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Preface

This master thesis was written as the final part of my master study in Offshore technology – Industrial Asset Management at the University of Stavanger. The thesis work has been done during the spring semester of 2015.

First I would like to thank Gassco and my external supervisor at Gassco Geir Hoff for giving me the possibility to write my Master's thesis for them. Geir Hoff has been most helpful giving me the guidance and information I needed for my studies. It would not have been possible to do this thesis without his support and help.

I would like to thank my supervisor Professor Srividya Ajit at the University of Stavanger for giving me the guidance and support during the work of this thesis. I would also like to thank the people in the administration for being helpful while working with this master thesis.

Last, but not least, I would like to thank my family supporting me.

Jon-Anders Lennertzen

Summary

Production- and safety critical valves are important safety barriers used in a pipeline network for production and transport of hydrocarbon gas. These valves, as part of a larger emergency shut down (ESD) systems, protect the facilities and plants that are part of the gas transport system against hazardous situations. They prevent accidents from occurring and escalating. The Petroleum Safety Authority (PSA) demands that these safety barriers are kept safe and reliable throughout the whole lifetime of the facilities and plants, and it is therefore important that Gassco, as the operator of the gas transport system, ensures that the valves are sufficiently maintained, monitored and tested during operation.

A sufficient testing regime is a necessary part of the overall maintenance program related to barrier valves in order to verify and ensure that their performance is good and that they function when demanded. Gassco has to verify to the PSA that the overall performance of their valves is in accordance to the safety requirements set for them.

This thesis analyses the test results of the production- and safety critical valves that are operated by Gassco. This has been done to evaluate their current testing regime and overall valve performance in accordance to the SIL (Safety integrity level) requirements in IEC 61508. The reported test results include measurements of closing times, internal leak rates and verification of barrier function for all valves. The methods and procedures discussed for analysis of failures reported in test results have to a great extent been based on the recommendations given in OLF 070, which is the guidelines to the IEC 61508 standard, as well as the OREDA handbook 2002 and a selection of other reports that refer to IEC 61508. Based on the literature and reported test results a procedure has been proposed that includes the steps from evaluating the risk of the reported failures and failure rate estimation to performance verification and updating of the test interval. Due to lack of information in the reported test results a number of assumptions had to be taken in the analysis, though the uncertainties related to the analysis are thoroughly discussed. Nevertheless, the results of the overall performance of the valves seem to be good.

In the last part a discussion is given as to how and how often the valves should be tested in the future and what is necessary in order to maintain the overall valve performance. The testing routines and methods used and the possible effects that the supplement of partial stroke testing (PST) and valve condition monitoring may have on valve performance are discussed.

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Abbreviations

AE	Acoustic Emission
CCF	Common cause failures
DAU	Data acquisition unit
DOP	Delayed operation
DD	Dangerous detected
DU	Dangerous undetected
ELP	External leakage of process medium
ESD	Emergency shut down
FST	Full stroke testing
FTC	Failure to close on demand
FTO	Failure to open on demand
HFT	Hardware fault tolerance
HPU	Hydraulic power unit
HSE	Health, safety and environment
LCP	Leakage in closed position
MPE	Ministry of Petroleum and Energy
MTTR	Mean time to failure
NCS	Norwegian continental shelf
PFD	Probability of Failure on Demand
PFD_{Avg}	Average Probability of Failure on Demand
PSA	Petroleum Safety Authority
PSF	Probability of systematic failure
PST	Partial stroke testing
SFF	Safe failure fraction

SIF	Safety instrumented function
SIL	Safety integrity level
SIS	Safety Instrumented System
SPO	Spurious operation
SD	Safe detected
SU	Safe undetected
TSP	Technical service provider
V-MAP	Valve Monitoring for Analysis and Performance

1. Introduction

1.1 Gassco

Gassco is a Norwegian state-owned company in the oil and gas industry founded by the Norwegian Ministry of Petroleum and Energy (MPE) in May 2001 at Karmøy, Rogaland. The establishment of the company was a result of a larger reorganization of the Norwegian oil and gas sector that took place in 2001. The reason for this reorganization was due to requirements that were introduced in the European Union's gas market directive at that time for organising the oil and gas transport operations to ensure neutral gas market conditions. (Gassco, 2015)

Gassco has functioned as the operator of the gas transport system from the Norwegian continental shelf (NCS) to customers in Norway and other European countries since the beginning of 2002. The gas transport system operated by Gassco is in fact one of the largest gas transport systems in the world with a subsea gas pipeline network stretching more than 8000 kilometres in total. The gas transport system from the NCS to European countries comprises offshore platforms, pipelines, gas processing plants and gas terminals throughout Northern Europe. (Gassco, 2015)

Figure 1: Map of the integrated gas transport system of pipeline network including offshore platforms, gas terminals and processing plants across Northern Europe (Statoil, 2010)

Gassco operates many of the land-based gas processing plants, offshore platforms and gas terminals across Northern Europe that are included in the gas transport system. An overview of processing plants, gas terminals and platforms that are currently operated by Gassco is shown in the table below.

Table 1: Overview of Gassco's operatorship across Europe

Gas processing plants:
Kollsnes (Statoil, TSP*)
Kårstø (Statoil, TSP)

Gas terminals:
Dornum, Germany
Dunkerque, France
Easington, UK
Emden, Germany
St Fergus, UK (Total, TSP)
Zeebrugge, Belgium

Offshore platforms:
B11 compressor platform
Draupner E and S riser platforms
Heimdal riser platform

*Technical service provider

In addition the gas processing plant at Nyhamna will be operated by Gassco in 2017 when the Polarled pipe-laying operation is scheduled to be completed (Statoil, 2015).

As an operator Gassco is committed to follow the operating regulations given by PSA (Petroleum Safety Authority) and the requirements found in the Norwegian Petroleum Activities Act. They are also committed to delivery demands in the contracts they have with the owners of the gas transport system (e.g. Statoil and Petoro) and Gassled, which is the joint venture that most of the owners are part of. (Gassco, 2015)

Gassco is responsible for managing the gas transport system and its infrastructure, and making sure that the operations are safe, reliable and efficient. This means that it is important to maintain the availability of all equipment that is involved, including pipelines, valves and other parts. Equipment is gradually degraded over time due to e.g. corrosion, which requires sufficient maintenance routines and testing routines to ensure that the equipment remains reliable at all times.

From a control room Gassco monitors and controls the whole pipeline network. Here the control room operators manage the gas capacity allocation through the pipelines and track the gas flow directions and velocities as well as pressure rates in the pipelines. If there is a failure in a part of the gas transport network the control room operators are notified. (Gassco, 2011a) The control room operators can then decide what further actions need to be taken, whether it be shutting down parts of the gas pipeline and reroute the gas or possible other actions.

Figure 2: Gassco's control room at Karmøy, Norway (Gassco, n.d.)

Gassco is also responsible for the planning of infrastructure development and further expansion of the gas transport system. They need to see to it that the implementation process is cost efficient and properly executed. (Gassco, 2013)

The gas flowing through the pipelines is primarily natural gas of hydrocarbons such as methane, ethane, buthane, propane and nafta. Natural gas has a wide range of applications for the consumers ranging from heating and cooking to various plastic products (e.g. plastic bags and drinking bottles). (Gassco, 2011a) In general the demands for gas and gas based products are high. Therefore it is of great importance to Gassco that their deliverability of gas is high. Their ambition is a yearly gas deliverability rate to the market of close to 100%. This is reflected in their vision which is (Gassco, 2013):

"Norwegian gas transport to Europe – reliable and forward-looking."

1.2 Background

The PSA of Norway sets the regulations for HSE (health, safety and environment) and emergency preparedness in the Norwegian oil and gas industry both onshore and offshore. Gassco, as the operator of gas transport system on the Norwegian continental shelf (NCS), is responsible for the operation and ensuring that it is safe and efficient. (Gassco, 2015) According to section 5 in the Management regulations and related guidelines (see The Management regulations, 2014) Gassco is required to have safety barriers in place at the facilities and plants in the gas transport system that at all times are able to detect possible failures and situations that could be hazardous and lead to accidents. Furthermore the barriers shall reduce the possibility of these failures and emergency situations from occurring and developing, and in case such situations occur the barriers shall prevent escalation to limit the possible harm and loss. It is important to maintain and test these safety barriers to ensure that their barrier functions are safeguarded throughout the lifetime of offshore and onshore plants.

In all plants connected to the gas pipeline network operated by Gassco there are safety barriers installed in form of emergency shut down (ESD) systems and safety critical valves that are supported by flaring systems. According to section 47 in the Activities regulations and section 47b in the related guidelines (see The Activities regulations, 2014) Gassco needs to have in place a well-functioning maintenance program for the ESD systems and safety critical valves in order to secure safe operation of the gas transport system. This implies that routines for testing of the ESD system and safety critical valves need to be in place to test their functional abilities. Further it is mentioned that where such established routines for testing of ESD systems are not in place the PSA recommends that a full-scale function test is carried out at a yearly basis. The full-scale function test should include testing of all the safety functions of the ESD system as well as full closing test and internal leakage test of the safety critical valves. Based on this Gassco has the option to have a testing regime for their ESD systems and safety critical valves that deviates from the recommendations given by the PSA as long as they can verify to the PSA that their testing regime is better or equally good.

1.3 Problem description

The topic of this thesis is developed in cooperation with Gassco. Gassco invests much time and effort in testing and maintenance of their production- and safety critical valves to sustain a high overall reliability and performance. A great deal of work is also put down in gathering of results from functional testing of the valves in order to verify to the PSA that the valves are regularly tested and operate safely. This thesis will assist Gassco on the way of verifying the overall performance of their safety critical valves and testing regime. Furthermore possibilities of improving the existing testing regime for the valves will be looked upon. The main questions that will be raised in this thesis based on mainly on the reported test results are:

- Examine if Gassco's testing regime of production- and safety critical valves ensures an overall safe operation of the gas transport system?
- Examine how often tests should be conducted?
- Examine how to maintain sufficient overall reliability of the valves and look at possibilities of improvement?

1.4 Objectives

The main objectives:

- Describe the failures, failure mechanisms and requirements that are set for production- and safety critical valves
- Describe the tests that are carried out by Gassco of the production- and safety critical valves and alternative methods that can be used for testing.
- Analyse the overall performance of production- and safety critical valves that are operated by Gassco based on the test results and how often the valves should be tested.
- Analyse the effect that partial stroke testing (PST) could have on the overall performance of the safety critical valves.
- Look at possibilities of improving the testing regime of production- and safety critical valves.

1.5 Limitations

The analysis of will focus only on the testing regime and reported test results of the production- and safety critical valves. The analysis of the overall performance of the valves will be limited to the guidelines of the IEC 61508 given in OLF 070 (OLF, 2004) for SIL verification and a selection of other reports. The estimation of failure rate, PFD, and test intervals will be based on many assumptions due to limited information given in the reported test results. However, the assumptions used in the calculations and related uncertainties will be thoroughly explained. Only the production- and safety critical valves will be included in the calculations as only these components are present in the test results. It is assumed that necessary maintenance actions and routines for the valves are in place. Possibilities for improving the testing regime are limited to suggestions for better routines concerning safety, and how condition monitoring and PST can be used when testing.

