding failure mechanisms by use of fault tree analysis. These failure mechanisms were analyzed for their detectability by sensors in a sensor-coverage table.

Further, calculation of diagnostic coverage has been done for each component and for the system as a unit, both with and without use of VDS. It is desirable to demonstrate that implementation of VDS increases the diagnostic coverage, which in next order extend functional test intervals.

This bachelor thesis concludes that implementation of VDS increases the diagnostic coverage for a ball valve from 42,42% (no coverage) to 90,91% (medium coverage) and consequently extend test interval for a ball valve.

Keywords: MRC Global, ValveWatch, Valve diagnostic system, Ball valve, SIS, SIL, PFD, Diagnostic coverage, Condition monitoring, Functional test interval

Sammendrag

Denne bacheloroppgaven har som formål å kalkulere «diagnostic coverage» ved hjelp av implementering av diagnosesystem for ventiler. Videre er det ønskelig å se hvordan en eventuell økning i «diagnostic coverage» kan bidra til å forlenge testintervall for kuleventiler.

Innledningsvis beskriver denne oppgaven utviklingen innen olje- og gassindustrien med tanke på hvordan fokuset har endret seg innen vedlikehold. Tidligere har fokuset vært på korrigerende vedlikehold, mens den teknologiske utvikling nå muliggjør tilstands- og ytelsesovervåkning på en helt ny måte. Ved å ta i bruk denne teknologien og ved å bruke informasjon rett har man et helt nytt og gunstig utgangspunkt for å planlegge og prioritere vedlikehold.

Videre i oppgaven har relevant litteratur, teorier og metoder blitt presentert. Noen eksempel på dette er kvalitativ-, kvantitativ-, primær- og sekundærdata.

Analysedelen starter med å identifisere alle mulige feilmoder for de forskjellige komponentene av en kuleventil, og for hele kuleventilen som en enhet. Videre har de identifiserte feilmodene blitt knyttet til sine respektive feilmekanismer ved hjelp av feiltreanalyser. De identifiserte feilmekanismene har deretter blitt brukt i en oversiktsanalyse hvor de ulike sensorenes evne til å avdekke feilene har blitt bestemt. På bakgrunn av denne informasjonen har det blitt kalkulert «diagnostic coverage» med og uten diagnosesystemet for ventilen, både hver del og hele ventilen som en enhet. Det er ønskelig å vise at ved å benytte seg av dette diagnosesystemet vil man få økt «diagnostic coverage», noe som også betyr at man får mulighet til å forlenge testintervall.

Denne bacheloroppgaven konkluderer med at ved å benytte seg av dette systemet vil «diagnostic coverage» for en kuleventil øke fra 42,42% (no coverage) til 90,91% (medium coverage) og dermed også få forlenget testintervall.

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1. Introduction

1.1 Background

Valves are critical and essential parts in an oil and gas production plant. If a failure occurs it can potentially cause enormous consequences, both for economical and safety reasons. All oil and gas being produced flows through valves, and this must be monitored and controlled in a safe and considerate way. Maintenance of high quality is prioritized to maintain a low risk level throughout the production. Historically it has been challenging to obtain this in combination with low cost and time-efficient maintenance.

Focus has historically been targeting on using corrective and scheduled maintenance strategies, rather than using condition and performance monitoring applications as a tool to plan and prioritize maintenance.

During production, valves has the task to operate in a safe and efficient way. Different mechanisms can cause the valves to fail, for example the elastomers and/or seat seals to wear, erosion from foreign or abrasive debris in the pipelines or incorrectly installations performed on the valve. These failures can often be undetectable, which can cause bigger losses/accidents due to the difficulties in preparing for such incidents. Consequences from these undetectable failures can therefore be heavily threatening for the production in form of larger defects or longer down-time which can lead to economic losses.

Today we experience an enormous progress in real time monitoring by use of sensors as data collectors. This development also includes software that support and allows efficient decision making by processing data, such as valve diagnostic system. By taking advantage of this technology there are huge benefits to obtain by surveilling and monitoring valves in production rather than traditional physical observation and testing. This method has several advantages and it can possibly contribute to reduce maintenance cost and downtime.

Multiple unwanted and hazardous events have occurred through the last decades, such as the tragic Piper Alpha disaster (Macleod & Richardson, 2018). These events have contributed to drive the industry to improve and be stricter about safety regulations and requirements. The positive effects, such as risk reduction, also leads to higher cost associated with for example regulations regarding test intervals. This makes the sensor technology even more beneficial and opens a wide range of potentials within the maintenance- and risk management genres.

Today, all in-operation risk calculations are based on reported accidents. This way to calculate is indisputable an inaccurate calculation method as potentially many failures are not reported, or even revealed. Experts also points to the basis of the calculations with skepticism as this is already occurred accidents, and the industry strive to decrease the total number of failures to a minimum.

With the development within sensor- and decision-making technology the industry is facing, there may be a totally different situation in the future, when considering the way that the risk management are treated. With further exploitation of this technology the possibilities are great, and there might even be a situation where no failures are recorded as sensors are able to detect failure indications at an early stage and the right decisions can be made based on this information.

1.2 Research question

How does increased diagnostic coverage of a ball valve by use of a valve diagnostic system affect the functional test interval?

1.3 Aim of project

Aim of this project is to discuss how increased diagnostic coverage by use of a valve diagnostic system affects the functional test interval for a ball valve.

1.4 Scope of work

This report will begin with a literature survey where the following headlines will be presented:

1. MRC Global, the company that has tested, developed and are now selling a valve diagnostic system called ValveWatch. ValveWatch is the valve diagnostic system that the analysis will be based on.
2. Ball valve, which is a typical valve for emergency shut down application.
3. Different failure categories such as dangerous detected- and safe detected failures are described.

4. Diagnostic coverage which basically is a measure of diagnostics effectiveness (Nix, 2017).
5. Safety Instrumented System (SIS) that is used to detect and act upon dangerous hazardous events in order […] "*to mitigate their consequences to humans, the environment, and material assets" (Hauge et al. 2009).*
6. Safety integrity level and probability of failure.
7. Fault tree analysis.

The thesis will now give a brief introduction to ValveWatch and its basic sensor, followed by a description of data collection methodologies that are relevant for this report, including why they are relevant and how they are to be used.

The methodologies and tools will from now on be implemented in the analysis. It starts by identifying failure modes based on judgement by collected data and experienced personnel. Identified failure modes will then be analyzed in a fault tree analysis to decide and visualize the different corresponding failure mechanisms. Next step will be to decide whether one/multiple sensor(s) can detect the failure in question. On basis of this analysis the diagnostic coverage will be calculated and compared with the traditional diagnostic coverage calculations without use of sensor technology. Further, a brief discussion of how increased diagnostic coverage affects functional test interval will follow.

1.5 Limitations and assumptions

- This reports analysis is based on a valve diagnostic system called ValveWatch.
- This report will mainly be based on real data collected on valves in operation, and information obtained from experienced personnel when demonstrating how ValveWatch can detect dangerous undetected failures.
- This report is limited to only include ball valves. It includes both floating- and trunnion ball with both floating- and fixed seat.
- This report only includes an analysis of dangerous failures and does not include safe failures.
- It is assumed that valves are installed in systems with right pressure range.

1.6 Abbreviations

- VW - ValveWatch
- VDS - Valve Diagnostic System
- O&G - Oil and gas
- ESD - Emergency shut down
- HSE - Health, safety and environment
- SIL - Safety integrity level
- SIF - Safety instrumented function
- SIS - Safety instrumented system
- PFD - Probability of failure on demand
- PoF - Probability of failure
- CoF - Consequence of failure
- DC - Diagnostic coverage
- DD - Dangerous detected failure
- DU - Dangerous undetected failure
- SD - Safe detected failure
- SU - Safe undetected failure
- RRF - Risk reduction factor
- IOT - Internet of things
- PLC - Programmable logic controller
- FTA - Fault tree analysis
- FTD - Fault tree diagram
- RBD - Reliability block diagram
- HIPPS - High-integrity pressure protection
- KPI - Key performance indicator
- λ_{DU} - Rate of DU failures

2. Literature Survey

2.1 MRC Global

MRC Global is a leading worldwide distributor of pipes, valves and fittings as well as providing services to the global energy and industrial markets. The company is located across the globe, 19 countries in total. Since the start of the company in 1921, MRC Global has collaborated with the world leading manufacturers of pipes, valves and fitting products and has over the years been a vital part in the ever-developing Oil and Gas (O&G) industry.

Figure 1: MRC Global, Bergen

In 1997 MRC Global started the participation of the original development of ValveWatch (VW), partly as a response to the Piper Alpha disaster because of its effect on the increased safety standards in the O&G industry (Jeeves et al., 2019). VW is the valve diagnostic system that will be further used in the analysis.

VW is in continuous development and growth as it is getting more and more attractive on the market, especially within the O&G industry both off- and onshore. VW is, as the name expresses, a way to watch the valves in production and is a so-called Valve Diagnostics System (VDS).

A VDS is a monitoring system used on valves and its components to allow personnel to identify and monitor the efficiency and performance of a system. This technology is beneficial as it gives precise real-time condition information. It provides the end user with useful data showing Key Performance Indicators (KPI) such as flow pressure, torque on the yoke and time to close/open. By tracking and comparing this data over a period it is possible to understand and reveal the development of "hidden" pattern in the system. By use of VDS, it is possible to improve the system integrity by identifying failure mechanisms in an early stage. This information is also useful as a basis for planning of maintenance actions tailored for each valve. Another advantage with this technology is a minimum need for physical inspections which consequently reduces the down-time.

The most advanced VDS today offer possibilities to share the data through online servers, which increases the availability with its associated benefits. The incredible development recent years within Internet of Things (IOT) discloses endless opportunities to bring the technology even another step forward.

Historically, VDS has been used for critical valves such as Emergency Shut Down (ESD) valves and High-Integrity Pressure Protection System (HIPPS) valves. New trends show that the system also is getting more relevant for production of critical valves such as safety relief valves (Esposito, 2011).

2.2 Ball valve

According to Solberg & Andersen (n.d., p. 216-221) there are several types of ball valves. In general, a ball valve is structured with a housing that consists of a ball, with a hole through it. Normally, when the ball valve is open, material can flow through the valve and its connected pipeline. When it is closed, there is no flow through the system. These types of valves close and open within a quarter-turn and are known for their reliable and bubble-tight sealing, which consequently is a solid choice in gas application where tight shutdowns are necessary. Ball valves are typically made of steel and can extend its duration using nickel plating.

The ball valves that have been decided to be further analyzed in this report can be divided into two types. The first one is called *trunnion ball valve*, which is used for higher pressure classes and larger dimensions. Trunnion ball is more suitable in these occasions because of the reduction in forces towards the seat. Designing of this type of valve includes additional mechanical anchoring at the top and the bottom that allows reduction in valve torque as the ball is supported in two places. Trunnion ball valve is an on/off valve, which means that it is either open or closed where the maximal rotation is 90 degrees.

Figure 2: Ball valve – trunnion

According to Schlumberger (n.d.), another type of ball valve is called *floating ball valve*. This is a valve where the ball floats between the seats and gets pushed towards the downstream seat and by this secure a close valve when in closed position. The seats can also vary between fixed and floating seats. Usually, there are valves with fixed seats that are only clogged in the downstream seat, but it is also possible with floating seats that includes clogging in the upstream seat as well. Valves with floating seats are normally available for lower pressure and smaller dimensions since the force from the ball against the seat increases together with pressure or dimension. Soft seated ball valves have limitations when it comes to high temperatures and it is therefore possible to use double clogging on each seat where one of them is made by metal, which also makes it fireproof.

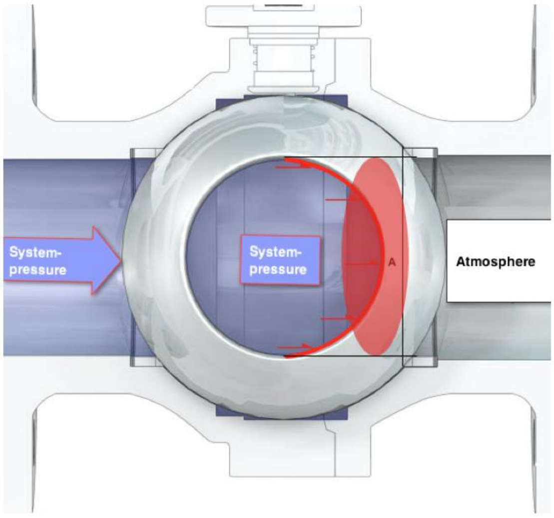


Figure 3: Ball valve – floating

2.3 Failures

According to the NOG 070 standard, failures are usually detected either by functional testing or diagnostic self-testing. A functional test is a test designed for a system to discover failures through Safety Integrity Function (SIF), which normally is undetected. SIF will be further elaborated in subchapter 2.5. Those failures that can only be detected by functional test are called Dangerous Undetected (DU) or Safe Undetected (SU) failures. This means that in an asset integrity context, functional test is a dominant factor as it potentially reveals critical dangerous undetected failures. Diagnostic self-testing is on the other hand a test conducted by the equipment itself with intention to identify Dangerous Detected (DD)- and Safe Detected (SD) failures.

Failure mode, failure cause and detection method are used to classify whether there is a dangerous undetected-, dangerous detected- or safe failure (SF). A safe failure is according to NOG 070 defined as it "*[…] does not have the potential to put the safety related system in a hazardous or fail-to-function state*". Dangerous undetected and dangerous detected failures can potentially cause harm to the system, environment or people.

It is desirable to avoid all dangerous undetected failures so that the only remaining failures are SU, SD and DD failures. DD failures may cause harm, but it is by right practice highly detectable prior to failure. As O&G constantly flows through valves and large forces are in action through opening and closing, the number of potential failures will be high. Typical failures for valves are corrosion from high temperatures, erosion from e.g. debris, worn out seats over time etc. A complete overview of all identified failures for ball valves are presented in subchapter 4.3.