1.6 Outline of thesis

In chapter 1 information of Gassco AS and how this company operate the Norwegian gas transport system according to the regulation set by Norwegian authorities. The problem of the thesis and the limitations made are also described.

A description of the function of the ESD (Emergency shut down) and PSD (Process shut down) valves operated by Gassco are given in chapter 2. Explaining the SIL (Safety integrity level) and PFD (Probability of failure on demand) are also found in chapter 2.

Chapter 3 gives information on possible failures of production- and safety critical valves, how these failures are classified and how the failures are detected.

The different testing methods of production- and safety critical valves are looked upon in chapter 4. The testing methods explained include FST (Full stroke testing), PST (Partial stroke testing), and internal leak testing, in addition to valve condition monitoring as supplement to testing.

Chapter 5 gives an overview of Gassco’s reported test results and related risk acceptance criteria for the measurements, along with a literature study of methods for analysis of failure data. This forms the basis for how the test results of valves can be analyzed.

Chapter 6 gives a description of the procedure chosen for the evaluation of the test results presented based on the information given in chapter 5.

Chapter 7 provides the analysis of the test results of the valves and discusses if the test intervals should be altered. The possible uncertainties and sources of error related to the reported test results are also discussed.

In chapter 8 routines for testing are proposed together with the use of PST and valve condition monitoring in order to maintain good performance of production- and safety critical valves.

Chapter 9 gives the conclusion of the thesis and further studies.

2. Safety barriers in the gas transport system

This chapter gives a description of the ESD system and the production- and safety critical valves (including actuators) as part of the ESD system. Furthermore requirements related to performance and safety risk of the ESD system is presented. The purpose is to give the reader a better understanding of the valves reported in Gassco's test results, and to give a theoretical basis for discussion of the results of the analysis.

2.1 Emergency shut down (ESD) system

In a gas transport system where combustible gas under high pressure flows through the pipelines there is need for a Safety instrumented system (SIS) to ensure that operations are safe and under control. An emergency shut down (ESD) system is a type of SIS used for shutting down the gas pipelines in emergency situations. (OLF, 2004) ESD systems are considered as low demand systems as they are rarely used more often than once a year (Rausand, 2014). An ESD system is composed of three subsystems (OLF, 2004):

- Field sensors
- ESD logic solvers
- Final elements

If emergency situations occur the sensors send ESD signals to the ESD logic solver system which interprets the signals and decides whether emergency shut down of the pipeline production is necessary or not. When the ESD logic solvers decide that a shut down is needed it sends ESD signals to the final elements that typically consist of the solenoid valves, actuators, and ESD valves. The solenoid valves act on the actuator to force the ESD valve to close. The ESD system has built-in redundancy (i.e. redundant channels of components performing the same function) to meet the safety requirements (Rausand, 2014). In this way the ESD system can still perform its intended barrier function if certain redundant components fail.

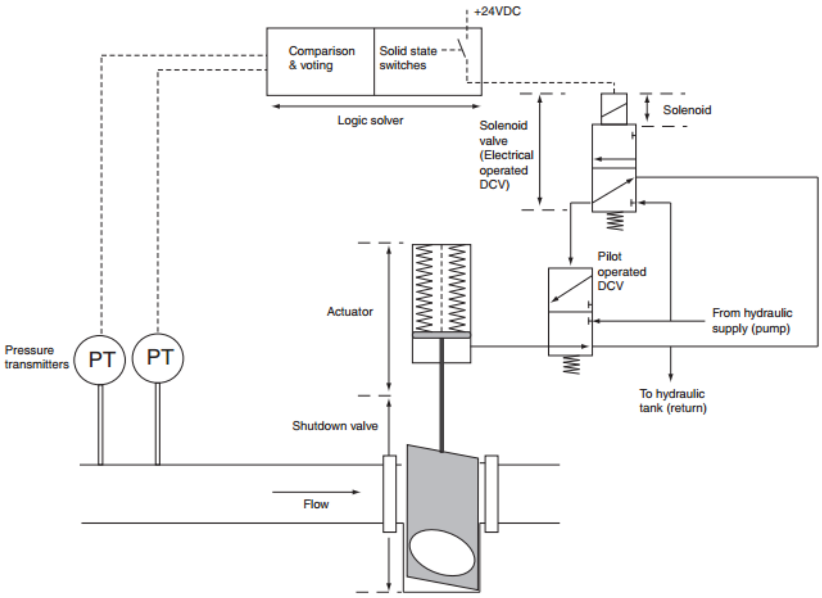


Figure 3: Diagram illustrating how an ESD system works (Lundteigen, 2010)

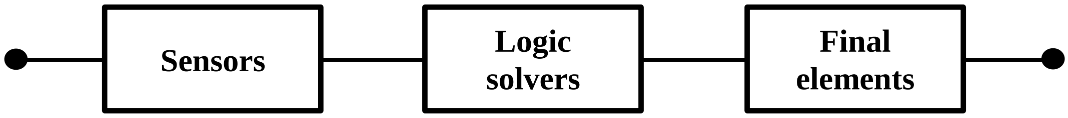


Figure 4: Relability block diagram of an ESD system

2.2 Production- and safety critical valves

The production- and safety critical valves operated by Gassco consist of ESD valves or PSD (process shut down) valves depending on their location in the pipeline system. The ESD valves are considered the most safety critical because they function as the last safety barrier of the pipeline before the gas reaches the plant. Therefore it is very important that these valves are reliable and function as they should during operation. The PSD valves are located further upstream and are used to support the ESD valves and limit the amount of gas reaching the ESD valves and flaring systems downstream. (Hoff, 2015)

These valves typically consist of a valve body, bonnet, stem, stuffing box, disc (gate/ball), seats and an actuator. However, the assembly could vary. The stuffing box and valve seats are important parts used to prevent gas leakages.

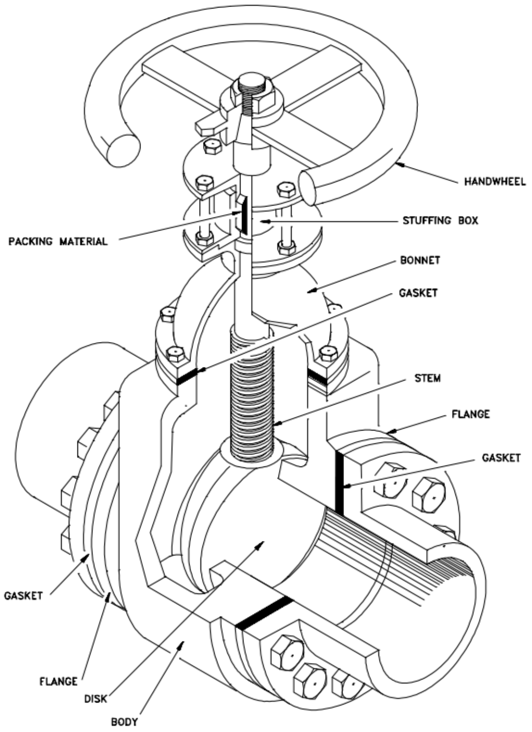


Figure 5: Illustration of typical valve parts (Seridium, n.d.)

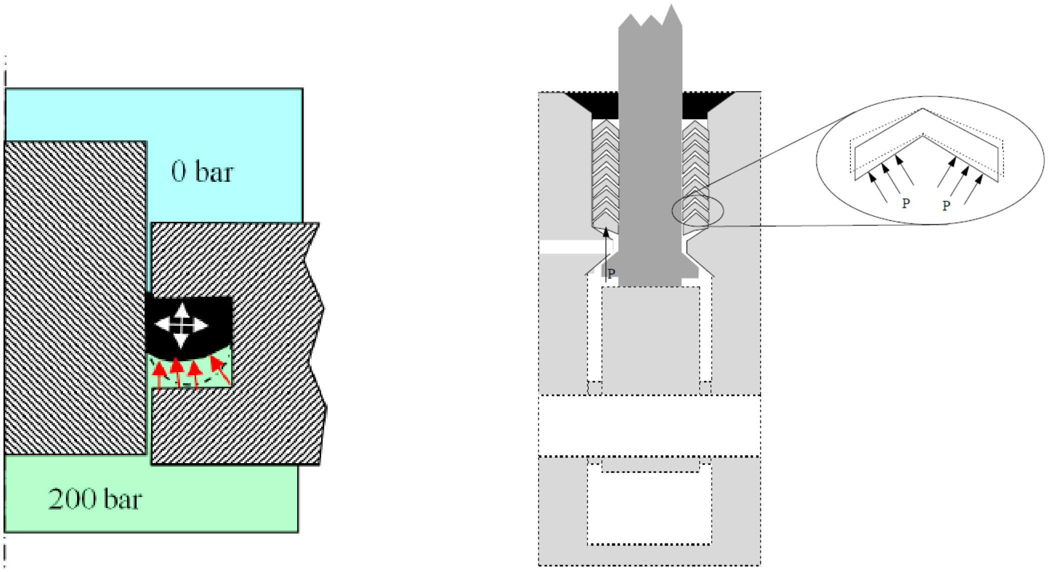
2.2.1 External sealing solution

The stuffing box and seats are important sealing solutions for production- and safety critical valves in order to prevent gas leakages and ensure safe operation. The stuffing box contains a packing material and is wrapped around the stem to seal between the bonnet and stem in order to prevent external gas leakages. A pressure gland is used to compress the packing to create a tight seal. (Smith & Zappe, 2004) The packing typically consists of five rings (OLF, 2013) of either of following types (based on Smith & Zappe, 2004; OLF 2013; American Seal & Packing, 2013):

- O-ring packing – This is a squeeze type of packing of circular rubber-based rings that deforms and squeezes between the bonnet and stem to create a tight seal when exposed to pressure from below.
- V-packing (Chevron) – This is a lip type of packing of V-shaped rings of PTFE that expands radially and unfolds to create a tight seal between the bonnet and stem when exposed to pressure from below.
- Braided packing – This is a compression type of packing of braided rings of reinforced graphite that expands radially to create a tight seal between the bonnet and stem when exposed to pressure from below.

(Altec Products, n.d.) (Ritu Polymers, n.d.) (OG Supply, n.d)

Figure 6: Illustration of O-rings (left), V-packing (middle), and braided packing (right)



(OLF, 2013) (Kværner Oil & Gas, 1999)

Figure 7: Sealing principle of O-rings (left) and V-packing (right)

Gassco prefers a stuffing box solution with either braided packing or V-packing for their production- and safety critical valves, as this is considered the safest and most robust solution. O-ring packing is considered the weakest solution of the three because its rubber material has limited strength and is sensitive to high pressures and temperatures (OLF, 2013) However, O-rings are generally cheaper to produce and used to be a common sealing solution for such valves in the past. In fact, some of oldest valves operated by Gassco still have O-ring packing (Hoff, 2015). One of the main challenges with O-ring packing in valves used in gas pipelines is that it is susceptible to explosive decompression. Gas tends to diffuse into the O-ring material when exposed to high pressure under operation. If the pressure inside cavity is lowered too rapidly during e.g. testing of the valve, the O-ring will fail to vent the trapped gas out fast enough causing it to explode and lose its sealing capability as the trapped gas escapes. (OLF, 2013)

2.2.2 Internal sealing solution

Valve seats are used to seal between the disc and valve body in order to prevent internal gas leakages, especially when the valve is in closed position. The seats are either fixed to the valve body or floating (spring-loaded to move more freely) (Kværner Oil & Gas, 1999). Floating seats are supported by secondary sealing (e.g. O-rings or V-packing) between the valve body and seats (OLF, 2013). The valves operated by Gassco primarily have hard, metal (e.g. tungsten carbide) seats that are either fixed or floating (Hoff, 2015). Hard seats are generally considered more fire safe and robust (e.g. to high pressures and temperature changes) than soft seats of polymer based materials (OLF, 2013).