2.4 Diagnostic coverage

Different systems are affected by different factors and hazardous events that can cause problems for the overall safety and production, because eventually everything will fail. Diagnostic coverage is, according to Nix (2017), basically a measurement of the effectiveness of diagnostics. A notable part by diagnostic coverage is that it only considers the dangerous failures, and do not take the safe failures into account. If safe failures occur, the system will not fall into a dangerous state.

The diagnostic coverage of a system, which is the ratio between the number of dangerous detectable failures and the number of all dangerous failures, can be expressed by the following formula:

$$\text{DC} = \frac{DD}{DD+DU} \quad \text{(Eq. 1)}$$

By use of this formula, diagnostic coverage can be calculated. As it illustrates, the higher number of detected dangerous failures, the higher diagnostic coverage. Ideally, all dangerous undetected failures will be revealed to become dangerous detected failures which gives 100% diagnostic coverage.

ISO 61508 evaluates diagnostic coverage as critical when analyzing the design of any safety function assessed. The diagnostic coverage can be divided into four denotations: none, low, medium and high.

None → $\text{DC} < 60\%$
Low → $60\% \leq \text{DC} < 90\%$
Medium → $90\% \leq \text{DC} < 99\%$
High → $99\% \leq \text{DC}$

The main purpose of implementing VDS to valves is to obtain the highest possible diagnostic coverage through condition monitoring and surveillance. It is critical to reveal as many failures as possible in a valve to keep the dangerous undetected failures to a minimum. This is important to be able to obtain the set safety requirements in an economical matter. If the diagnostic coverage is too low, it may be necessary to install additional valves to assure that if one valve fails there will be another one to execute the required task (additional redundancy). A high diagnostic coverage will therefore be economically efficient.

2.5 Safety instrumented system

Safety Instrumented System (SIS) plays a big role in the O&G sector as well as in other high integrity safety sectors such as the nuclear industry. SIS "[…] *are frequently used in the O&G industry to detect the onsets of hazardous events (e.g., gas leakages and high pressures) and to mitigate their consequences to humans, the environment, and material assets*" (Hauge et al. 2009). It can be divided into three parts; detection, decision making and action, which can be sensors, Programmable Logic Controller (PLC) and valves respectively.

According to RealPars (2018), SIS is used to detect and act upon hazardous events that can be dangerous for humans, environments and material assets. SIS works in a way that a PLC or other logic controller unit are fed by information from sensors (readers). This logic controller unit decides what the outcome of the process should be depending on the preset conditions. If any actions on the monitored system are required, because of e.g. high pressure, an action to prevent any further development and reduce the risk is needed. The execution of this is done by a final element, such as a valve or other condition regulator units. A combination of the three elements; logic controller, reader and final element is called Safety Instrumented Function (SIF).

A SIS task is to monitor and act upon certain predetermined conditions that are violated, to maintain safety. It is vital to understand that the SIS is an independent extra set of devices in addition to the basis process control system.

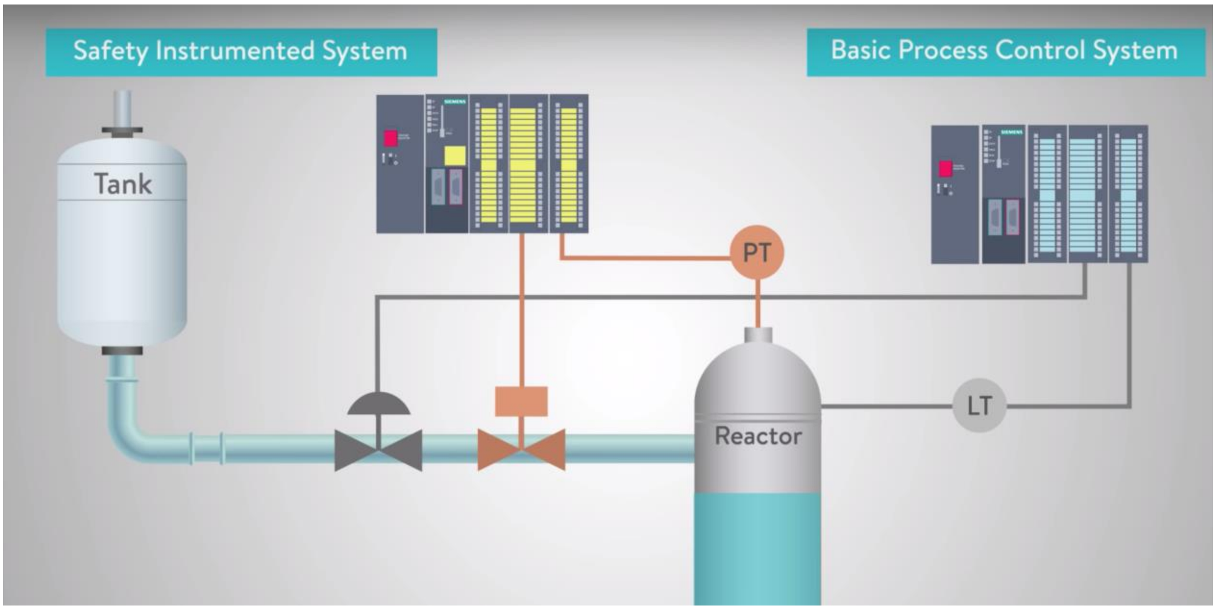


Figure 4: Safety instrumented system and basis process control system

2.5.1 Safety integrity level and Probability of failure on demand

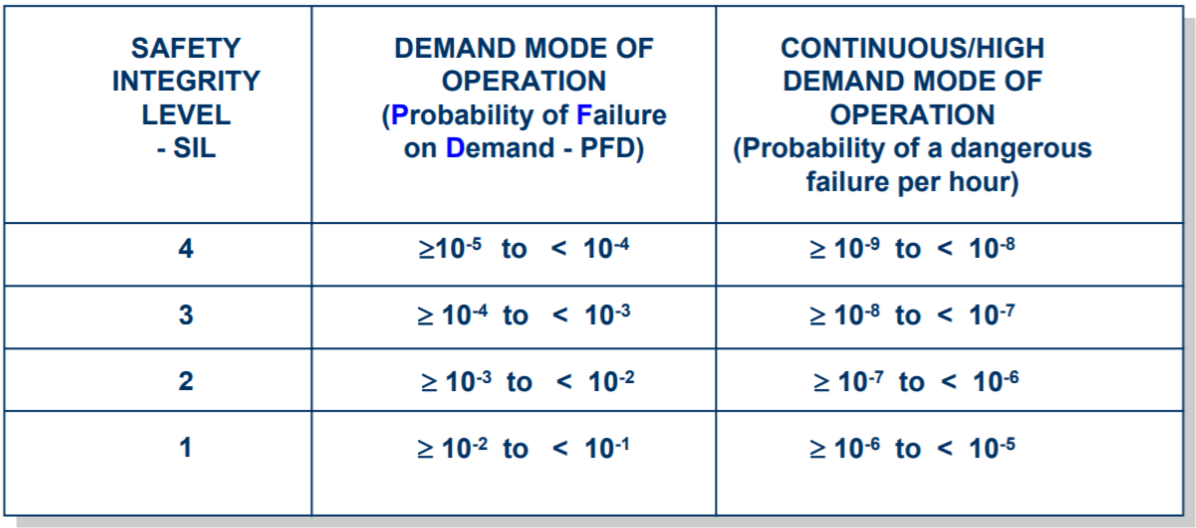
When applying SIS to a system, it is necessary to measure the reliability and performance of the SIF. To do so, it is desirable to introduce Safety Integrity Level (SIL), which is a way to measure the performance of a SIF.

The chance that SIF do not respond as intended when it is called upon is called Probability of Failure on Demand (PFD). Examples of this could be that the sensor that should detect high flow rate is not reading correctly, or that the logic controller unit itself is not processing data properly. Events like this could result in wrong decision making. Another example could be that a valve that are told to close are not able to close more than e.g. 80%. All single components in a SIS have their own PFD greater than 0, and these PFDs are normally combined to calculate the representative PFD for a system/equipment (RealPars 2018).

The value of PFD is as illustrated in fig. 5 directly connected to a corresponding Safety Instrumented Level (SIL). This is a grade from 1 to 4, that is related to the likelihood of the SIF not performing its intended function. SIL grade 1 correspond to highest PFD, and vice versa SIL grade 4 correspond to lowest PFD. The SIL rate, and therefore also PFD, are essential when a system is to be designed. Another indicator in the SIS methodology is Risk Reduction Factor (RRF). This is "[…] *the number of times that risk is reduced as a result of application of safeguard* […]" (Mathur, 2013).

In other words, SIL describes a SIFs ability to reduce the risk. RRF can be calculated by taking the inverse of PFD. An example of calculation could be:

PFD: 0.0001 → RRF= $\frac{1}{0.0001} = 10000$



SAFETY INTEGRITY LEVEL - SIL	DEMAND MODE OF OPERATION (Probability of Failure on Demand - PFD)	CONTINUOUS/HIGH DEMAND MODE OF OPERATION (Probability of a dangerous failure per hour)
4	$\geq 10^{-5}$ to $< 10^{-4}$	$\geq 10^{-9}$ to $< 10^{-8}$
3	$\geq 10^{-4}$ to $< 10^{-3}$	$\geq 10^{-8}$ to $< 10^{-7}$
2	$\geq 10^{-3}$ to $< 10^{-2}$	$\geq 10^{-7}$ to $< 10^{-6}$
1	$\geq 10^{-2}$ to $< 10^{-1}$	$\geq 10^{-6}$ to $< 10^{-5}$

Figure 5: Safety integrity levels

2.5.2 Predicted PFD

When designing a system, predicted PFD, which is denoted PFD_0, is calculated as an expected number of failures over a period that must not be exceeded to maintain a given SIL. Calculations of PFD_0 is based on:

I. *a system reliability model that is compatible with the system topology and the assumptions made*
II. *a set of reliability parameters*

(Hauge et al. 2009).

Several factors will influence the calculation of PFD_0. These are related to operating and environmental conditions, maintenance, testing and modifications. It is hereby required that when the SIS is installed, the predicted PFD_0 will be in accordance with the required SIL. E.g. SIL2 as it is required for ESD valves the PFD_0 must be $10^{-3} \leq PFD < 10^{-2}$ (fig. 5). The predicted PFD_0 is the product of two parameters: λ_{DU}, which is the rate of dangerous undetected failures, and τ, which is the functional test interval. λ_{DU} and τ is by this used to detect the level of PFD_0 that should meet the SIL requirements, and are a part of a formula for PFD:

$$PFD_0 = \lambda_{DU} \cdot \tau \qquad \text{(Eq.2)}$$

Reliability data may be obtained from different sources such as: OREDA database, expert judgements, manufacturers and so on. The problem using such reliability data is that it basically just reflects random failures caused by normal degradation, and do not take systematic failures into account. Systematic failures can occur from inadequate maintenance, operation or design, as well as exposure by outside unexpected factors. Reliability data will therefore create a significant uncertainty in the predicted PFD_0.

2.5.3 SIS follow-up during operation

According to NOG 070, which is a simplification and application standard base on IEC 61508 and IEC 61511 for the Norwegian O&G industry, certain requirements are to be followed in the operation phase. One of these requirements is that the performance of a system should be assessed and compared to the premises laid down in the design phase. The SIL requirements are not met if the actual PFD > PFD_0 and the operator consequently must improve the safety. Calculation of actual PFD, denoted PFD_i, should be calculated several times since operational circumstances may vary in time. Every new calculation is donated a number; i = 1, 2, 3...

From calculated diagnostic coverage it is possible to calculate a predicted PFD_0, but as in every part of the production the prediction of PFD can deviate from the reality. To be able to maintain e.g. SIL2 it is necessary to determine the actual PFD_i to ascertain that it meets the SIL2 requirements, which also means that the actual PFD_i should not be higher than the predicted PFD_0. These requirements lead to a formula where it is possible to calculate the PFD by multiplying dangerous undetected failures with functional test interval, as well as ascertain that the required SIL is maintained:

$$PFD_i \leq PFD_0 \Leftrightarrow \lambda_{DU_i} \cdot \tau_i \leq \lambda_{DU_0} \cdot \tau_0 \qquad \text{(Eq. 3)}$$

In an O&G production plant there are multiple potentially hazardous events that could occur. To cover all systems and equipment with SIS is uneconomically, time-consuming and a nearly impossible task. Different systems and components require different operation integrity levels. SIS is primarily used for systems and equipment that are at high risk, typically where Consequence of Failure (CoF) is permanently high. This means that the only adjustable parameter is Probability of Failure (PoF), which could be controlled by an SIS and in this way reduce the risk. ESD valves are highly critical valves which requires a relatively low PFD

$(10^{-3} - 10^{-2})$ to meet the SIL level 2 (most common SIL level for ESD valves). In a SIS perspective, an ESD valve is a part of SIF, and it operates as a final element that can close/open in case of unwanted situations.

In the design phase, a system is designed to meet the stated requirements. This must be followed up in the operational phase to document that these requirements really are met. This must be documented by use of eq. 3, which means that the number of dangerous undetected failures is essential.

2.6 Fault tree analysis

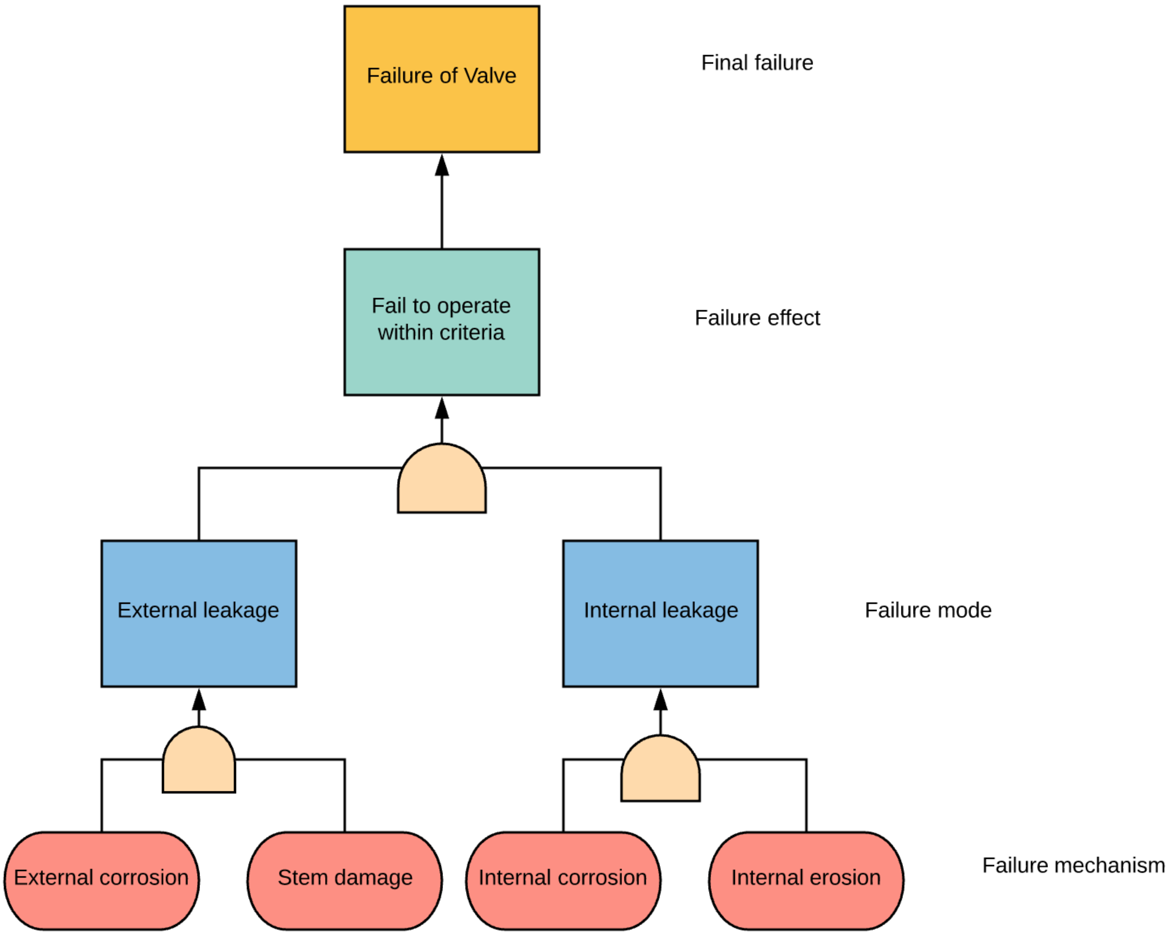


Figure 6: Example of fault tree diagram

Fault Tree Analysis (FTA) is a tool used to develop reliability and safety analysis and is conducted through a Fault Tree Diagram (FTD).

“*Fault tree diagrams (or negative analytical trees) are logic block diagrams that display the state of a system (top event) in terms of the states of its components (basic events). Like*

reliability block diagrams (RBDs), fault tree diagrams are a graphical design technique, and as such provide an alternative methodology to RBDs" (Weibull, n.d.).
The main difference between FTD and RBD is that when using fault tree, you look at the failure combinations of a component, and in RBD you look at the successful combinations of a component.

The diagram above illustrates the coherence between an unwanted event in a valve and the potential cause. The diagram provides a list of possible combinations of failure, the probability of frequency of the unwanted event and a list of significant events. The different events are connected by different gates. The orange symbol indicates that only one of the coming events is necessary for main event to occur.

There are several reasons why you should perform FTA, and the main reason is that the analysis helps to find and describe the risk-based path to a root cause of a failure. Using the information gathered from the analysis, it is possible to develop and execute actions to mitigate the risk level. FTA should, according Quality-One (2015), be applied when:

- A Hazard Analysis previously indicated a safety concern
- There is a new design with new content
- There is a current design with modifications, which may include changes due to past failures
- There is a current design being used in a new environment or change in duty cycle (no physical change made to design)
- Investigation of a safety or regulatory concern
- A picture of the failure would be more beneficial than a written inductive analysis

3 Materials and Methods

3.1 Materials

3.1.1 Ball valves

To prove that ValveWatch increases the DC and by this extend the functional test interval, there will be performed an analysis on a specific type of valve called ball valve. Because of limited availability of data and information, this analysis confines the results to one type of valve to make it more specific. Ball valves have been described in detail in subchapter 2.2.

3.1.2 ValveWatch

ValveWatch (VW) is a real-time monitoring system and it monitors the performance of each component while in operation. VW collects reliable data from different sensors and this data can be used for further analysis. The data will be stored in a software and further on be compared with in-service performance. There are given several criteria for each valve, and these must be fulfilled to ensure that the valve functions as intended.

According to MRC Global (2019), the basic sensors that are used in a VW system are pressure sensor, strain sensor, dynamic pressure leak sensor, position transmitter and acoustic leak sensor. The number of sensors may variate from system to system depending on needed diagnostic coverage. Critical valves such as ESD valves may for example benefit from extended coverage, which can be obtain by installation of additional pressure sensors in different components, e.g. in the cavity between the valve and the body of the valve. An overview of which and where the basic sensors are installed is presented in fig. 7.

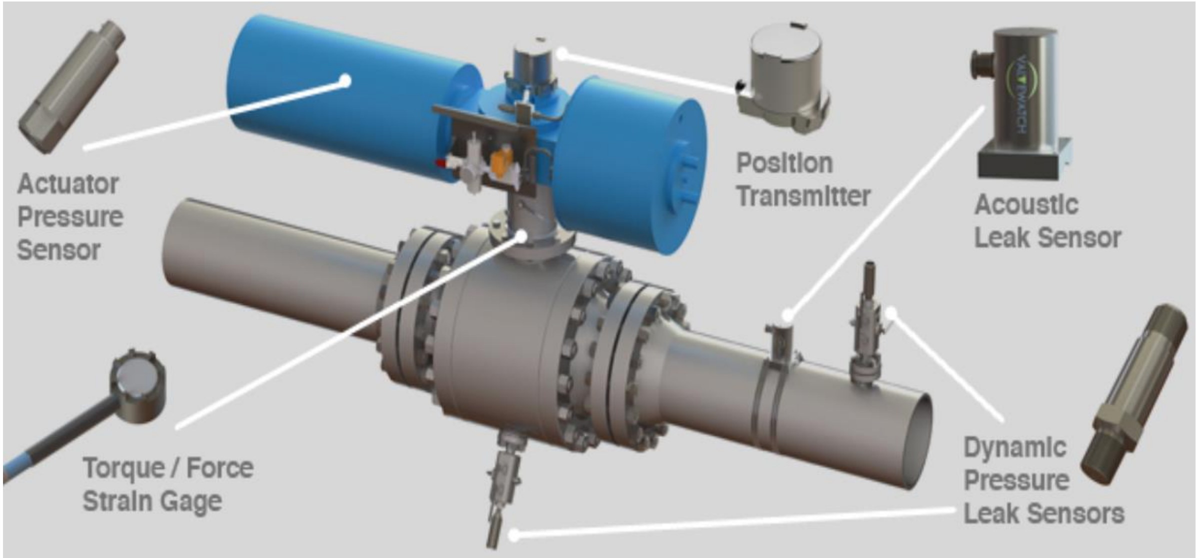


Figure 7: Valve diagnostic system - sensors

3.1.3 Condition diagnostics of a valve

3.1.3.1 Limit switch

A limit switch is a mechanical component that is used to detect when a movable object has reached its end position. It consists of an actuator that is connected to a set of contacts. Objects are linked to the actuator, and the contact will either make or break the connection. The limit switch is a device that is used to provide a confirmation signal indicating whether the valve is open or closed.

3.1.3.2 Position transmitter

To establish the travel from start to end position, a position transmitter provides the operator with measurement of valve travel during a stroke and is important in combination with pressure sensor and strain gage. The position transmitter will provide a signal from 0-100%.
The sensor itself is mounted on top of the actuator and is often used together with the limit switch.

Figure 8: Position transmitter

3.1.3.3 Pressure sensor

A pressure sensor measures the pressure in e.g. actuator, solenoid or cavity. It is mounted in the pressurized section of the component and is available in various pressure ratings to optimize scaling. The sensor measures a value which is further transmitted into an electrical signal. The pressure sensor is made of a stainless-steel construction and ranges from 3.5 to 700 bars, which is quite a broad specter. It also includes a high over pressure capability and have hazardous area certifications.

Figure 9: Pressure sensor

3.1.3.4 Torque/force strain gage (strain sensor)

To monitor mechanical performance of the valve and the actuator, a strain sensor is installed directly on the yoke. The target is to see dimensional changes on the yokes, such as deformation of the element. Strain gages main purpose is to analyze forces translated between the valve and the actuator and can be used to measure torque or thrust. On gage valves, strain sensor is used to measure thrust while on ball valves it is used to measure torque. Because of the high forces involved between the valve and the actuator, the strain sensor is made of high strength titanium epoxy.

Figure 10: Torque/force strain gage sensor

3.1.3.5 Acoustic leak sensor

If water leaves the pipe through a leakage it creates a distinctive noise with different frequencies. Smaller leaks create a high-frequency sound while larger leaks create a lower frequency sound. An acoustic leak sensor is used to detect and characterize the different leak sounds and differentiate these from those of normal water flow through the distribution system.

The sensor is mounted on the valve itself or on the pipe and is non-intrusive to the system. A closed valve and a pressure difference across the valve are needed for the sensor to detect any leak.

Figure 11: Acoustic leak sensor

3.1.3.6 Dynamic pressure leak sensor

The dynamic pressure sensor is used to detect leaks in the pipe and the sealed cavity compartment of the valve. By installing equal dynamic sensors in upstream, downstream and cavity positions on the valve, it can detect leaks by observing difference in pressure at each location. Further, the collected data from surveillance is used to confirm seal integrity.

Figure 12: Dynamic pressure leak sensor

3.1.4 VW interface and tests

The VW software is fed by data from the sensors presented in previous subchapter. ValveWatch is an online condition and performance monitoring system for critical valve systems, including ESD systems (ValveWatch, 2019). To support decision making and performance monitoring, the VW interface (fig. 13) gives a good understanding of a system's condition.

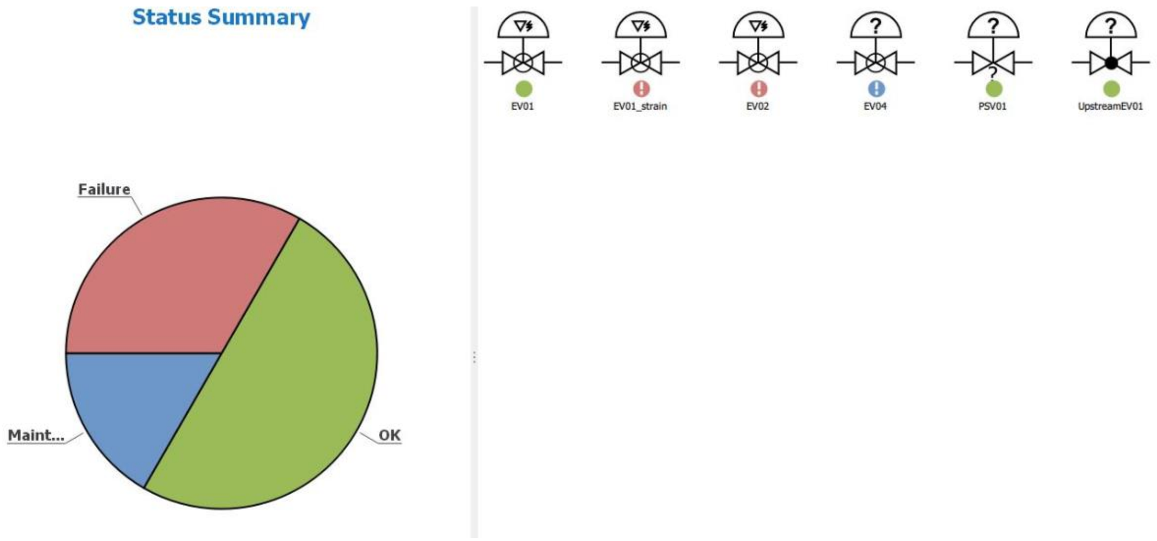


Figure 13: ValveWatch sensor interface

Fig. 13 is an example of the VW interface system presenting condition monitoring of six valves. Each valve and their condition are individualized and ranked as either: "OK", "Maintenance" or "Failure". The software decides a ranking of the valve on basis of several preset limits. For example, a valve is ranked as "Maintenance" if the limit for friction has been violated in the VW software.

This example illustrates that not all valves are ok, and consequently these has to be further analyzed. To diagnose these valves, a further look into performance data such as travel, torque, pressure and time to open/close is crucial.

As mentioned, the VW system provides graphs that illustrate the behavior of the valve when it is opening/closing. The graph below (fig. 14) illustrates a closing valve in a pipe with no flow, where the blue line shows an old test when the friction is too high related to the stated criteria for the valve. Consequently, maintenance has been accomplished. The red line shows a test after maintenance, showing a much smoother closing travel as well as more than two seconds reduction in time to close. In this way, VW confirms whether a valve performs as required or not. It is also a useful tool to monitor change in performance over time.