2.3 Valve types used by Gassco

The production- and safety critical valves that are operated by Gassco and represented in the test results consist of three valve types (Gassco, 2011b); trunnion ball valves, slab gate valves, and double expanding gate valves. A short description of the valve types is given below.

2.3.1 Trunnion ball valve

The trunnion ball valve uses a spherical ball with a hole as a blocking element, which is rotated 90 degrees to move the valve from closed or open position. The ball is fixed between the stem and trunnion, and is suited in pipelines with high gas pressures and larger dimensions. (Smith & Zappe, 2004) The trunnion ball valves operated by Gassco are 10” and larger (Hoff, 2015). Trunnion ball valves typically use floating seats to seal on the upstream side (Dickenson, 1999), though some the trunnion ball valves used by Gassco also have floating seats on the downstream side as a backup seal (i.e. a double piston effect). When rotated to closed position the upstream pressure forces the spring-loaded upstream seats against the ball to create a tight seal. In case the upstream seats leak the spring-loaded downstream seats are forced against the ball to form a tight seal (Kværner Oil & Gas, 1999).

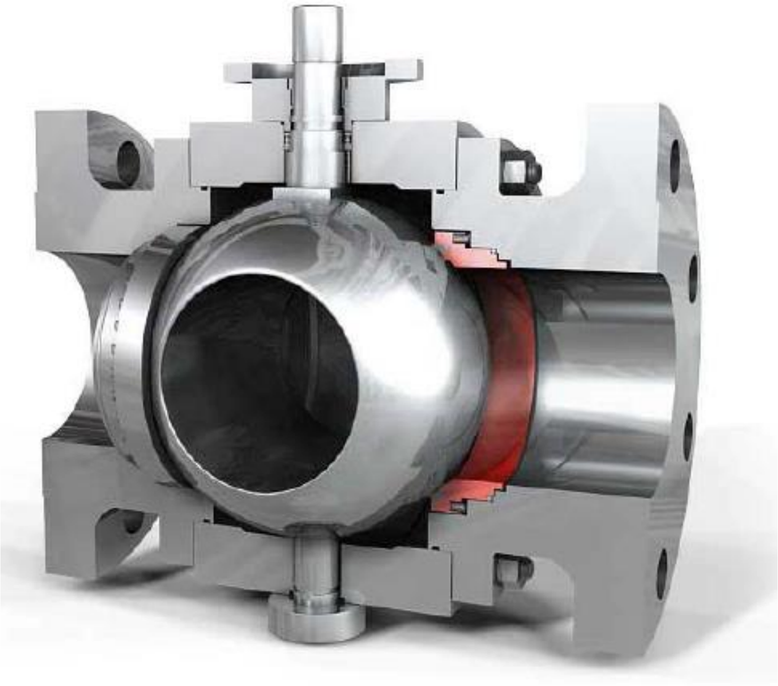


Figure 8: Trunnion mounted ball valve shown in closed position (OLF, 2013)

2.3.2 Slab gate valve

The slab gate valve is a linear motion valve where a gate, which is connected to a stem, is moved vertically to open or close the valve. The slab gate valves operated by Gassco are either normal-acting (fail to open) or reverse-acting (fail to close), though the preferred choice today are reverse-acting slab gate valves (Hoff, 2015). Slab gate valves use a slab as a blocking element with a hole in either the lower or upper end depending on if it is normal-acting or reverse-acting. Slab gate valves are equipped with fixed seats on the downstream side and floating seats on the upstream side (OLF, 2013).

The main difference between normal-acting slab gate valves and reverse-acting slab gate valves is their initial position - which is open for normal-acting gate valves and closed for reverse-acting gate valves. Hence the force of the actuator is needed to change their positions. Because reverse-acting valves move back to closed position if the actuator fails they are considered the safer option. Furthermore normal-acting slab gate valves tend to have more failure modes. Dirt and debris could gather at the bottom of the valve and prevent the valve from lowering into fully closed position. This is less of a problem for reverse-acting slab gate valves because here the disc is initially located at the bottom and is lifted up, thus minimizing the risk of dirt, debris and hydrates being left behind. (Hoff, 2015)

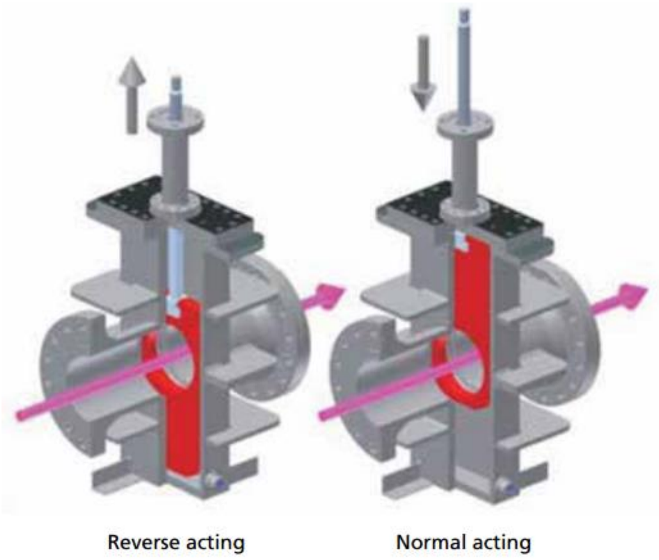


Figure 9: Concept of a normal-acting and reverse-acting slab gate valve (Cameron, 2013)

2.3.3 Double expanding gate valve

Gassco also uses a special type of through conduit slab gate valves called double expanding gate valves (Gassco, 2011b). These valves have a disc that is split in two parallel slab disc halves that slide diagonally against each other when the valve is closing and slide diagonally away from each other when opening. The principle of double expanding gate valves is that the two slab disc halves are exposed to pressure and expand against the seats to form a tight seal both when the valve is closing and opening. In this way this type of valve not only acts as a barrier to the gas flow while it is in closed position, but it also protects the cavity while in open position. (Kværner Oil & Gas, 1999)

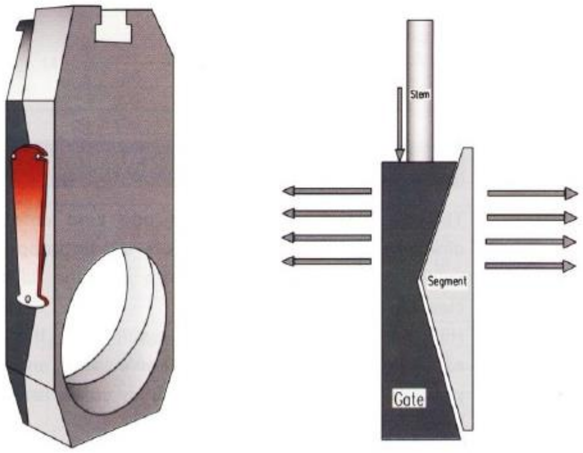


Figure 10: Principle of double expanding gate valve disc (J Flow Controls, n.d.)

2.4 Actuators used by Gassco

The production- and safety critical valves operated by Gassco have double-acting actuators that are either hydraulic or pneumatic (Hoff, 2015). Their main function is to provide an active force on the valve stem for opening and closing of the valve. Gassco requires that their actuators are capable of performing 2.0 times the maximum torque needed to open the valve (Hoff, 2015).

Double-acting actuators have a cylinder with double-acting piston located in between two pressurized chambers. The upper pressurized chamber is supplied with hydraulic fluid (for hydraulic actuators) or air (for pneumatic actuators), while the lower pressurized chamber is filled with compressed nitrogen gas. Solenoid valves are used to control the supply of hydraulic fluid and nitrogen gas between the cylinder and reservoir tanks. The differential pressure between the two chambers on either side of a double-acting piston is used to control the movement for opening and closing of the valve. (Kværner Oil & Gas, 1999)

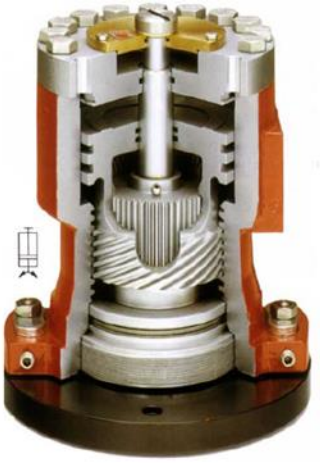


Figure 11: Illustration of a double-acting hydraulic actuator (EUC Vest, n.d.)

2.5 Safety integrity level (SIL) requirements

The standards IEC 61508 and IEC 61511, along with the guidelines given in OLF 070 to the application of these standards in the Norwegian petroleum industry, cover safety performance requirements for low demand systems such as ESD systems. These standards and guidelines are recommended by the PSA for verification of the performance of ESD systems and valves. (OLF, 2004)

The performance requirements of an ESD system can be expressed in terms of the SIL (Safety integrity level) classification given in IEC 61508 for low demand mode systems (i.e. systems that are demanded at most once a year). However, ESD systems may perform more than one safety instrumented function (SIF) in which each SIF could have different SIL requirements. The SIL classification ranges from SIL1 to 4, where SIL4 has the most stringent requirements for performance. The demanded SIL reflects the safety risk of the given system – the higher the safety risk the higher the required SIL (and thus the lower the PFD_{Avg} value). For each SIL the acceptance criteria is expressed as upper and lower limits of the average probability of failure on demand (PFD_{Avg}). (OLF, 2004) The relationship between the SIL and the acceptance criteria is shown in table 2.

Table 2: SIL acceptance criteria (based on OLF, 2004)

SIL	PFD_{Avg}
4	$10^{-5} \leq PFD_{Avg} < 10^{-4}$
3	$10^{-4} \leq PFD_{Avg} < 10^{-3}$
2	$10^{-3} \leq PFD_{Avg} < 10^{-2}$
1	$10^{-2} \leq PFD_{Avg} < 10^{-1}$

Since SIL is based on the overall performance of an ESD system (or SIF) the sum of PFD contributions of all sub systems (or included components) together must not exceed the acceptance criteria for the required SIL (OLF, 2004). This means that the sum of the PFD contributions of sensors, logic system and final elements determine whether the SIL requirement for the system (or SIF) is met or not. The final elements can generally be considered to contribute the most to the PFD_{Avg} of the system. According to Rausand (2014) the final elements can in many cases contribute as much as 50-80% of the total PFD_{Avg}.