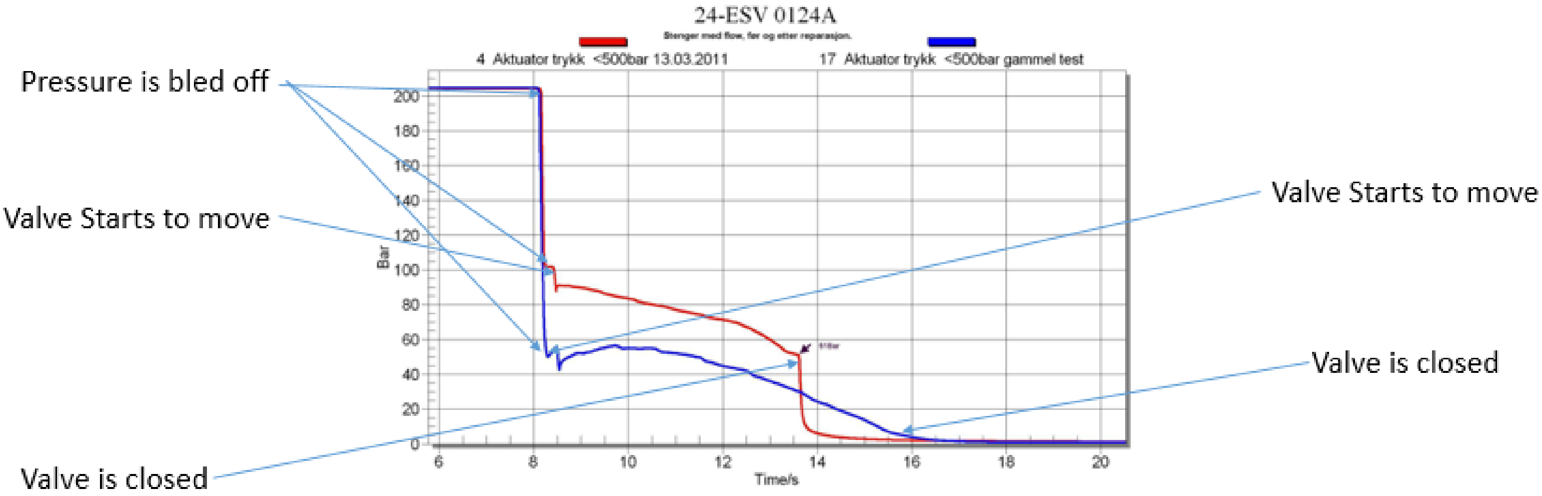


Figure 14: Closing pipe with no flow

3.2 Data collection and analysis

3.2.1 Quantitative

Quantitative method is, according to Dalland (2012), collection of data that provides us with solid numbers, often referred to as "hard data". This method can for example involve a survey of a group of people about a specific topic. Such surveys provide us with the opportunity to perform arithmetic operations based on the collected data. It is important to be aware of how exact the collected data are, and if it is possible to have a reliable conclusion based on the specific information. An example of uncertain data can arise if the survey is based on 20 people where 8 people answered yes, and 12 people answered no. This survey is not representative for an entire population, and it shows the importance of being critical both when collecting data and when reading other surveys.

Through this bachelor thesis the focus on standards have been prioritized, such as ISO 61508, ISO 61511 and guidelines such as NOG 070. These standards and guidelines, together with well-known theory and tools referenced to multiple sources, have been used as quantitative data throughout the thesis.

3.2.2 Qualitative

Unlike quantitative data, qualitative data are often referred to as “soft data”. Qualitative method involves gathering information that doesn’t provide directly measurable results, but instead are based on experience and interpretation by a person. There are several ways to collect qualitative data, and information can be gathered through interviews, surveys and observation (either directly or indirectly).

An example of qualitative method is to examine what should be done to improve the production process in a company. To solve this, it can be expedient to make use of an informal interview of an employee that has great precondition to help or provide useful input. Through this type of examination there is not much formalization, but it can provide a deeper understanding of the real issue.

ValveWatch is based on qualitative data, which is the background of the thesis. Collected data from surveillance have been collected together with interpretation by experienced personnel.

3.2.3 Validity

Validity explains that the parameters that are being measured needs to have relevance for the problem that are being evaluated, and it is therefore important to be critical to the methods used. Some methods can be especially chosen and/or angled to provide an assertion false support, which causes the credibility to be vague and therefore the method to have a low validity. Ideally, high validity is wanted, which can be achieved by minimizing the possibilities of failure in data. To achieve this, it is important to be critical, not only to the sources but also to the specific information that is used by the sources.

The validity in interpretation of data collected from ValveWatch is likely to vary from the experience and knowledge of the person interpreting. Expert judgement in every situation is therefore important to maintain the highest validity possible. Interpretation has therefore been conducted together with people working daily with development and analysis of ValveWatch.

3.2.4 Reliability

The data that is being used must be as precise and reliable as possible. It is important to be aware of and to specify eventual margin of errors and sources that supports eventual inaccuracies. It is desirable to achieve a reliability as high as possible. A high reliability tells that, for example, an experiment is verifiable, which means that when another person/group execute the experiment they will receive the same results, assuming the same conditions. Reliability and validity do not depend on each other, which means that one of them can be high and the other one low at the same time.

This report is partly based on well acknowledged standards and guidelines, which means the foundation of theory can be classified as high reliability. Data collected by ValveWatch prior and after maintenance are reflecting a valves condition in a precise matter, which means that ValveWatch data have high reliability.

3.2.5 Primary and secondary data

The importance of collecting data while writing a thesis is decisive, but it is also equal to the importance of separating between primary and secondary data. Primary data, often referred to as main data, can for example be collected through a market research, and are often used by scientists who tries to prove a theory. Secondary data on the other hand are information collected and referred to by others, often to other purposes.

Both primary and secondary data have been important in developing this bachelor thesis, through collection of common theory and methods as secondary data and more specific data regarding SIL, PFD, VW, etc. Implementing these two types of data in combination with each other is decisive to create a coherent thesis with information to be conveyed in a relevant matter.

4 Results and Discussion

4.1 Brief introduction

In the operational phase, the performance of a system such as ESD valves should be assessed and compared to the premises laid down in the design phase (NOG 070, 2018). This is of high importance due to several reasons. If a company is not able to demonstrate that the operational PFD is met according to the governmental requirements, it may result in restrictions such as shut down of production. Another important factor is the high cost associated with frequent functional testing of ESD valves. Functional tests require full production shutdown, which results in production losses. By this, it is desirable to extend functional test intervals to a maximum, as long as the required PFD is met.

The objective of this analysis is to explain how installation of VW contributes to increased DC compared to traditional inspection methods and further explain the importance of functional test intervals.

4.2 Identification of failure mode and failure mechanisms

Components that this analysis will account for are actuator, solenoid and valve. These components are the most critical and complex to surveille during operation and will therefore be closely analyzed. The first step is to identify the most common failure modes for all three components. These failure modes will be treated separately for each component in a fault tree analysis with purpose to identify all corresponding failure mechanisms. Further, examples collected from previous VW tests will be presented to substantiate detection of failure mechanisms, which are also part of the foundation of the fault tree analysis. A short description of the fault tree made for the actuator (fig. 15) will be given, to make a better understanding of this has been worked through.

As mentioned in subchapter 2.8, the main function of a fault tree is to look at the failure combination of a component. The upper box (yellow) is the result of all the individual failures that have been identified, which for the actuator is “Failure of actuator”. The bottom boxes (red) are the identified failure mechanisms, and arrows connecting these failure mechanisms to the corresponding failure modes boxes (blue). Further, failure modes are linked to the failure effect (green) which at the end reaches the failure result (yellow).

4.2.1 FTA of Actuator

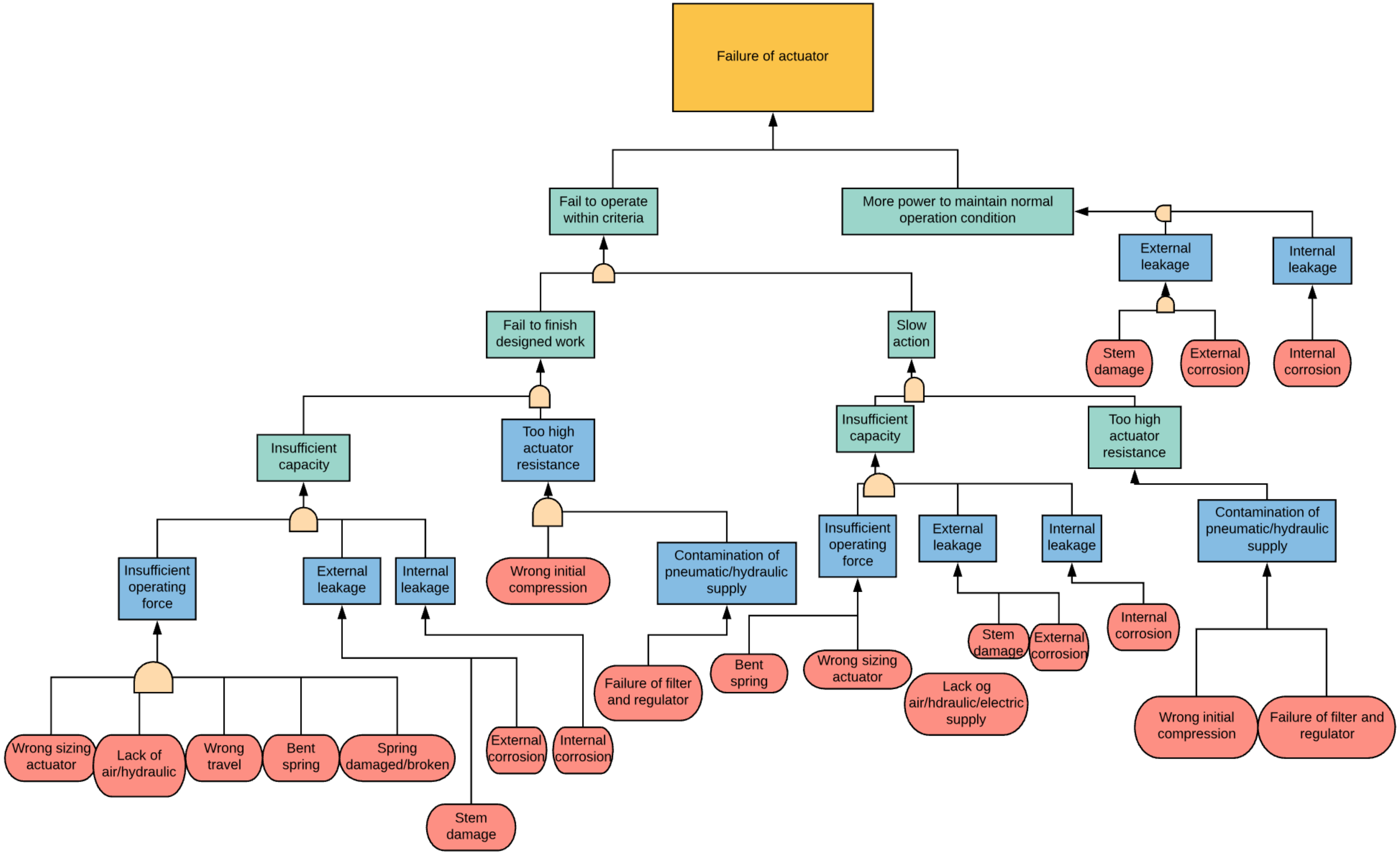


Figure 15: Fault tree analysis – actuator

4.2.2 FTA of solenoid

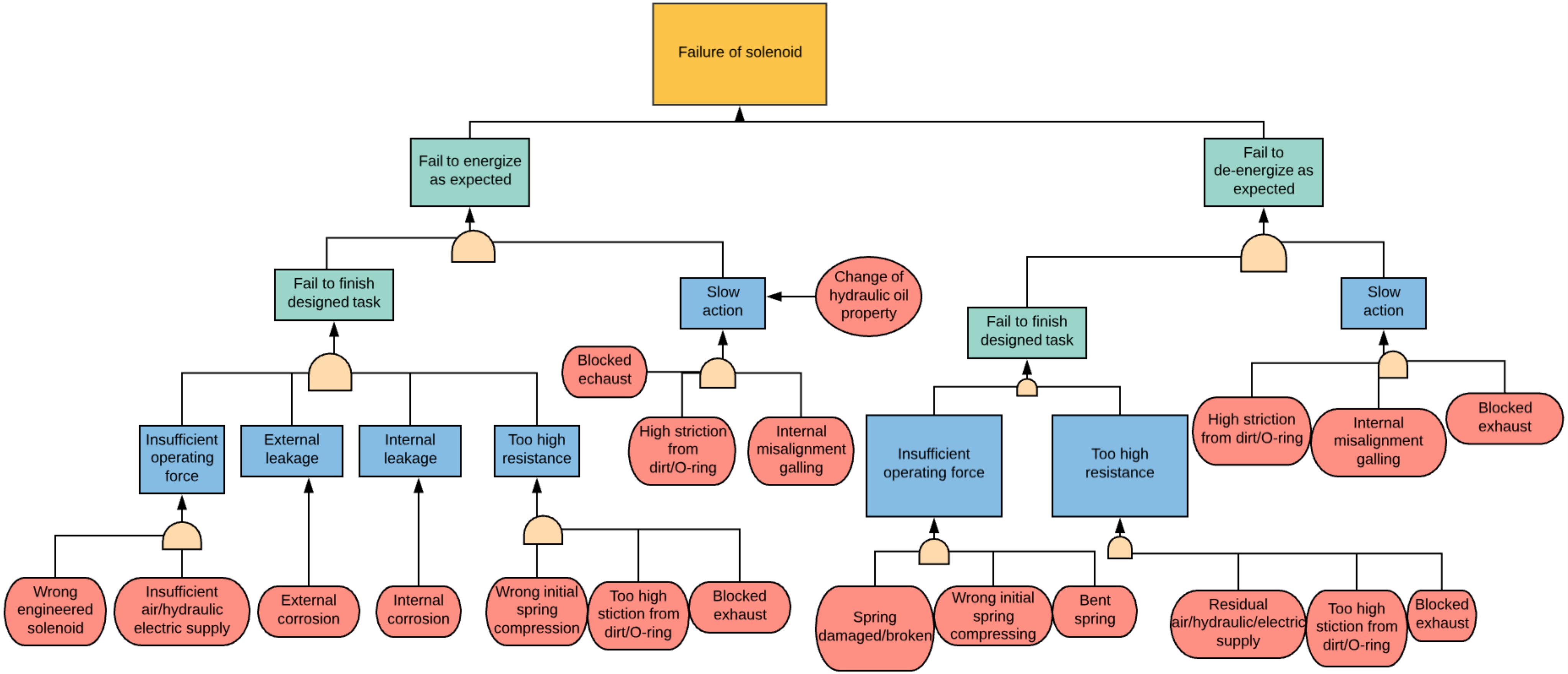


Figure 16: Fault tree analysis - solenoid

4.2.3 FTA of Valve

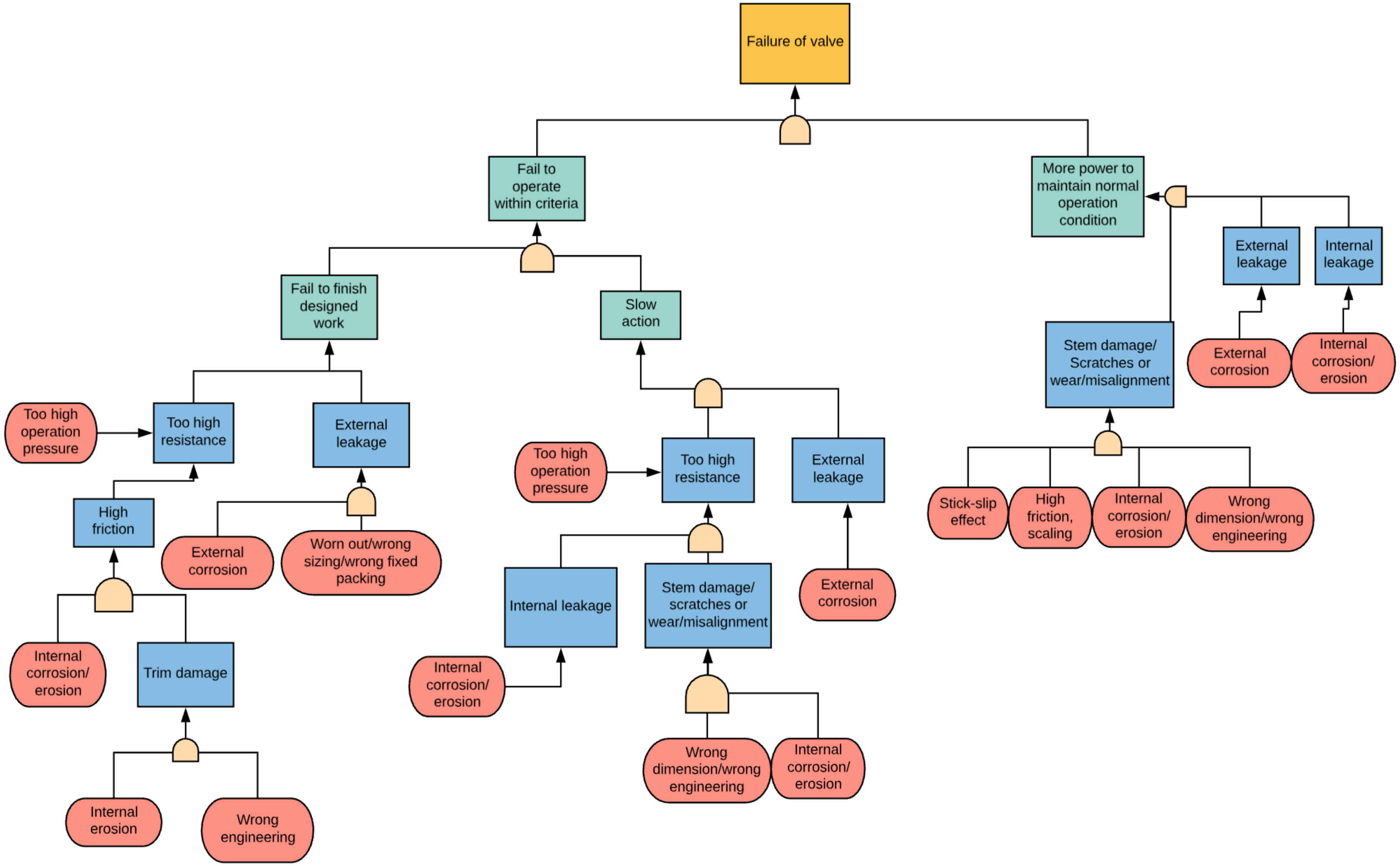


Figure 17: Fault tree analysis - valve

4.2.4 Signature curve

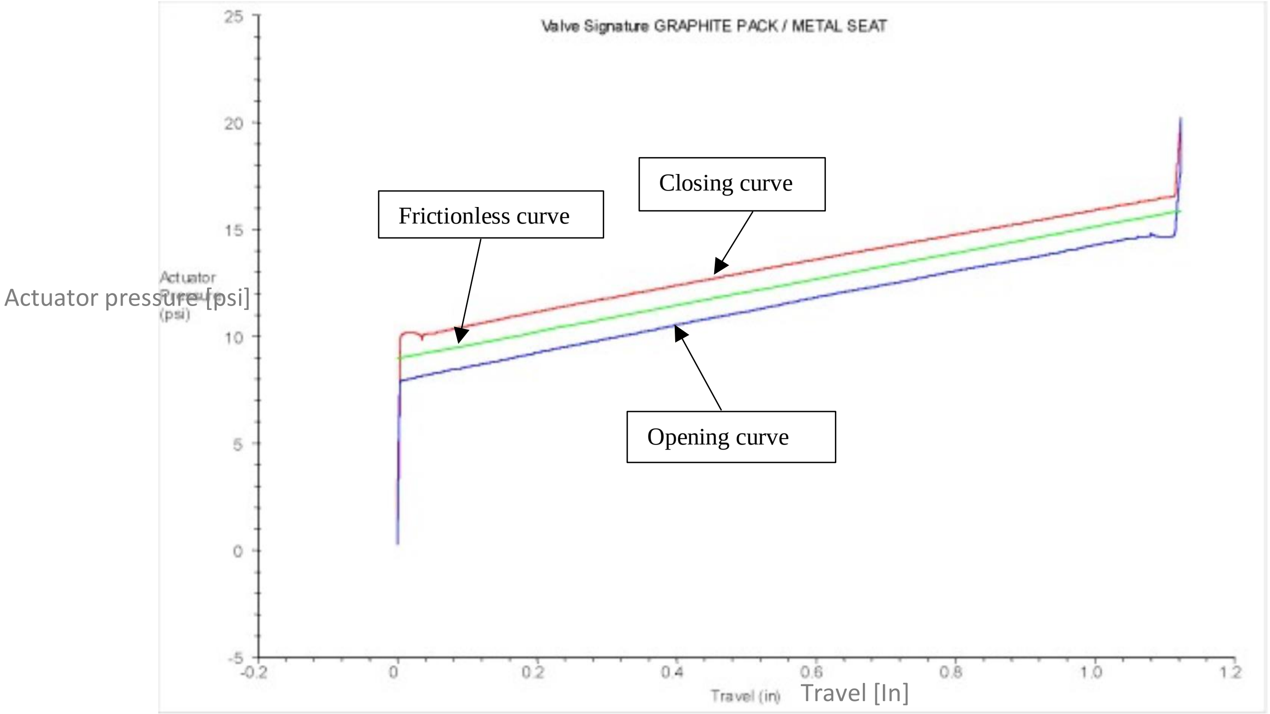


Figure 18: Signature curve

Fig. 18 is an illustration of a fail to open valve, with open (blue)/close (red) signature curves that are nearly perfect but suffers from friction caused by packing/seals. The curves are linear as there is no abnormal friction due to e.g. corrosion. However, there will always be friction from packings/seals, which is represented in the graph as the deviation from the green curve. The green curve is an impossible frictionless curve, which tells us that the net spread of the blue and red line is 2 x friction.

There is a nonlinearity in pressure at both ends of the linear area indicating resistance from the ball valve as it reaches the full travel, which is an important indicator. Although the graph is nonlinear, it is not representing unwanted resistant from corrosion, but increased friction as the ball valve reaches the seat.

The curves are a presentation of ideal curves and any deviation in the linearity might be an indicator of friction. It is also important to mention that the curves are sloped and not horizontal, as a result of a spring actuator. The spring coefficient and actuator size are factors that govern the angle of the slope.

4.2.5 VW test of valve that suffers from debris

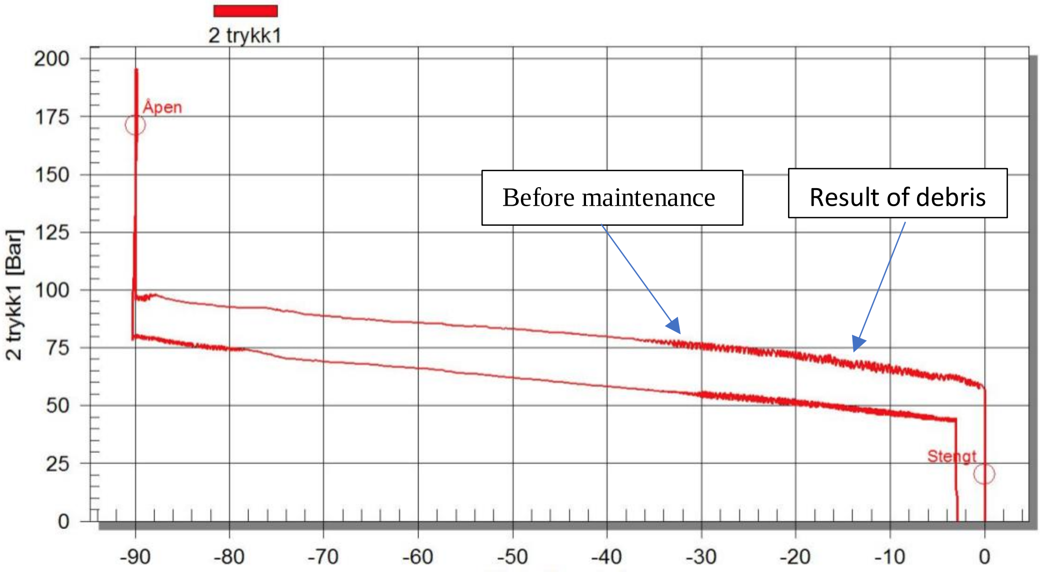


Figure 19: ValveWatch test of valve that suffers from debris

Figure 19 is a graphic VW test of a real valve. This is two curves illustrating the travel of a valve from closed to open, and open to closed position. At 0-degree position (closed), the first curve illustrates that the valve travel from entirely closed to open position. Further, the second curve illustrates the travel from open to closed position. The curve shows that the valve is not able to entirely close as it stops at approximately 3 degrees from closed position.

The characteristic stuttering at the ends of the open/close and close/open test can be explained as exposure of debris in the area where the ball and seat are in contact with each other. This may result in periodical friction as indicated in the graph. This may also be the reason that the valve is not able to close entirely. According to the fault tree analysis - valve (fig. 17) “high friction/scaling” may lead to “stem damage/scratches or wear/misalignment” which next may lead to “more power to maintain normal operation condition”.

This is an illustration of how VW can detect failure mechanisms which can be further analyzed to determine the possible result of the failure. It can be helpful to combine the results of performance development graphs with the fault trees of this report in order to optimize the maintenance plan.

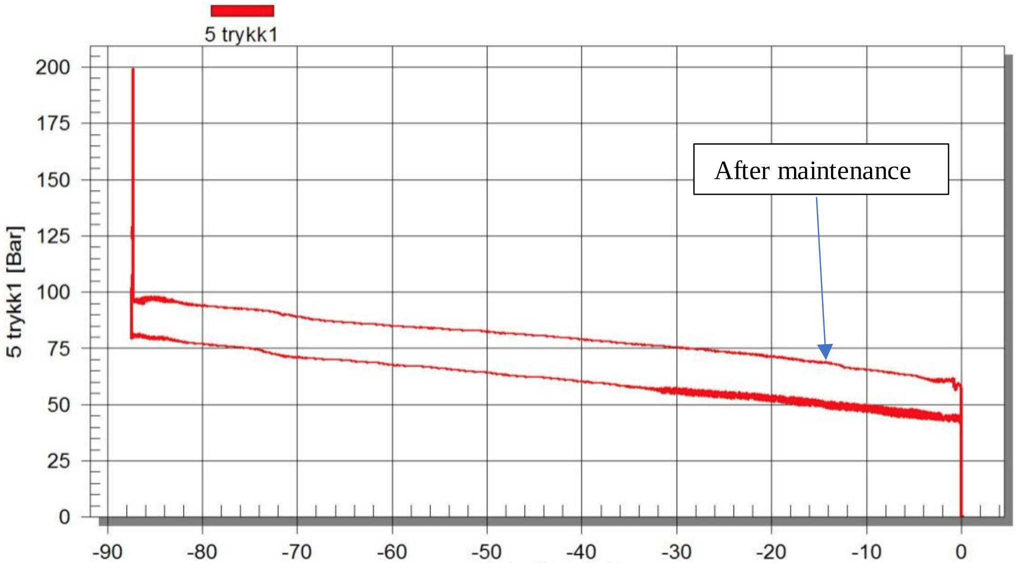


Figure 20: ValveWatch test after corrective maintenance

Fig. 20 is a graphic VW test of the valve presented in previous section (fig. 19), after corrective maintenance. The conducted corrective maintenance is cleaning and lubrication using diesel, which clearly has a positive effect in reducing the friction as the valve travel from closed to open. This graph clearly shows that the valve can close entirely, and no longer suffer from the characteristic stuttering illustrated in fig. 19.