For SIL verification of a SIF it is only required in IEC 61508 to quantify the random hardware failures, since the PFD is based on random hardware failures (OLF, 2004). The PFD value calculated for SIL verification includes only the random hardware failures that are considered dangerous failures (either DD or DU). As a minimum the random hardware failures that are considered DU failures should be quantified, though it is recommended that DD failures and systematic failures also are quantified (OLF, 2004).

In addition to the PFD acceptance criteria for SIL, there are also architectural requirements in IEC 61508 concerning hardware safety integrity. Each subsystem of an ESD system or SIF is classified as either type A or type B - where typically valves and solenoids are classified as type A, while software related components such as logic systems are classified as type B. (Lundteigen & Rausand, 2006) Specific hardware safety integrity requirements are given for type A and B subsystems in terms of Hardware Fault Tolerance (HFT) and Safe Failure Fraction (SFF). HFT expresses how many faults that can be tolerated by the subsystem before its safety function fails. For instance, a 1oo3 voted subsystem will have a HFT = 2. The SFF can be understood as the fraction of the failure rates for safe and dangerous detected failures of the total failure rate of the subsystem. (Lundteigen & Rausand, 2006)

Gassco generally demands that their ESD systems satisfy SIL2, though for some of the newer and more redundant ESD systems SIL3 is demanded (Hoff, 2015).

3. Failures of production- and safety critical valves

The reliability and availability of valves to a large degree depend on the detection and prevention of possible failures. When planning preventive maintenance actions such as testing, inspection and condition monitoring of valves it is important to know what type of valve failures that are likely to occur, how dangerous they are, and why the failures occur. In this chapter a classification of failures is given along with a description of typical failure modes and possible failure mechanisms of production- and safety critical valves used in gas pipelines. The purpose is to give a basis for evaluating failures among the valves operated by Gassco based on the measurements reported in the test results.

3.1 Failure classification

Failures that prevent production- and safety critical valves from performing their barrier functions as intended could have different failure causes. In order to evaluate and differentiate possible failures of Gassco's valves based on test results a classification of failures can be used. According to OLF 070 (2004) failures can be classified as:

- Random hardware failures, which most often are physical in nature and can be related to ageing or stress.
- Systematic failures, which are often non-physical failures that cannot easily be quantified and that are related to design or interaction (e.g. software errors, human errors, insufficient maintenance etc.)

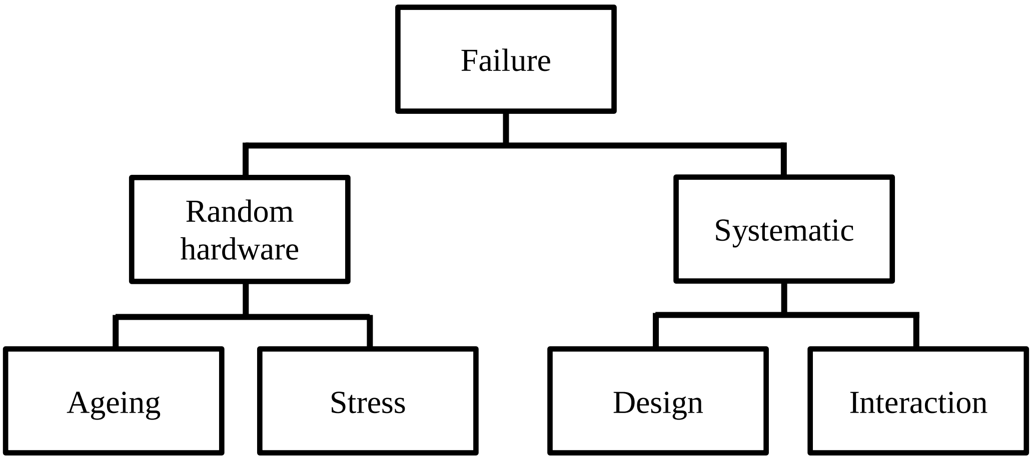


Figure 12: Failure classification (OLF, 2004)

Furthermore the failure modes (see section 3.2) that relate to either random hardware failures or systematic failures can result in failures that are dangerous (D) or safe (S) failures that are detected (D) or undetected (U) (OLF, 2004):

- Dangerous detected (DD) failures
- Dangerous undetected (DU) failures
- Safe detected (SD) failures
- Safe undetected (SU) failures

DD and SD failures are typically failures that can be detected by automatic self-testing, while DU and SU failures remain hidden and can only be detected by function testing or on demand (Rausand & Høyland, 2004). Dangerous failures of production- and safety critical valves can be understood as valve failures that pose a great safe risk to operation and that prevents the valve from performing its safety barrier function as opposed to safe valve failures which can be considered non-critical or spurious failures. (OLF, 2004) Safety critical valves can be assumed to function as safety barriers as long as DU failures are not present (Rausand & Høyland, 2004).

3.2 Failure modes related to production- and safety critical valves

A failure mode describes how a fault, which is a certain state that results from a failure, can be observed (Rausand & Øien, 1996). The main failure modes of safety critical valves are (based on Lundteigen & Rausand, 2007; Rausand, 2014; OREDA, 2002):

- FTC - Failure to close on demand
- DOP - Delayed operation (valve closes too slowly)
- LCP - Internal leakage in closed position
- ELP - External leakage in closed position
- SPO - Spurious operation (valve closes unexpectedly)
- FTO - Failure to open on demand

These are all failure modes that can be considered as undetected failures of safety critical valves. According to ISO 14224 (2006) the failures modes FTC, DOP and LCP can be considered critical failures. In OREDA (2002), which contains historical failure data for offshore equipment such as safety critical valves, failures are divided into the three severity classes critical, degraded, and incipient independent of the failure mode. For failure data presented in the handbook for safety critical valves the failures that relate to e.g. the failure modes DOP and LCP are sometimes classified as degraded or incipient. Degraded and incipient failures could be considered as non-critical failures when they do not immediately prevent the valve's ability to perform its safety function (ISO 14224, 2006). Based on this it is necessary to evaluate the severity and potential safety risk related to the valve failures reported in Gassco's test results.

3.3 Failure mechanisms of production- and safety critical valves

Production- and safety critical valves are exposed to many failure mechanisms that can degrade their performance and result in the failure modes mentioned in section 3.2. It is important to pinpoint that these failure modes do not necessarily relate to failures that originate from the valves themselves – the failures may originate from other parts of the ESD system such as solenoid valves, power supply, sensors, or logic system to name a few. In the following typical failure mechanisms that will degrade safety critical valves (including the actuators) used in gas pipelines over time under normal operational are discussed.

3.3.1 Wear and corrosion

External corrosion on the surface of the safety critical valves operated by Gassco is in general not a problem because they are located on land or topside, and because of their robust design. Due to the clean gas flowing through the pipelines and valves, internal corrosion of the valve body, disc, and seats is usually also considered a minor problem. The particles that could occur in the gas flow are in general so small that the damage caused by erosion and wear to the valves is very limited. (Hoff, 2015)

However, it is important to avoid corrosion of the valve's stem, especially for slab gate valves with rising stems. The upper part of the stem is in contact with air which makes it exposed to corrosion. The stem is covered by a corrosion protective layer, but weather conditions such as wind blowing small particles like sand and dust could cover the stem and create problems. If these particles are carried up and down by the stem they could wear and tear off the protective layer and expose the upper part of the valve stem to pitting corrosion. In the worst case particles (such as sand or rust) following the stem movement can cause damage to the stuffing box and packing material inside and cause it to blow out, thus making the valve susceptible to external leakage. (Hoff, 2015)

Another possible corrosion problem may be related to the grease plugs and other plugs used in safety critical valves. Especially the plugs of the older type from the early 1970s that were made of black steel, and that still are present in some of the older valves, are inclined to corrode compared to newer types of plugs today. Furthermore plugs that are screwed straight into the valve body are especially susceptible to corrosion, and need to be carefully looked after since replacement costs of these plugs can be very high. However, these plugs must be replaced from time to time, as corrosion of the plugs could potentially cause gas leakages. (Hoff, 2015)

3.3.2 Blockage

A problem that could occur from time to time is related to the compressor that is used to pressurize the gas in the pipeline. The compressor can sometimes leak oil that has the tendency to allocate on the valve's sealing surfaces. This could potentially block and prevent the sealing mechanisms of the seats and cause internal leakage. (Hoff, 2015)

Hydrate formation is another problem that could occur and potentially prevent the valve from opening and closing properly. These hydrates are formed when the gas in the pipelines are in contact with water under relatively low temperatures and appear as solid ice-like blocks. (OLF, 2013) Water is not present in the gas pipeline during normal operations. Even so, water is sometimes used in certain maintenance operations related to the safety critical valves and gas pipelines. Though the valves are full bore and thus have the same opening diameter as the pipelines, there is in practice a slight increase in the opening diameter in the valve's cavity. (Hoff, 2015) When gas and water flow across the valve, then the valve will act as a water separator because the pressure and temperature are lower in the cavity due to the slight difference in opening diameter. As a result water could accumulate in cavity and form hydrates. For normal-acting slab gate valves this could potentially block the gate from closing entirely. (Hoff, 2015; OLF, 2013)

3.3.3 Chemical degradation

A MEG (mono ethylene glycol) inhibitor is sometimes injected into the gas pipelines to dissolve hydrate formation. Certain valve materials such as PTFE and rubber, which are used in e.g. seats and stem packing, are vulnerable to degradation from such chemicals. (Hoff, 2013; OLF, 2013) This could again weaken the sealing solutions (seats or stuffing box) and lead to leakages. However, to encounter these problems heating cables may be used instead of MEG injection to dissolve hydrate formations (OLF, 2013).

3.3.4 Fatigue

The gas flow passing through the pipeline and safety critical valves is usually laminar under normal operation (OLF, 2013). However, the pressure inside gas pipeline and valves is high, and the valve and actuator could suffer from fatigue damage due to persistent strain and repeated function testing and leak testing over time. The valves are exposed to variations in pressure, loads and temperature over time that could lead to fatigue damage. In order to reduce the risk of fatigue damage of the valve, it is desirable that the valve is not closed or opened too fast during function testing and that the pressure is not lowered too fast during leak testing. (Hoff, 2015)

4. Testing of production- and safety critical valves

In this chapter function testing of safety critical valves and its importance is explained. Different testing methods for detecting "hidden" and dangerous failures related to the failure modes FTC, DOP, and LCP are then described, along with a presentation of two valve condition monitoring systems that could be used to support testing of valves. The contents of this chapter will later be used as a basis for discussing the results of the analysis of the performance of Gassco's safety critical valves, as well as for possibilities of improving the existing testing regime.

4.1. Functional testing of production- and safety critical valves in general

As mentioned in section 1.2 it is required that safety critical valves used in gas pipelines are able to execute their barrier function to shut off the gas flow and prevent escalation when demanded. To ensure this it is necessary to have routines for testing as part of the overall maintenance program. Possible DU failures of safety critical valves related to the failure modes FTC, DOP and LCP could remain hidden if routines for functional testing are not in place in addition to other preventive maintenance activities (e.g periodical inspections, condition monitoring, planned replacements of parts etc.). Because these valves rarely close due to low demand, functional testing is needed in order to confirm that their barrier function is working as required, and also to reveal possible hidden failures that could prevent the valves and related ESD system from executing their barrier functions on demand (OLF 2004; Rausand, 2014).

Function testing must according to OLF 070 (OLF, 2004) involve testing of the whole loop of the ESD system, not just the safety critical valves. The closing function of a valve is tested all the way from when you first push the manual ESD button to activate the ESD system until the electronic ESD signal reaches the solenoid valves and actuator unit that force the safety critical valve to move to closed position.

The tests of production- and safety critical valves included in Gassco's testing regime are (Hoff, 2015):

- Full stroke test (FST)
- Partial stroke test (PST)

- Internal leak test
- External leak test
- Visual inspection

However, Gassco's test results only include results from testing of the closing function and measurements of closing times and internal leak rates. Therefore this chapter will limit the focus to describing FST, PST, and internal leak testing.

4.2 Full stroke test (FST)

Full stroke testing (FST) is a full function test of the barrier function. The test involves complete testing of the closing and opening function of the valve. (Metso, 2010) Important test parameters that are measured include closing time, actuator pressure and break out torque/thrust needed to move the valve. Internal leak testing is typically performed as a part of FST while the valve is in closed position.

Gassco performs FST once a year (Hoff, 2015). It is generally recommended that FST is supplemented by PST in order to satisfy the performance requirements set for safety critical valves. (Summers & Zachary, 2000)

4.3 Partial stroke test (PST)

Partial stroke testing (PST) is an alternative function testing method that is recommended as a supplement to FST. PST is normally carried out with shorter test intervals than for FST. Gassco's test interval for PST is every 6 months (Hoff, 2015). PST involves partial closing and opening movement of the valve - typically 10-20% (Metso, 2010) preferably in a non-repeating pattern to limit wear of the valve disc (Hoff, 2015).

An advantage of PST is that it may give an opportunity to extend the testing intervals for FST as it improves the PFD_{Avg} value. (Rausand, 2014) However, it is generally not recommended that PST fully replaces FST as it can typically only detect 60-70% of the DU failures covered by FST (based on Lundteigen & Rausand, 2007; Summers & Zachary, 2000). The PST coverage of different failure modes related to safety valves may be considered as the following (Lundteigen & Rausand, 2007):

- 100% for delayed operation
- 20% for external leakage
- 95% for fail to close on demand
- 0% for internal leakage in closed position

Different technologies exist for PST of safety critical valves. Summers and Zachary (2000) describes three different methods that can be used for PST:

- Mechanical limiting devices
- Position control
- Solenoid valve control

Mechanical limiting devices used for PST of valves typically include custom-made devices such as jacks, jammers and collars that are used to limit the movement of a valve during opening and closing (Summers & Zachary, 2000). However, this PST method is not a preferred by Gassco (Hoff, 2015).

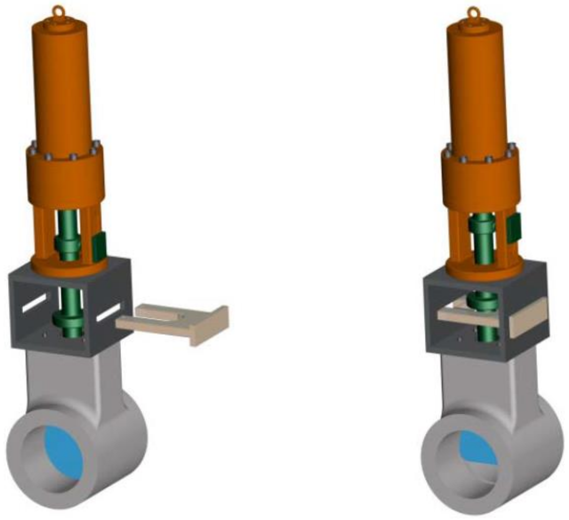


Figure 13: Example of a mechanical limiting device (Cameron, 2011)

PST with position control is a method which involves installing a positioner on the valve to control its movement to a certain point when opening and closing. Both conventional and smart positioners are available. The smart positioners can be remote controlled and configure automatically to the valve, while conventional positioners are controlled and configured manually. (ABB, 2012) While conventional positioners have to be supplemented with e.g. a position transmitter or limit switch to confirm if the PST has been successful (Summers & Zachary, 2000), certain smart positioners are capable of continuously collecting and logging data and diagnostics during the PST. (ABB, 2012) Gassco requires that all new ESD valves are equipped with positioners (Hoff, 2015).

The third PST method involves the use of solenoid valves where the partial movement of the valve is based on the timing the electrical pulsing of solenoid valves. The principle is that the valve begins moving to closed position when the solenoid valve starts pulsing and returns to open position when the timed pulsing stops. Usually a position transmitter or limit switch is used to confirm if the PST has been successful. (Summers & Zachary, 2000) Two different ways of implementing this method are either to integrate PST with the ESD system or to use a separate PST package that may require the use of an additional solenoid valve (Lundteigen & Rausand, 2007). The two solutions for PST using solenoid valves are illustrated in Figure 4.

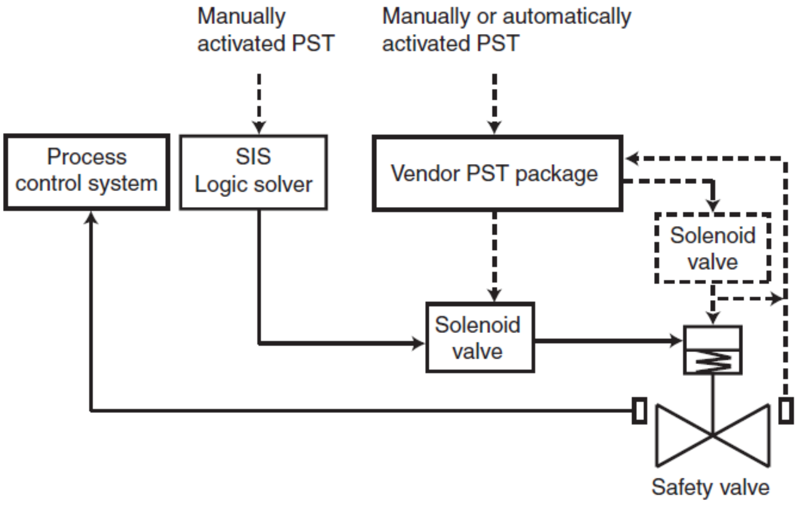


Figure 14: Solutions for PST with solenoid valves (Lundteigen & Rausand, 2007)

4.4 Internal leakage test

Internal leak testing of safety critical valves is as mentioned in section 4.2 executed together with FST, which is once a year. Leak testing is done when the valve is closed position, and typically involves either pressure testing or acoustic measurement. Gassco requires a minimum waiting time of 15 minutes after closing of the valve and lowering of the pressure before measuring the internal leak rate. This is considered the time it takes for the internal leak rate to gradually decrease and stabilize on a certain level, i.e. the “true” value. Furthermore maximum allowable rate for lowering of pressure is 3 bar per minute. (Hoff, 2015) Some of the important parameters for internal leak testing include the testing time, and the pressures, temperatures, volumes, and noise/vibrations related to the gas flow across the valve.

4.4.1 Pressure testing

Pressure testing is based on the principle of differential pressure that pressure from a highly pressurized area will try to find a way to escape to an area where the pressure is lower. Pressure testing is typically carried out in form of either a full valve leak test with full differential pressure over the valve or a through cavity leak test. Pressure testing can for some valves be done by sealing off a section of a known volume of the downstream pipeline. The full valve test typically involves measurement of either the pressure build-up or pressure decay in the downstream pipeline section, while the through cavity leak test measures the pressure build-up or decay in cavity when either the upstream side or both upstream and downstream sides are pressurized. The through cavity leak test can be carried out for valves that have active floating seats both on the upstream and downstream side so that the valve is sealed on both sides. The internal leak rate measured will then combine the leakage through both the upstream and downstream seats, and it may be difficult to know which side contribute the most to the total leakage. A manometer (differential pressure sensor) is typically used to measure the pressure build-up or pressure decay. (Gassco, 2011b; Hoff, 2015)

4.4.2 Acoustic measurement

Another internal leak testing method used by Gassco is acoustic measurement (Hoff, 2015). Acoustic measurement for internal leak testing is typically carried out using the acoustic emission (AE) measurement method. The AE measurement, similar to pressure testing, requires differential pressure across the valve (Gassco, 2011b). In principle AE measurement involves using acoustic emission (AE) sensors (either handheld detector devices or installed sensors) to detect acoustic signals emitted from possible turbulence in the gas flow due to internal leakage. Turbulence in a gas flow can be related to the Reynolds number, where turbulence equivalent to a Reynolds number value in the range of 1000-10000 typically produce an acoustic emission (Kaewwaewnoi, Prateepasen & Kaewtrakulpong, 2005).

The AE equipment is usually configured to detect acoustic signals within a certain high frequency range in order to filter out most of the unwanted background noise. However, in order to ensure that the location and measurement of the internal valve leakage is correct and accurate the AE sensors should be positioned on different locations on the valve body and on the upstream and downstream side. (Score Group, 2015)

4.5 Valve condition monitoring as supplement to testing

As supplement to the tests that are described in section 4.3 and 4.4 it is possible to use condition monitoring systems periodically to monitor the test parameters during testing of production- and safety critical valves. Typical parameters that could be important for Gassco to monitor during testing of their production- and safety critical valves include valve movement and position, closing and opening times, actuator and accumulator pressure, stem force (break out torque/thrust), and internal leak rate in closed position (turbulence, pressure, temperature, and gas flow rate).

Condition monitoring could also be used on continuous basis to ensure safe operation of the valves and ESD system, and alert the operators whenever the valves need to be tested or maintained. The need for human interaction might be reduced because the need for testing and maintenance could be reduced. This could again reduce the safety risk exposure of the testing personnel. For Gassco it is important that the condition monitoring systems are able to alert of possible failures of the production- and safety critical valves at an early stage before failures occur. (Hoff, 2015) This could give Gassco the opportunity of predicting when it is necessary to test the valves. It is also important that the condition monitoring system is able to alarm the control room operators if valve failures do occur and that it gives them an opportunity to troubleshoot the valves where failures have been detected. In this way the control room operators can inform the maintenance personnel of which valves that have failed and what actions that needs to be done.

Today, a variety of systems and solutions exist for valve condition monitoring. Two examples of valve condition monitoring systems that can be used to support testing of safety critical are V-MAP delivered by Score Group and ValveWatch delivered by Solberg & Andersen AS.