4.2.6 VW test of actuator that suffers from corrosion

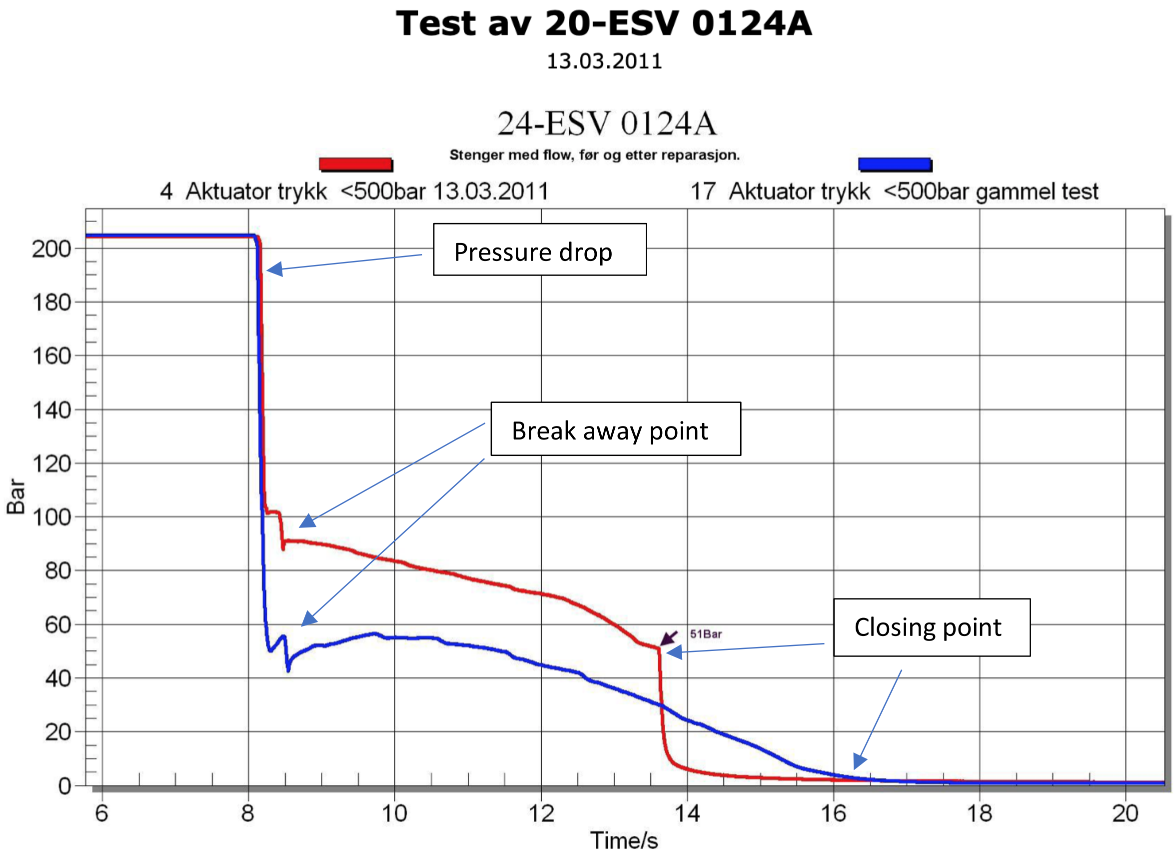


Figure 21: ValveWatch test of actuator that suffers from corrosion

The test in fig. 21 is a graphic VW test of a real actuator in a production line that is run to close with flow. It was conducted a VW diagnostic test on the actuator because of suspicion of high friction in the actuator as a result of nonlinear travel while operating.

The first test (blue) reveals high friction due to a few key indicators. The first indicator is that the curve is nonlinear after the break away point. Further, the curve experience difficulties in closing entirely. As shown, the blue test uses a few more seconds to close because of the friction and is therefore not able to fulfil the acceptable criteria for the valve because of insufficient force capacity. Another readable indicator from the graph is that the pressure drop after approximately 8,25 seconds is relatively large. This can typically be an indicator of high seat friction, or in combination with nonlinearity it be an indicator of high friction in the actuator, which typically is caused by corrosion.

As the blue test is analyzed, it is determined that there is need for maintenance. After this has been done a new test should be run to evaluate and verify the improved valve condition. This is shown in the red test and it clearly shows improvement in linearity and time to close.

4.3 Sensor coverage of components

The identified failure mechanisms for the different parts in the previous subchapter will now be used in tables where the main purpose is to determine whether the different sensors or maintenance actions can detect the failure mechanisms. From these sensor coverage schemes it will be possible to calculate a diagnostic coverage for each part and the whole system as a unit. Data and information from analysis done by MRC Global have been collected and further analyzed.

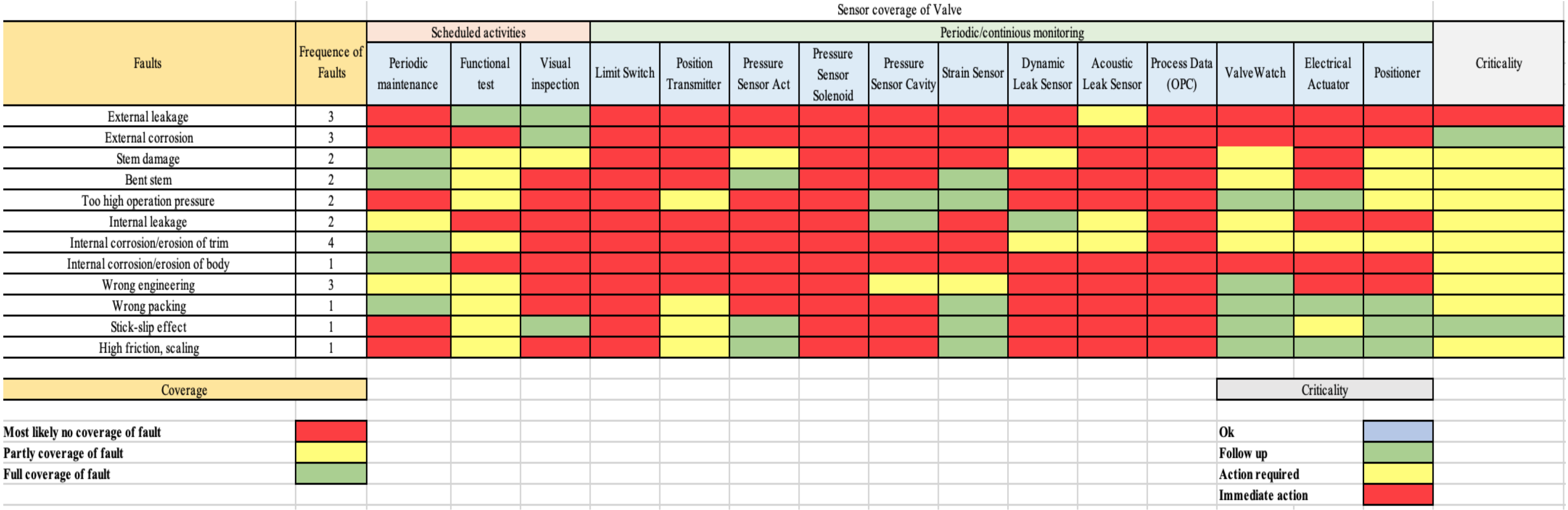
One individual decision-making table for each of the different component has been done. The red color indicates that there will not be any failure detection, yellow is partially failure detection and green is fully failure detection.

The first column consists of all the different failure mechanisms that were detected while working with the different fault trees. The next column is frequency, which indicates how many times this failure mechanism occurs for the individual failure modes. Traditionally, scheduled maintenance activities can be split into periodic maintenance, functional test and visual inspection. These are the ones that are used to determine how the sensor coverage would be if there was no ValveWatch system.

The last part of this table is named “periodic/continuous monitoring”. There are nine different sensors that have been investigated, which together results in the sensor coverage of ValveWatch. If one of the panels in a row is green, the ValveWatch system will manage to detect failure mechanism. Occasionally, there are two yellow panels in one row, yet no green. Nevertheless, this might result in either fully or partly coverage. This depends on whether the different sensors together can fully detect all failures that occurs or not, which can vary between frequencies of the specific failure in the component.

There is a slight difference in the decision-making table for the valve compared to the other parts, where instead of analyzing the failure mechanisms it is an analysis of faults. The reason for this is the criticality of the valve, and the high number of failures that possibly can occur. Therefore, the focus on the valve failure itself is increased.

4.3.1 Sensor coverage Valve



Sensor coverage of Valve

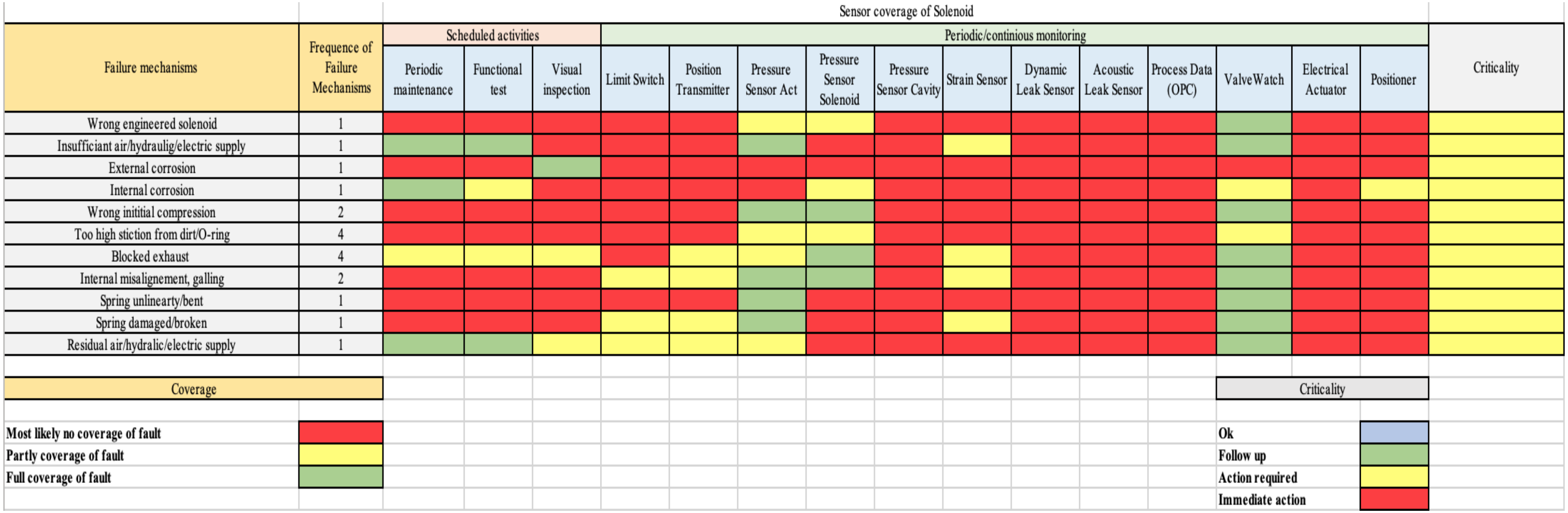
Faults	Frequence of Faults	Scheduled activities			Periodic/continious monitoring												Criticality
		Periodic maintenance	Functional test	Visual inspection	Limit Switch	Position Transmitter	Pressure Sensor Act	Pressure Sensor Solenoid	Pressure Sensor Cavity	Strain Sensor	Dynamic Leak Sensor	Acoustic Leak Sensor	Process Data (OPC)	ValveWatch	Electrical Actuator	Positioner	
External leakage	3	🟥	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥
External corrosion	3	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩
Stem damage	2	🟩	🟨	🟨	🟥	🟥	🟨	🟥	🟥	🟥	🟨	🟥	🟥	🟨	🟥	🟨	🟨
Bent stem	2	🟩	🟨	🟥	🟥	🟥	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟨	🟥	🟨	🟨
Too high operation pressure	2	🟥	🟨	🟥	🟥	🟨	🟥	🟥	🟩	🟩	🟥	🟥	🟥	🟩	🟩	🟨	🟨
Internal leakage	2	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟩	🟨	🟥	🟨	🟥	🟥	🟨
Internal corrosion/erosion of trim	4	🟩	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟥	🟨	🟨	🟨	🟨
Internal corrosion/erosion of body	1	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨
Wrong engineering	3	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟩	🟥	🟥	🟨
Wrong packing	1	🟩	🟨	🟥	🟥	🟨	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟨
Stick-slip effect	1	🟥	🟨	🟩	🟥	🟨	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟨	🟩	🟩
High friction, scaling	1	🟥	🟨	🟥	🟥	🟨	🟩	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟩	🟩	🟨

Coverage	
Most likely no coverage of fault	🟥
Partly coverage of fault	🟨
Full coverage of fault	🟩