These systems can monitor and log typical test parameters such as (based on Score Group, 2011; Juvik et al, 2002):

- The valve movement during testing of closing function. A position transmitter is then installed to indicate if the valve is in open, closed, or partially open position.
- The internal leak rate during internal leak testing of the valve in closed position. These systems use AE sensors for leak detection. ValveWatch can also be installed with differential pressure sensors for leak detection. The sensors are installed on the upstream and downstream side and on cavity for both systems. The sensors compare the pressure fluctuations or sound coming from cavity and the upstream and downstream sides to detect leakage. If the sounds correlate then the valve is leaking.
- The break out torque/thrust needed to close and open the valve during testing. Strain gauges are for both systems installed at the actuator yoke to measure the stem force.
- The actuator pressure (either hydraulic or pneumatic). Pressure transmitters are installed on the actuator to measure the hydraulic or pneumatic input force to the actuator.

For both systems a data acquisition unit (DAU) is used to collect the data from all the sensors. The DAU sends the collected data back to a control room server where it is stored. A computer with V-MAP or ValveWatch software installed is then used to analyse the data. Both the V-MAP and ValveWatch software can be used for data trending and comparison to previous measurements (see Juvik et al, 2002; Score Group, 2011). The software checks the analysed valve data against predetermined acceptance criteria, and alerts the control room operators if any valves fail to meet the acceptance criteria. (see Solberg & Andersen, 2011; Score Group, 2011)

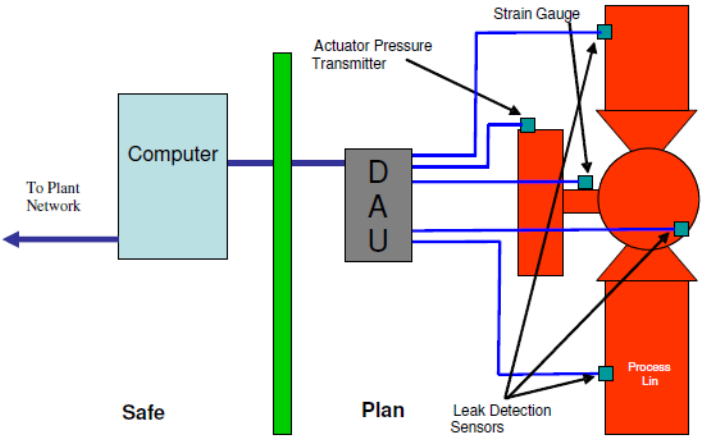


Figure 15: Illustration showing how the V-MAP system works (Hale, 2011)

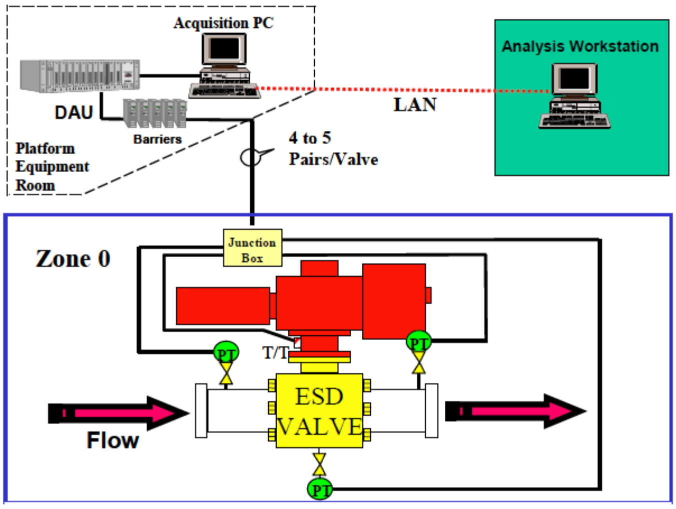


Figure 16: Illustration showing how the ValveWatch system works (Hale & Seatter, 2006)

Today, both V-MAP and ValveWatch are installed at platforms and plants all over the world, and in most cases the experience from users of these systems seem to be positive (see Hale & Seatter, 2006; Hale, 2011). Though, there has been reported some issues related to the use of such systems due to power outages and clogging of sensors (Hale & Seatter, 2006).

Some of the benefits that could be worth mentioning of using such valve condition monitoring systems could be that they can:

- Monitor and log certain parameters such as actuator pressure, stem force, and pressures on a continuous basis in order to detect possible degradation and failures of valves at an early stage. (Hale, 2011)
- Measure the internal leak rate when a valve is in closed position automatically by using the AE sensors or differential pressure sensors without the need for human intervention. (Hale, 2011)
- Track the valve movement and log the time elapsed for closing and opening of a valve during FST or PST. The actuator pressure and break out torque/thrust needed for valve movement is logged at the same time in order to indicate possible cause of delays in the closing and opening times.
- Collect data from all sensors during testing of a valve and compare it to acceptance criteria. Possible irregularities are then detected and analysed in order to locate the source of the problem.
- Detect possible failures of a valve or actuator that may occur in between the testing intervals.

- Provide reports and trending of the data received from the sensors that can be used for further analysis and possible improvement of the testing regime and maintenance program.

5. Background for analysing test results

In this chapter the reported test results and related acceptance criteria are presented, followed by a literature study in order to find quantitative methods that could be relevant for failure rate estimation, updating of PFD, and updating of the test interval for the valves represented in Gassco's test results.

5.1. Reported test results

The basis for evaluating the testing routines and overall performance of the production- and safety critical valves operated by Gassco in this thesis is the reported test results. The data includes test results for a total of 100 valves covering the years from 2007 till 2014. The valves are located on land or above sea level on installations and plants across Northern Europe. As mentioned in section 2.3 the valves used are of the following types; trunnion ball valves, slab gate valves and double expanding gate valves. Most of the valves are of the trunnion ball type. For some of the valves reported there is given no information about the valve type, and they are considered in this thesis as an unknown type.

The collection of valves are of different dimensions (some < 10"), though the majority of them comprise large valves that are in the range 30" to 42". As mentioned in section 2.2, the valves are categorized as either ESD or PSD. PSD valves are generally considered less safety critical because they are placed further upstream in the pipeline system and support the ESD valves. The majority of the valves represented in the test results are ESD valves. However, for 20 of the 100 valves in the reported test results it is unclear whether they are categorized as ESD or PSD valves based on the information given in the test results. Similarly for 4 of the valves in the test results no information is given of the valve type which means they could be either a ball or gate type valve. For 2 of the 4 valves just mentioned neither valve type is known nor if they are ESD or PSD.

All reported test results are based on annual FST and internal leak tests. The test results cover tests of closing function and measurements of closing times and internal leak rates. For most of the valves test results from all tests have been included, except for results from 2007 that are missing for many of the valves.

It is also important to note that not all the valves show results for all the type of tests and all the years from 2007 to 2014. Limited information is given for why the results are missing for a fraction of these valves, though for some it is reported that they have not been tested.

5.2 Risk acceptance criteria

Gassco has specific risk acceptance criteria concerning test of closing function and measurements closing times, and internal leak rates. The most critical failure mode is considered by Gassco to be FTC (Hoff, 2015). Therefore the test of closing function is either acceptable or unacceptable. This is also the acceptance criteria for external leakages, but results for these failure modes are not included in the reported test results. Acceptance criteria related to measurements of closing times and internal leak rates are classified as acceptable, tolerable, or unacceptable based on the ALARP (As low as reasonably practical) principle (see NORSOK Z-013, 2010):

- Unacceptable risk (red) – the safety risk is at an unacceptable level and repair is needed immediately
- Tolerable risk (yellow) – the safety risk is tolerable, but further evaluation and planning to repair needs to be done in order to lower the risk to as low as reasonably practical
- Acceptable risk (green) - the safety risk is at an acceptable level

General acceptance criteria given by Gassco for the valves represented in the test results are shown in tables 3 – 5. Though, it is worth mentioning that these are general acceptance criteria and do not apply for all of the valves. All valves are considered safety critical with respect to closing function, but the acceptance criteria shown for closing times and internal leak rates only apply for the ESD valves (Hoff, 2015). Also, certain ESD valves have somewhat stricter or more relaxed acceptance criteria for closing times and internal leak rates. For instance, certain ESD valves have an unacceptable limit for internal leak rate of >0.1 kg/s or >1.0 kg/s (Gassco, 2011b).

Table 3: Acceptance criteria for closing function of safety critical valves (Gassco, 2011b)

Closing function	General acceptance criteria	
	Acceptable	Unacceptable
	Able to close on demand	Unable to close on demand

Table 4: Acceptance criteria for closing times of ESD valves (based on Gassco, 2011b; Hoff, 2015)

Closing time (in seconds)	General acceptance criteria		
	Acceptable	Evaluation	Unacceptable
	≤ 2 sec per inch of valve diameter + 10%	2 sec per inch of valve diameter + 10% - 20%	> 2 sec per inch of valve diameter + 20%

It is recommended in NORSOK S-001 (2008) that acceptable closing time for ESD valves should not exceed 2 sec per inch of valve diameter. Risk assessments of the respective valves may however give more thorough evaluations of the safety risk related to the closing times. As seen in table 3 Gassco has assessed that the closing time can be considered acceptable if it does not exceed 2 sec per inch of valve diameter + 10%, and unacceptable if it exceeds 2 sec per inch of valve diameter + 20%. This means that the closing time for a 30” valve is acceptable it does not exceed 66 sec. A closing that is 10% to 20% higher than 66 sec can be considered tolerable but a further evaluation is needed to plan for repair.

Furthermore closing times that are reported lower than 1 second per inch of valve diameter are generally considered undesirable and too fast, as it may inflict damage to the valve (Hoff, 2015).

Table 5: Acceptance criteria for internal leak rates of ESD valves in closed position (based on Gassco, 2011b; Hoff, 2015)

Internal leak rate in closed position (in kg/s)	General acceptance criteria		
	Acceptable	Evaluation	Unacceptable
	≤ 0.05 kg/s	0.05 kg/s - 0.2 kg/s	> 0.2 kg/s

As shown in table 4 internal leak rates are acceptable if they are lower than 0.05 kg/s for most ESD valves, but could be considered tolerable as long as the internal leak rate does not exceed 0.2kg/s. Similar as for closing times, an evaluation is needed to plan for repair if the internal leak rates are above the acceptable limits.

5.3 Literature study of relevant methods

In the following, literature of methods for updating and estimating failures rates, PFD, and test interval are discussed.

5.3.1 Methods for updating of failure rate

Methods for estimating and updating failure rates of valves are presented in OREDA (2002), OLF 070 (OLF, 2004), and Hauge and Lundteigen (2008). They all present methods for failure rate estimation based solely on operational data for a homogeneous sample of components (i.e. components that have identical functions and operate under the same environmental and operational conditions). Furthermore the methods presented are based on the assumption that the failure rate is exponentially distributed and thus constant in time. Hence it is assumed that all components are in the useful life phase of the bath tub curve (OREDA, 2002). The equation based on operational data of homogeneous components presented in OREDA (2002), OLF 070 (OLF, 2004), and Hauge and Lundteigen (2008) are very similar, only with different denotations. However, the equation shown in OLF 070 (OLF, 2004) differs from the other two as it takes into account the total time of the test intervals of all components, while OREDA (2002) and Hauge and Lundteigen (2008) takes into account the total observed time in operation of all components. The uncertainty of the failure rate estimate based on operational data is expressed in OREDA (2002) and Hauge and Lundteigen (2008) in form of a 90% Chi-squared (χ^2) confidence interval.

The uncertainty related to failure rate estimates that are only based on operational data can potentially be high, especially if the operational data basis is limited. Due to this methods based on Bayesian estimation of failure rates that combine the operational data with prior knowledge and expert judgements have been proposed by OLF 070 (OLF, 2004) and Haugen and Lundteigen (2008). The prior knowledge is expressed as a best failure rate estimate from design and a conservative failure rate estimate from design that expresses the uncertainty of the best failure estimate from design. The resulting failure rate estimate that combines prior knowledge with operational data is assumed to be gamma distributed. Here it is assumed that the lifetimes of the components are exponentially distributed, and that the prior distribution expressing the prior knowledge is gamma distributed. This gives a gamma posterior distribution that combines the prior knowledge and operational data. The resulting failure rate estimate mentioned above is thus the expectation of this posterior distribution. Except for slightly different denotations of the parameters the procedures presented in OLF 070 (OLF, 2004) and Hauge and Lundteigen (2008) are quite similar in terms of estimating failure rate.

OREDA (2002) also presents a different method for failure rate estimation that can be used if we have non-homogeneous samples of components that are assumed to be exponentially distributed. By following this method all components are sorted into multiple homogeneous samples. The variation between the samples is measured, and then an average failure rate estimate is derived based on all these samples. If there is no variation (or negative value of the variation) between the homogeneous samples, then the estimated failure rate using the multi-sample method will be equal to the failure rate estimate for a homogeneous sample of components.

5.3.2 Methods for updating of PFD

Various methods can be used to estimate the PFD contribution of the different components of an ESD system that are in accordance to IEC 61508 and IEC 61511.

In OLF 070 (OLF, 2004) simple and conservative equations are presented for updating and estimation of PFD. OLF 070 refers to many equations found in the PDS handbook. The suitability of equations presented is dependent on the redundancy of the given components. A β-factor is included in the equations for redundant components to take into account the fraction of common cause failures (CCF) shared between the channels of redundant components. This β-factor is therefore not included in the equation for non-redundant components. As a minimum OLF 070 (OLF, 2004) requires that the PFD shall be estimated based on DU random hardware failures, but preferably also include DD failures. Also, additions to the equations are proposed that also quantify the systematic failures (i.e. a PFS value - probability of systematic failure) and downtimes due to repairs. The equations presented assume perfect tests with 100% detection coverage.

Rausand (2014) presents an alternative PFD equation where it is assumed imperfect tests with less than 100% detection coverage. This means that not all DU failures are expected to be detected in each test. The fraction of DU failures that are not detected by tests is assumed to be covered and repaired during each overhaul interval.

Lundteigen and Rausand (2007) discuss the effects that PST could have on PFD when used as supplement to FST for safety valves. The equation presented here assumes that PST is imperfect testing due to the fact that the test fails to detect all dangerous valve failures as mentioned in section 4.3. Therefore the detection coverage is set as a fraction of the detection coverage of FST. The equation includes FST, PST and the diagnostic tests, though the diagnostic test interval is often considered so short that it can be neglected (Lundteigen & Rausand, 2007).

5.3.3 Methods for updating of test interval

Both OLF 070 (OLF, 2004) and Hauge and Lundteigen (2008) present procedures that can be used for updating the test intervals of safety critical valves. The procedure presented in OLF 070 (OLF, 2004) is simply to check how changing the test interval affects the estimated PFD of the given component. Based on a comparison between the estimated PFD and the acceptance criteria set for PFD one can consider whether to change the test interval or not. If the results show that an increase of the test interval is acceptable OLF 070 (OLF, 2004) mentions that the total increase should not exceed 50% or be more than 0.5 year. Furthermore up to a 10% increase in the PFD value due to change of test interval could be accepted.

In Hauge and Lundteigen (2008) two different quantitative procedures for updating of the test interval of safety critical valves are presented. The first method is quite simple and is restricted to either halving or doubling the existing test interval, while the other method is more flexible and allows for smaller adjustments of the existing test interval. Unlike OLF 070 (OLF, 2004) the two procedures presented in Hauge and Lundteigen (2008) for updating of the test interval are not based on PFD. Hauge and Lundteigen (2008) further recommend that the quantitative methods are supported by qualitative evaluation before changing the test intervals.

6. Chosen procedure for analysis of test results

The literature study and Gassco's criteria together with limitations in the test results are the basis for how the test results given by Gassco are evaluated. The steps followed in this solution strategy are mainly based on the procedures presented in OLF 070 (OLF, 2004) and Hauge and Lundteigen (2008).

6.2.1 Determination of DU failures

In order to determine the number of failures based on Gassco's test results the risk acceptance criteria given by Gassco for the failure modes FTC, DOP, and LCP are used (see section 5.2). Since there is little information given in the test results of the reasons for high measurements of closing times and internal leak rates it is assumed that all failures are caused by the valves. Due to lack of information about the probability and consequences of each failure reported in the test results it is assumed that the measurements that exceed the unacceptable limits of Gassco's risk acceptance criteria are DU failures, while measurements that are within the tolerable evaluation limits or acceptable limits are safe. Furthermore measurements that are reported in the test results as "Not OK" but where the measured value is missing are considered unacceptable and therefore counted as DU failures.

6.2.2 Estimation of failure rate

Failure rates for the valves operated by Gassco are assumed to be exponentially distributed and constant in time. This means that all valves are assumed to be in the useful life phase of the bath tub curve, as mentioned in section 5.3.1. Gassco considers all valves represented in the test results as one homogeneous group of valves as they all have the same safety function which is to shut off the gas flow. The valves are also considered to operate under similar operational and environmental conditions.

The failure rate based on DU failures from the test results for a homogeneous sample of valves can be expressed as (based on OREDA, 2002; Hauge & Lundteigen, 2008):

$$\hat{\lambda}_{DU} = \frac{x}{t_n} \qquad (1)$$

The factor x is here expressed as the total number of DU failures for all valves. t_n ($= n \cdot t$) is here the total observed time in operation t for n number of valves. Due to lack of information the calendar time is used. Hence downtime due to testing and maintenance are not included in the calculation.

The uncertainty in the failure rate estimate is expressed using a Chi-squared 90% confidence interval is used (based on OREDA, 2002; Hauge & Lundteigen, 2008):

$$\left[\frac{\mathrm{Z}0.95{,}2n}{2\tau}, \frac{\mathrm{Z}0.05{,}2(n+1)}{2\tau}\right] \qquad (2)$$

The Z0.95,ν and Z0.05,ν represent the upper 95% and 5% percentiles respectively with ν degrees of freedom. The values of these can be derived using Chi-squared formulas in Excel. With the 90% confidence interval the probability is 90% that the confidence interval covers the true failure rate value.

If few failures are observed or the test results are considered uncertain, the failure rate estimate based on the test results could be combined with prior knowledge. It is considered if the failure rate estimate based on test results should be combined with prior knowledge. This prior knowledge is expressed as an assumed failure rate from design λ_{DU}. $\lambda_{DU} = 2.0 \cdot 10^6$ is derived from table A.1 in OLF 070 (OLF, 2004). The uncertainty of the failure rate from design is reflected using a conservative failure rate $\lambda_{DU\text{-}CE}$ which is assumed to be $2 \cdot \lambda_{DU}$ (based on Hauge & Lundteigen, 2008). $\lambda_{DU\text{-}CE}$ reflects the weight that is put on the prior knowledge in the combined failure rate - the higher the value of $\lambda_{DU\text{-}CE}$ compared to the λ_{DU}, the less weight is put on prior knowledge.

As mentioned in section 5.1 Bayesian estimation is used to derive the failure rate combining prior knowledge and test results. The combined failure rate is gamma distributed and is expressed as (based on Hauge & Lundteigen, 2008; OLF, 2004):

$$\ddot{\lambda}_{DU} = (\alpha + x) / (\gamma + t_n) \qquad (3)$$

The parameters α and γ reflect the contribution and weight put on the prior knowledge, while the x and t_n reflect the contribution and weight that is put on the test results. α and γ in equation 3 are expressed as (based on Hauge & Lundteigen, 2008; OLF, 2004):

$$\alpha = \lambda_{DU} / [\lambda_{DU\text{-}CE} - \lambda_{DU}]^2 \qquad (4)$$

and

$$\gamma = \alpha \cdot \lambda_{DU} \qquad (5)$$

6.2.3 Updating the PFD

The probability of failure on demand (PFD) for a valve can be understood as the as its safety unavailability (Rausand & Høyland, 2004):

$$\text{PFD} = \frac{1}{\tau}\int_0^{\tau} \bar{A}\,(t)dt = \frac{1}{\tau}\int_0^{\tau} F\,(t)dt \qquad (6)$$

In this analysis PFD is used as the performance indicator for the valves in Gassco's test results. The target PFD is set to 1%, which corresponds to the minimum requirement for SIL2. Because the test results only include information about the valves in general and not the components of the ESD system or SIFs, it is assumed for simplification that the valves alone cover the SIL of the ESD system or SIF. This is based on the assumption given in section 6.2.1 that all detected DU failures are regarded as valve failures.

The failure rate estimate derived using the equations from section 6.2.2 are used to update the PFD of the valves. The valves are conservatively assumed to be non-redundant (1oo1) and the test interval τ = 8760 hours because Gassco carries out FST and internal leak tests annually as mentioned in section 5.1. Due to the assumption of non-redundant valves the β-factor expressing CCF is not included in the PFD estimation equation.

The PFD based on annual FST and internal leak tests are used in the evaluation of Gassco's test results. It is assumed perfect testing and 100% FST coverage of DU failures. Hence the valves are assumed to be as good as new between each test. For 1oo1-voted valves the PFD can be calculated using the following equation when $\lambda_{DU} \cdot \tau$ is small (see OLF, 2004; Rausand & Høyland, 2004):

$$\text{PFD} \approx \lambda_{\text{DU}} \cdot \frac{\tau}{2} \qquad (7)$$

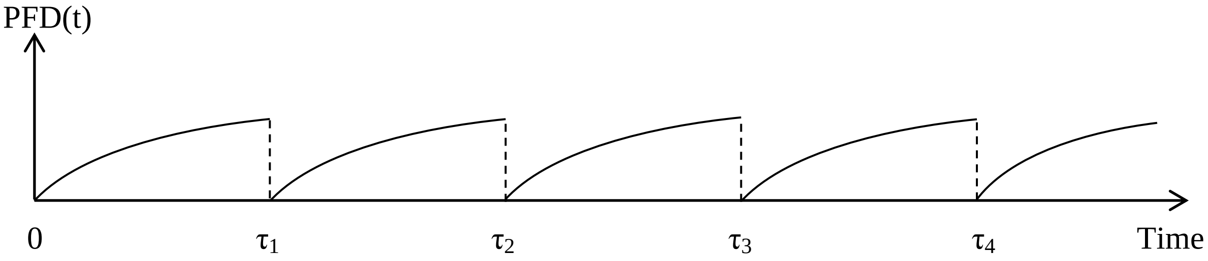


Figure 17: PFD with perfect testing

Gassco also carries out PST of the valves every 6 month, in addition to annual FST (Hoff, 2015). The possible effect that PST could have on the PFD of Gassco's valves when used as supplement to FST is evaluated. Different PST test intervals are evaluated; τ_{PST} = 1 month, 2 month, 3 month, 6 months. The PST coverage of DU failures is assumed to be θ_{PST} = 60%. This PST coverage fraction is derived from Lundteigen and Rausand (2007). As mentioned in section 4.3 this is because PST fails to detect all the potentially dangerous and hidden failure modes covered by PST, such as LCP. It is assumed that the diagnostic test interval is so small that it is negligible. The equation used to calculate PFD when PST is taken into account is thus (based on Lundteigen & Rausand, 2007):

$$PFD \approx PFD_{FST} + PFD_{PST} = (1 - \theta_{PST}) \cdot \lambda_{DU} \cdot \frac{\tau_{FST}}{2} + \theta_{PST} \cdot \lambda_{DU} \cdot \frac{\tau_{PST}}{2} \qquad (8)$$

Only DU failures are taken into consideration in equation 7 and 8. This means that MTTR (mean time to failure) and systematic failures (PSF) is not included in the calculation.