Criticality	
Ok	🟦
Follow up	🟩
Action required	🟨
Immediate action	🟥

Figure 22: Sensor coverage - valve

4.3.2 Sensor coverage Solenoid



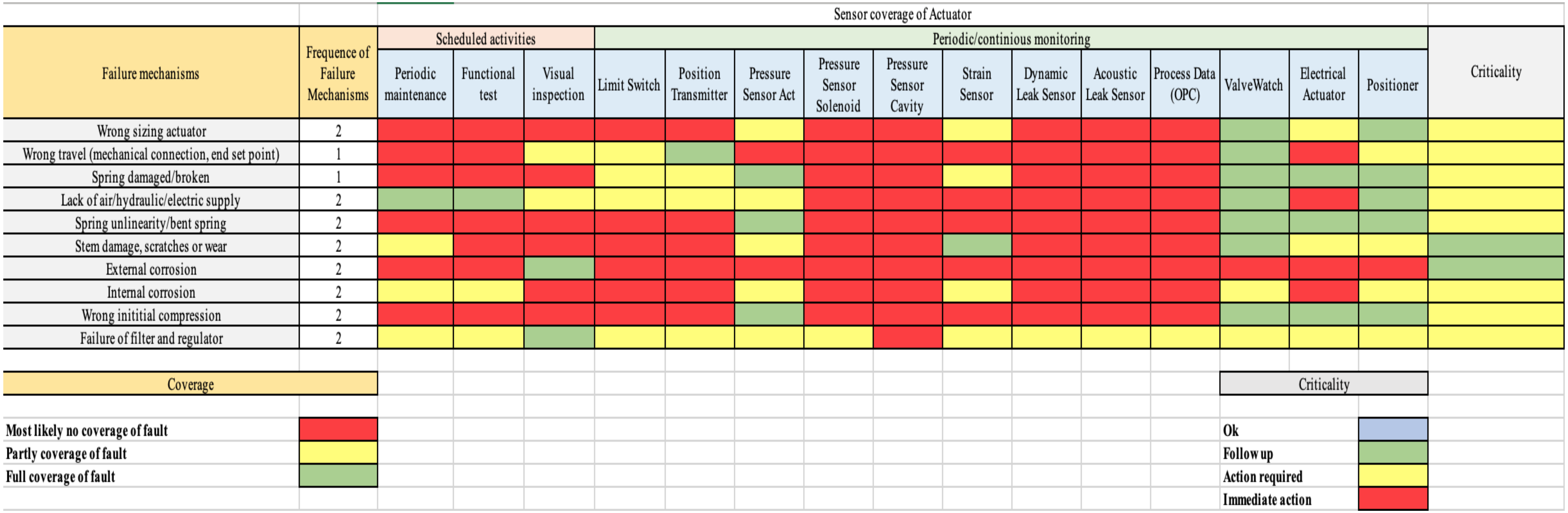
		Sensor coverage of Solenoid														
		Scheduled activities			Periodic/continious monitoring											
Failure mechanisms	Frequence of Failure Mechanisms	Periodic maintenance	Functional test	Visual inspection	Limit Switch	Position Transmitter	Pressure Sensor Act	Pressure Sensor Solenoid	Pressure Sensor Cavity	Strain Sensor	Dynamic Leak Sensor	Acoustic Leak Sensor	Process Data (OPC)	ValveWatch	Electrical Actuator	Positioner	Criticality
Wrong engineered solenoid	1	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟨
Insufficiant air/hydraulig/electric supply	1	🟩	🟩	🟥	🟥	🟥	🟩	🟥	🟥	🟨	🟥	🟥	🟥	🟩	🟥	🟥	🟨
External corrosion	1	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟨
Internal corrosion	1	🟩	🟨	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟨	🟥	🟨	🟨
Wrong inititial compression	2	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟨
Too high stiction from dirt/O-ring	4	🟥	🟥	🟥	🟥	🟥	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟨
Blocked exhaust	4	🟨	🟨	🟨	🟥	🟨	🟨	🟩	🟥	🟨	🟥	🟥	🟥	🟩	🟥	🟥	🟨
Internal misalignement, galling	2	🟥	🟥	🟥	🟨	🟨	🟩	🟩	🟥	🟨	🟥	🟥	🟥	🟩	🟥	🟥	🟨
Spring unlinearty/bent	1	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟨
Spring damaged/broken	1	🟥	🟥	🟥	🟨	🟨	🟩	🟥	🟥	🟨	🟥	🟥	🟥	🟩	🟥	🟥	🟨
Residual air/hydralic/electric supply	1	🟩	🟩	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟨

Coverage	
Most likely no coverage of fault	🟥
Partly coverage of fault	🟨
Full coverage of fault	🟩

Criticality	
Ok	🟦
Follow up	🟩
Action required	🟨
Immediate action	🟥

Figure 23: Sensor coverage – solenoid

4.3.3 Sensor coverage of Actuator



Sensor coverage of Actuator

Failure mechanisms	Frequence of Failure Mechanisms	Scheduled activities			Periodic/continious monitoring											
		Periodic maintenance	Functional test	Visual inspection	Limit Switch	Position Transmitter	Pressure Sensor Act	Pressure Sensor Solenoid	Pressure Sensor Cavity	Strain Sensor	Dynamic Leak Sensor	Acoustic Leak Sensor	Process Data (OPC)	ValveWatch	Electrical Actuator	Positioner	Criticality
Wrong sizing actuator	2	🟥	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟨	🟥	🟥	🟥	🟩	🟨	🟩	🟨
Wrong travel (mechanical connection, end set point)	1	🟥	🟥	🟨	🟨	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟨	🟨
Spring damaged/broken	1	🟥	🟥	🟥	🟨	🟨	🟩	🟥	🟥	🟨	🟥	🟥	🟥	🟩	🟩	🟩	🟨
Lack of air/hydraulic/electric supply	2	🟩	🟩	🟨	🟨	🟨	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟩	🟨
Spring unlinearity/bent spring	2	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟨
Stem damage, scratches or wear	2	🟨	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟩	🟥	🟥	🟥	🟩	🟨	🟨	🟩
External corrosion	2	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩
Internal corrosion	2	🟨	🟨	🟥	🟥	🟥	🟨	🟥	🟥	🟨	🟥	🟥	🟥	🟨	🟥	🟨	🟨
Wrong inititial compression	2	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟨
Failure of filter and regulator	2	🟨	🟨	🟩	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨

Coverage

Most likely no coverage of fault 🟥
Partly coverage of fault 🟨
Full coverage of fault 🟩

Criticality

Ok 🟦
Follow up 🟩
Action required 🟨
Immediate action 🟥

Figure 24: Sensor coverage – actuator

4.4 Calculation of diagnostic coverage

This chapter will include Diagnostic Coverage (DC) calculations on component level and the whole system as a unit, both with and without installation of VW. The results from calculation of diagnostic coverage from traditional surveillance methods and VW will be compared and discussed. Real experience data from valve diagnostics tests will be used to support and explain how VW will increase the diagnostic coverage by detection of dangerous undetected failures.

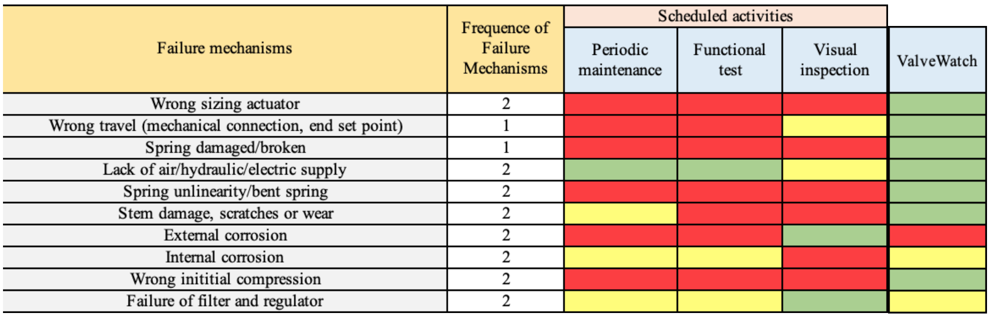
As well as calculating the diagnostic coverage with the use of VW, the analysis will present diagnostic coverage before implementing VW. This will provide knowledge of how VW can reveal dangerous undetected failures to make them become dangerous detected failures, and how the diagnostic coverage increases. After analyzing the diagnostic coverage with and without VW there will be a discussion of benefits regarding test intervals.

In the calculation of diagnostic coverage, it is assumed that dangerous undetected failures are categorized as “most likely no coverage” (red) and “partly coverage of fault” (yellow). This means that the only dangerous detected failure is “full coverage of fault” (green).

The following formula will further be used to calculate the diagnostic coverage for each component:

$$\mathrm{DC} = \frac{DD}{DD+DU} \quad \text{(Eq. 1)}$$

4.4.1 Actuator



Failure mechanisms	Frequence of Failure Mechanisms	Scheduled activities			
		Periodic maintenance	Functional test	Visual inspection	ValveWatch
Wrong sizing actuator	2	🟥	🟥	🟥	🟩
Wrong travel (mechanical connection, end set point)	1	🟥	🟥	🟨	🟩
Spring damaged/broken	1	🟥	🟥	🟥	🟩
Lack of air/hydraulic/electric supply	2	🟩	🟩	🟨	🟩
Spring unlinearity/bent spring	2	🟥	🟥	🟥	🟩
Stem damage, scratches or wear	2	🟨	🟥	🟥	🟩
External corrosion	2	🟥	🟥	🟩	🟥
Internal corrosion	2	🟨	🟨	🟥	🟨
Wrong inititial compression	2	🟥	🟥	🟥	🟩
Failure of filter and regulator	2	🟨	🟨	🟩	🟨

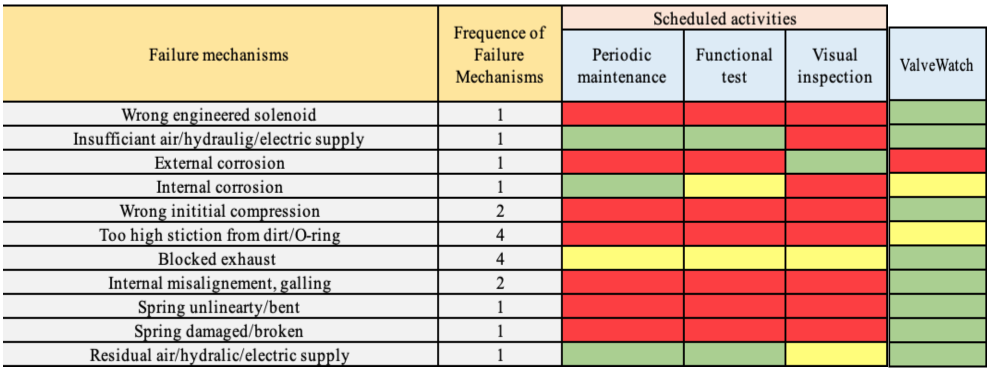
Figure 25: Traditional maintenance compared with ValveWatch - actuator

	Number or fails	Number of DD	Number of DU	DC
With VW	**10**	**9**	**1**	**90%**
Without VW	**10**	**3**	**7**	**30%**

Figure 26: Comparison of coverage with and without ValveWatch

From the sensor coverage of the actuator it is possible to separate the number of failure mechanisms that are being detected without VW, through scheduled activities and how many that can be revealed by VW. This separation is then used to divide the failures into dangerous detected and dangerous undetected failures before calculating diagnostic coverage for both scenarios (with and without VW). Diagnostic coverage of the actuator without VW is 30%, while the use of VW increases the diagnostic coverage to 90%. According to ISO 61508, a diagnostic coverage at 30% indicates no coverage, and installation of VW will on the other hand increase the diagnostic coverage to medium coverage at 90%.

4.4.2 Solenoid



Failure mechanisms	Frequence of Failure Mechanisms	Scheduled activities			ValveWatch
		Periodic maintenance	Functional test	Visual inspection	
Wrong engineered solenoid	1	🟥	🟥	🟥	🟩
Insufficiant air/hydraulig/electric supply	1	🟩	🟩	🟥	🟩
External corrosion	1	🟥	🟥	🟩	🟥
Internal corrosion	1	🟩	🟨	🟥	🟨
Wrong inititial compression	2	🟥	🟥	🟥	🟩
Too high stiction from dirt/O-ring	4	🟥	🟥	🟥	🟨
Blocked exhaust	4	🟨	🟨	🟨	🟩
Internal misalignement, galling	2	🟥	🟥	🟥	🟩
Spring unlinearty/bent	1	🟥	🟥	🟥	🟩
Spring damaged/broken	1	🟥	🟥	🟥	🟩
Residual air/hydralic/electric supply	1	🟩	🟩	🟨	🟩

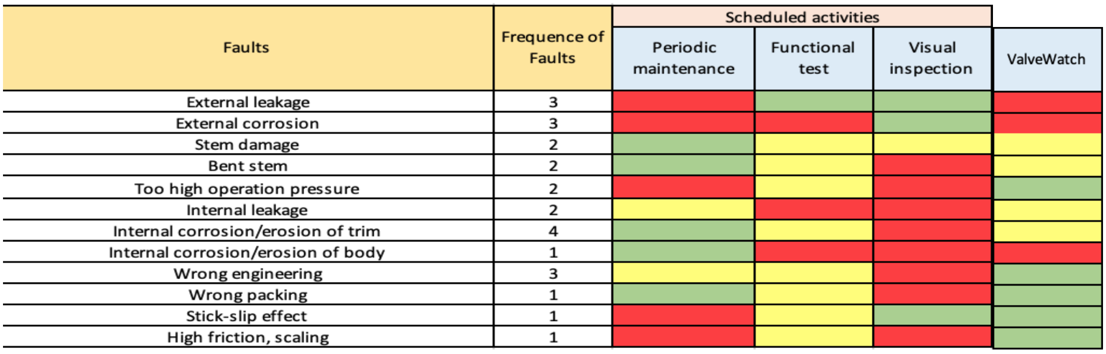
Figure 27: Traditional maintenance compared with ValveWatch - solenoid

	Number or fails	Number of DD	Number of DU	DC
With VW	**11**	**10**	**1**	**90,91%**
Without VW	**11**	**4**	**7**	**36,36%**

Figure 28: Comparison of coverage with and without ValveWatch - solenoid

Without any sort of surveillance by a valve diagnostic tool, the solenoid only detects 7 out of 11 failure mechanisms. The diagnostic coverage is 36,36%, which means that there is no coverage according to ISO 61508. Installation of VW can therefore be a better solution with a medium coverage from a diagnostic coverage at 90,91%.

4.4.3 Valve



Faults	Frequence of Faults	Scheduled activities			ValveWatch
		Periodic maintenance	Functional test	Visual inspection	
External leakage	3	🟥	🟩	🟩	🟥
External corrosion	3	🟥	🟥	🟩	🟥
Stem damage	2	🟩	🟨	🟨	🟨
Bent stem	2	🟩	🟨	🟥	🟨
Too high operation pressure	2	🟥	🟨	🟥	🟩
Internal leakage	2	🟨	🟥	🟥	🟨
Internal corrosion/erosion of trim	4	🟩	🟨	🟥	🟨
Internal corrosion/erosion of body	1	🟩	🟥	🟥	🟥
Wrong engineering	3	🟨	🟨	🟥	🟩
Wrong packing	1	🟩	🟨	🟥	🟩
Stick-slip effect	1	🟥	🟨	🟩	🟩
High friction, scaling	1	🟥	🟨	🟥	🟩

Figure 29: Traditional maintenance compared with ValveWatch - valve

	Number or faults	Number of DD	Number of DU	DC
With VW	**12**	**11**	**1**	**91,67%**
Without VW	**12**	**8**	**4**	**66,67%**

Figure 30: Comparison of coverage with and without ValveWatch - valve

As explained in subchapter 4.4, it is more suitable to look at faults in general instead of failure mechanisms because of the criticality of the valve. Compared to the actuator and solenoid, the diagnostic coverage of the valve without any form of valve diagnostic tool is much higher at 66,67%, resulting in a low coverage. Diagnostic coverage with VW on the other hand is also higher than the other components at 91,67%, giving it a medium coverage.

4.4.3.1 DC calculation of the system as a unit

	Number or fails	Number of DD	Number of DU	DC
With VW	**33**	**30**	**3**	**90,91%**
Without VW	**33**	**14**	**19**	**42,42%**

Figure 31: Comparison of coverage with and without ValveWatch – system as a unit

The table above shows the total number of failures, dangerous detected- and dangerous undetected failures with corresponding diagnostic coverage for the whole system as a unit (the ball valve). The calculated diagnostic coverage for the system as a unit is the most valuable and essential because it covers all parts of the valve in operation. The resulting diagnostic coverage for the whole system is 90,91%, which is a drastic increase compared to 42,42%. This shows that VW increases the diagnostic coverage from no coverage to medium coverage.

4.4.3.2 Conclusion

Diagnostic coverage has been calculated for the actuator, the valve, the solenoid and the system as a unit. Calculation was done before and after installation of VW. For each of the calculations it is easy to see that the coverage was much higher after installation of VW.

For the whole system as a unit, the coverage was 41,41% without use of VW and 90,91% coverage when using VW. This concludes that the system initially had no coverage, yet after installing VW the coverage was improved to medium.

4.5 Functional test interval

As explained in subchapter 2.3, functional tests will detect failures that are usually dangerous undetected. A diagnostic coverage of 90,91% tells us that 9,09% of the total failures are yet to be detected, and it is therefore necessary to conduct functional tests periodically. To obtain an optimized test plan regarding both economical and safety aspects, the functional test interval must be evaluated.

To understand how an increased diagnostic coverage can affect the functional test intervals, one must understand how different parameters relate to each other:

- A higher diagnostic coverage decreases the number of dangerous undetected failures.
- As the number of dangerous undetected failures decreases, the PFD and the functional test intervals consequently can be expanded. This is explained through the formula for PFD: $PFD = \lambda_{DU} \cdot \tau$. The functional test interval can therefore be determined by the formula: $\tau = \frac{PFD}{\lambda_{DU}}$. This explaining how functional test interval increases through decreasing of dangerous undetected failure rate.
- The required PFD relate to the required SIL, e.g. SIL2 requires $10^{-3} \leq PFD < 10^{-2}$ ref. figure 13.

As mentioned in subchapter 2.5.3, $PFD_i \leq PFD_0$ is the acceptable criteria for the required SIL, which can also be considered when determining λ_{DU}. The failure rate can be unbiased calculated through: $\lambda_{DU_o} = \frac{x_o}{t}$, with x_o being predicted number of dangerous failures and t being the time between two functional tests. Since this is an unbiased calculation, Hauge et al. (2009) explains that it is usually a 95% confidence interval for SIS components with the upper limit for the dangerous undetected failure rate often 2-3 times higher than the calculated value.

Further, x_o is to be compared with the actual number of dangerous failures, x_1, to verify if the predicted dangerous undetected failures correspond with the reality. This directly affects the undetected failure rate and can therefore be decisive in evaluation of the functional test interval. If $x_1 < x_o$, the dangerous undetected failure rate decreases, which further can be used to decrease the functional test interval, and vice versa if $x_1 > x_o$. To maintain SIL2 in the second scenario it is therefore important to reevaluate the functional test interval to satisfy the requirements for the safety level. Difference in the predicted and actual number of failures over a period requires therefore updated calculations and functional test intervals.

In operation it is occasionally a need for actions from ESD valves, and if these valves have installed VW it is constantly processing feedback of condition and performance through opening and closing. This can affect the functional test interval by VW collecting the same data through unplanned actions as by functional tests. If the functional test interval is set to one year, yet an unforeseen opening/closing of the valve 10 months after the last functional test occurs, this can replace the planned functional test. The condition and performance data collected by VW can from this unforeseen action be further evaluated and used as basis in planning of maintenance. Functional test intervals are therefore able to be more flexible and optimized by use of VW, compared to traditional maintenance methods.

Every parameter in an O&G production relates to each other in a way, which means that optimizing a single parameter can therefore be beneficial to the system. The most efficient way to increase functional test intervals is to lower the number of dangerous undetectable failures and hereby increase the diagnostic coverage.

4.5.1 Benefits of functional test interval from increased diagnostic coverage

The constant focus on economic benefits as well as the increasing requirements within safety and environment affects the ongoing development of efficient and reliable tools. As explained, increasing diagnostic coverage will directly extend the functional test, which means that downtime and reliability will be positively affected.

Extending functional test intervals results in less maintenance expenses as well as less downtime when in operation. For example, an increase of the functional test interval from 6 to 12 months will halve the downtime and therefore halve the expenses. From condition monitoring performed by ValveWatch, it is also possible to detect where and why a failure occurs, which will further decrease eventual downtime by detection of the failure in an early stage. This is strongly beneficial compared to traditionally corrective maintenance actions where the whole valve must be disassembled and controlled piece by piece. It is also worth mentioning that there is always a risk for inducing failures to valves under maintenance. An example for this could be that the sealings are overtighten when assembled, which can result in too high friction. Both expenses regarding performing functional test and superficial downtime are massive and are therefore economically decisive to reduce.

Regarding health, safety and environment (HSE), continuous monitoring of valves will increase the safety for both personnel and environment. Constant feedback on condition of the valves provides safety for the personnel working around the production as well as decreasing the risk of pollutants, considering the environment. It also requires less physical surveillance from personnel, which will decrease the risk of work-based injuries as well as increasing functional test interval reduces the necessity of frequent maintenance actions.

5 Discussion

When performing functional tests on ESD valves, normally the whole production is forced to temporarily shut down. Without any valve diagnostic surveillance, there will be uncertainty and difficulties related to prioritizing which valve is most critical regarding maintenance actions. Even with high focus and large resources used on maintenance planning and scheduling, valves without any sign of failures may be unnecessary tested due to restricted knowledge on condition of the valves. Additionally, in case of a detected internal failure, restricted knowledge will in many cases cause the whole valve to be disassembled in order to verify the correct failure mechanism.

This thesis is primarily based on qualitative data such as experienced based reports and conversations with experts in cooperation with MRC Global. The results regarding calculation of diagnostic coverage using ValveWatch have therefore relied on MRCs method for collection and interpretation of data from valves in production. Because of their experience in the O&G industry and their worldwide reputation, the reliability will be considered as relatively high. On the other hand, VW is a VDS in continuous development, which means that it needs verification on its quality over time to be able to develop a reputation in the industry.

The results in this thesis confirms through analysis that the diagnostic coverage increases considerably using VDS as a replacement for traditional maintenance. As a result, the diagnostic coverage was calculated to a percentage of 90,91 which tells us that 9,09% of the dangerous failures are still to be detected for ball valves. This means that there are still room for further improvement, as a diagnostic coverage lower than 100% causes a necessity of occasional functional tests to verify the condition of the valve. It is also important to emphasize that the diagnostic coverage can vary between different types of valves.

A decisive factor for eventual O&G companies wanting to invest in a VDS is the economical aspect of such a system. To substantiate the economic benefits in implementing a VDS it is important to relate it to the safety parameters. Obtaining a certain safety requirement of valves without any form of monitoring system can be challenging and it can cause a necessity of redundancy of valves. This means that multiple valves are installed in series, to ensure that if one valve fails the next one will perform the required function. A VDS can therefore substitute this type of redundancy and obtain the safety requirement with only one valve.

6 Conclusion

The connection between functional test intervals and diagnostic coverage has been explained in this report. All possible potentially failure modes with corresponding failure mechanisms for a ball valve have been identified to illustrate how the implementation of a Valve Diagnostic System increases the diagnostic coverage. Further, these failure mechanisms and the different sensors have been analyzed with purpose to illustrate the sensor coverage, which is decisive when calculating diagnostic coverage. Diagnostic coverage by traditionally maintenance actions has also been calculated.

By implementation of Valve Diagnostic system, this report document that the diagnostic coverage raises from 42,42% (no coverage) to 90,91% (medium coverage) for a ball valve. This means that it is possible to extend the functional test interval, which gives multiple advantages.

This bachelor thesis conclude that it is possible to extend functional test interval by implementation of Valve Diagnostic System, as it gives increased diagnostic coverage.

7 Suggestions for further work

For all O&G systems it is desirable to have the highest diagnostic coverage as possible. This thesis concluded that there will be a 90,91% coverage for the ball valve after installation of VDS, yet this is only documented as medium coverage according to ISO 61508.

It is important to emphasize that no statistical data has been collected and analyzed during this thesis which means that the conclusion is just an approach. A suggestion for further work is therefore related to the collection of data, where it is important to have mass data to obtain a more precise result of work. One recommendation will be to collect data from several equal valves for a specific period of time as a foundation for analyzation.

Even with high diagnostic coverage (>99%), there is still a need for functional tests. The only difference is the expanded intervals for the functional test when comparing to medium coverage. If the diagnostic coverage reaches 100%, there will not be a need for functional test anymore. Once this is the scenario, how will this affect the way the industry measure and diversify the performance of critical systems and equipment?

References:

- Esposito, S. (2011) *Evolution of Valve Diagnostics* [Internet]. Flow Control. Available at: <https://www.flowcontrolnetwork.com/evolution-of-valve-diagnostics/> [Read 15 Mars 2019].
- Haugen, S., Lundteigen, M. A. and Rausand. M. 2009. *Updating failure rates and test intervals in the operation phase: A practical implementation of IEC 61511 and IEC 61508.* Esrel 2009.
- Jevees, S., Zhu, P., Liyanage, J.P. (2019) Condition and performance monitoring (p. 1-10).
- Lundteigen, M.A. (2009) *Concepts and methods for safety and reliability assessment in design and operation:* Norwegian university of science and technology.
- Macleod, F. & Richardson, S. (2018) Piper Alpha: The Disaster in Detail. *The Chemical Engineer,* 925 (26) July/August.
- Mathur, G. (2013) *Understanding Safety Integrity Level (SIL) and its Effects for Field Instruments* [Internet]. Available at: <https://www.automation.com/pdf_articles/Understanding_SIL_and_effects.pdf> [Read 15 March 2019].
- MRC Global (2019) *Company* [Internet] <https://www.mrcglobal.com/Company> [Read 01 February 2019].
- MRC Global (2019) *Sensors* [Internet]. MRC Global. Available at: <https://www.mrcglobal.com/Global-Region/Products/ValveWatch/Sensors> [Read 15 Mars 2019].
- Norwegian oil and gas association (2001) *Application of IEC 61508 and IEC 61511 in the Norwegian petroleum industry.*
- Nox, D. *ISO 13849-1 Analysis – Part 5: Diagnostic Coverage (DC)* [Internet]. Machinery Safety 101. Available at: <https://machinerysafety101.com/2017/02/27/iso-13849-1-analysis-part-5/> [Read 25 February 2019].
- Quality-One (2015) *Fault Tree Analysis (FTA)* [Internet]. Available at: <https://quality-one.com/fta/> [Read 05 February 2019].
- RealPars (2018) *What is a Safety Instrumented System?* Available at: <https://www.youtube.com/watch?v=W2YUNnfATBY&t=609s> [Read 06 Mars 2019].

- Schlumberger (n.d.) *How does it work: Ball Valves* [Internet]. Houston: Schlumberger. Available at: <https://www.products.slb.com/en/valves/valve-academy/how-does-it-work-ball-valves> [Read 15 February 2019].
- Solberg & Andersen (n.d.) *Ventilteknikk.* OLF Guideline 119. Bergen: MRC Global.
- Weibull (n.d.) *Fault Tree Analysis* [Internet]. Weibull. Available at: <https://www.weibull.com/basics/fault-tree/index.htm> [Read 15 Mars 2019].
- Willey, R.J. (2014) *Layer of Protection Analysis*. Boston: Department of Chemical Engineering, Northeastern University.

Figures:

- Jevees, S. (n.d)
- MRC Global (2019) *Acoustic Sensor/MRC Global*. Available at: <https://www.mrcglobal.com/~/media/Images/ValveWatch/ValveWatch_Image_Sensor_05.ashx?la=en>
- MRC Global (2019) *Actuator Pressure Sensor/MRC Global*. Available at: <https://www.mrcglobal.com/~/media/Images/ValveWatch/ValveWatch_Image_Sensor_02.ashx?la=en>
- MRC Global (2019) *Company* [Internet] Available at: <https://www.mrcglobal.com/Company>
- MRC Global (2019) *Dynamic Pressure Sensor/MRC Global.* Available at: <https://www.mrcglobal.com/~/media/Images/ValveWatch/ValveWatch_Image_Sensor_04.ashx?la=en>
- MRC Global (2019) *MRC Global/Base property*. Available at: <http://baseproperty.no/wp-content/uploads/2016/07/IMG_4678.jpg>
- MRC Global (2019) *Strain Sensor/MRC Global*. Available at: <https://www.mrcglobal.com/~/media/Images/ValveWatch/ValveWatch_Image_Sensor_03.ashx?la=en>
- MRC Global (2019) *ValveWatch sensors/MRC Global*. Available at: <https://www.mrcglobal.com/~/media/Images/ValveWatch/ValveWatch_HeaderImages_Sensors.ashx?la=en>
- RealPars (2018) *What is a Safety Instrumented System?* Available at: <https://www.youtube.com/watch?v=W2YUNnfATBY&t=609s>
- Saferisk (2018) *Layers of protection analysis/Safe risk*. Available at: <https://static1.squarespace.com/static/5509e7d8e4b08082d8a35833/t/5589356be4b04b4d3bc48db0/1506552984958/LOPA?format=500w>
- Universell (2019) *Høgskulen på Vestlandet.* Available at: <https://www.universell.no/tilretteleggere/hoegskulen-paa-vestlandet/
- Valve (n.d) *Floating ball valves*. Available at: <https://www.valve.no/floating-ball-valves-are-more-than-just-floating-ball-valves-part-1/>
- Valve Magazine (2015) *Trunnion ball valve*. Avaliable at: <http://www.valvemagazine.com/magazine/sections/features/8859-unique-operating-dynamics-of-trunnion-mounted-ball-valves.html>