6.2.4 Updating of test interval

In order to evaluate the length of the test interval quantitatively different approaches are considered. Firstly the updated PFD with the current test interval is compared against the target PFD = 1%. The updated PFD is considered acceptable if it is lower than the target PFD, though as a minimum a calculated PFD value lower than 1.1 times the target PFD may be considered acceptable (OLF, 2004).

Secondly the two approaches presented in Hauge and Lundteigen (2008) for evaluating the test interval are considered. The first approach considers only halving or doubling the current test interval. Here the estimated failure rate based on Gassco's test results, $\hat{\lambda}_{\text{DU}}$, and related 90% confidence interval is compared to the assumed failure rate from design, λ_{DU}:

- If $\hat{\lambda}_{\text{DU}} < \frac{\lambda_{DU}}{2}$ and the Chi-squared 90% confidence interval for $\hat{\lambda}_{\text{DU}}$ below λ_{DU} then test interval τ can be considered doubled.
- If $\hat{\lambda}_{\text{DU}} > 2 \cdot \lambda_{DU}$ and the Chi-squared 90% confidence interval for $\hat{\lambda}_{\text{DU}}$ above λ_{DU} then test interval τ can be considered halved.

The second approach considered takes into account the λ_{DU}, the current test interval $\tau = 12$ months, and the failure rate combining Gassco's test results with prior knowledge $\ddot{\lambda}_{DU}$. The equation used for the updated test interval is expressed as (Hauge & Lundteigen, 2008):

$$\ddot{\tau} = \frac{\lambda_{DU}}{\ddot{\lambda}_{DU}} \cdot \tau \qquad (9)$$

The calculated $\ddot{\tau}$ is rounded down to the first allowable test interval (i.e. either every 1, 3, 6, 9, 12, 18, 24, or 36 months).

7. Analysis of valve performance and test interval

In this chapter the overall performance and the test intervals of the valves will be looked upon. Evaluating if the test intervals used are sufficient or done often enough to ensure safe performance of the valves will be considered. Considering if the test interval should be prolonged and still meet the SIL requirements might reduce costs for Gassco, while tests done more frequent might result in increased costs. The registered testing results are categorized into three groups – acceptable (no maintenance needed), tolerable (safe, but maintenance should be considered) or unacceptable (dangerous failure, maintenance must be done).

7.1 Quantifying failures in the test results

In general little information is provided in the reported test results of the causes of the slow closing times or high internal leak rates, though for failures to close it has been reported that they are due to failures of the HPU (hydraulic power unit). All the DU failures reported in the test results are therefore for simplification assumed to be caused by the valves as mentioned in section 6.2.1, even though some of these failures could possibly be related to other components such as the actuator, solenoid valves, or other parts of the ESD loop.

The registered measurements for the 100 production- and safety critical valves in the test results have been checked against Gassco's risk acceptance criteria. The detailed results of this work are shown in appendix A. In all, a total of 706 tests of the closing function are registered for the valves during the period from 2007-2014. Most of the results that have not been registered or missing during this time period are from 2007, as mentioned in section 5.1. The closing times of the valves are registered in 674 of the 706 tests. Similarly measurements of internal leak rates of the valves are registered in 681 of the 706 tests.

Time has been spent during the work on this thesis to gather important test results and related information about the valves, and to check these up against Gassco's risk acceptance criteria. Test results that indicate that a valve has failed to close are considered DU failures. This is also considered the most critical valve failure mode to Gassco as mentioned in section 5.2. The main results of this work are shown in table 6 below.

Table 6: Dangerous and safe valve failures derived from the reported test results

	Failure mode	**Number of failures**
Dangerous undetected (DU) failures (unacceptable risk)	Failure to close on demand (FTC)	3
	Valve closes too slowly (DOP)	1
	Leakage through closed valve (LCP)	5
Safe undetected (SU) failures (tolerable risk)	Valve closes too slowly (DOP)	5
	Leakage through closed valve (LCP)	11

From table 6 we see that a total 9 DU failures have occurred during the time period of 8 years of testing of 100 valves. For 3 of the DU failures related to LCP shown in table 6 it is not known based on the reported test results whether the related risk is tolerable or unacceptable as it is only stated that the internal leak rate is higher than 0.05kg/s (see table 5 in section 5.2). Therefore the actual number of DU failures could potentially be lower.

The DOP failure in table 6 could strictly be considered as a FTC failure since the closing time measured is over 2 times the tolerable limits of Gassco's acceptance criteria. Hence a total of 4 reported failures to close on demand have been revealed by 706 tests over a time period of 8 years. From this we get a failure fraction for FTC of all valves equal to 0.57%. In the same period for 5 of 681 leak tests the internal leak rates exceed the tolerable limits, if we include the 3 measurements mentioned above that may or may not exceed the tolerable limits. Hence we get a failure fraction for LCP of all valves equal to 0.73%.

However, the failure fraction for LCP could potentially be 0.29% depending on whether 3 of the LCP failures actually exceed the tolerable limits or not. It is also worth mentioning that the failure fraction for FTC and LCP can potentially change if more results from the time period 2007-2014 are reported. As mentioned in section 5.1 the number of reported tests results from the first year 2007 is scarce. In appendix A we see that test results have been reported only for about 30 of the valves in 2007.

Furthermore, as shown in table 6, 16 of the test results reported for closing times and internal leak rates are within the tolerable limits of Gassco's risk acceptance criteria from section 5.2. These closing times and internal leak rates are not considered dangerous as the valves can still perform their required safety function, though plans for repair are carried out to prevent development into dangerous failures. This is reflected in the reported test results where some of the closing times and internal leak rates that are within the tolerable limits one year not necessarily are lower the year after.

7.1.1 Discussion

It is reasonable to assume that measurements of closing times and internal leak rates that are within the limits that Gassco considers as acceptable are safe and not seen as failures. Similarly measurements that are considered by Gassco as unacceptable can be considered dangerous failures. However, measures that need evaluation are not classified as unacceptable by Gassco and are therefore not considered dangerous, but evaluation is needed to find out if it is necessary to reduce the risk from tolerable to acceptable. In order to do so it is necessary to know the failure causes related to each failure mode in order to evaluate the related risk. Also the risk and consequences related to e.g. an internal leakage could vary from valve to valve depending on e.g. the dimension, valve design, and location in the pipeline system.

In the results above the total number of DU failures is equal to 9. However, as pointed out the actual number of DU failures could potentially be lower. The failure fraction for LCP could potentially be 0.29% depending on whether 3 of the LCP failures actually exceed the tolerable limits or not. It is also worth mentioning that the failure fraction for FTC and LCP can potentially change if more results from the time period 2007-2014 are reported. In section 5.1 for instance, it is mentioned the number of reported tests results from the first year 2007 is scarce, and this can also be seen in appendix A where the test results have been reported only for about 30 of the valves in 2007.

7.2 Determining failure rate

The first step after determining the number of DU failures is to estimate the mean failure rate of the valves. All valves in the test results are considered homogeneous and in the useful life phase. Hence no variation is assumed between the valves. We have $n = 100$ valves, $x = 9$ DU failures, and $t_n = 8$ years of observed time in operation (in calendar time). By using equation 1 to estimate the failure rate based on the test we get:

$$\hat{\lambda}_{DU} = \frac{x}{t_n} = \frac{x}{n \cdot t} = \frac{9}{100 \cdot 8 \cdot 8760} = \underline{1.28 \cdot 10^{-6}}$$

The next step is to reflect the uncertainty of the failure rate estimate above. This is done using a Chi-squared 90% confidence interval:

$$\left[\frac{1}{2t_n} z_{0.95,2x}, \frac{1}{2t_n} z_{0.05,2(x+1)}\right] = \left[\frac{1}{2 \cdot 100 \cdot 8 \cdot 8760} z_{0.95,2 \cdot 9}, \frac{1}{2 \cdot 100 \cdot 8 \cdot 8760} z_{0.05,2(9+1)}\right] =$$

$$\left[\frac{1}{2 \cdot 100 \cdot 8 \cdot 8760} \cdot 9.39, \frac{1}{2 \cdot 100 \cdot 8 \cdot 8760} \cdot 31.41\right] = [6.70 \cdot 10^{-7}, 2.24 \cdot 10^{-6}]$$

From this we have that the actual failure rate of the valves should be in the range from $6.70 \cdot 10^{-7}$ to $2.24 \cdot 10^{-6}$. The mean initial design failure rate of the valves is assumed to be $\lambda_{DU} = 2.00 \cdot 10^{-6}$, as mentioned in section 6.2.2. This value is based on operational experience for topside ESD valves. Because the confidence interval is quite narrow and covers the assumed initial failure rate, the failure rate could be based only on the test results.

However, in this case it is believed that the estimated failure rate $\hat{\lambda}_{DU} = 1.28 \cdot 10^{-6}$ still is uncertain. Therefore Bayesian estimation is used to reflect uncertainty in $\hat{\lambda}_{DU}$ by putting trust into prior knowledge. The initial failure rate λ_{DU} is assumed to be the expected failure rate. The uncertainty of the expected failure rate is taken into account through a conservative failure rate λ_{DU-CE} which is the standard deviation of λ_{DU}. This is conservatively assumed to be $\lambda_{DU-CE} = 2 \cdot \lambda_{DU} = 4.00 \cdot 10^{-6}$ as mentioned in section 6.2.2.

Equation 3 is used to update the failure rate by combining the initial failure rate with the test results.
With $\alpha = \frac{\lambda_{DU}}{[\lambda_{DU-CE} - \lambda_{DU}]^2} = \frac{2.00 \cdot 10^{-6}}{[4.00 \cdot 10^{-6} - 2.00 \cdot 10^{-6}]^2} = \underline{5.00 \cdot 10^{5}}$, $\gamma = \alpha \cdot \lambda_{DU} = 5.00 \cdot 10^{5} \cdot 2.00 \cdot 10^{-6} = \underline{1.00}$, $x = 9$, and $t_n = 100 \cdot 8 \cdot 8760 = \underline{7008000 \text{ hours}}$ we get:

$$\ddot{\lambda}_{DU} = \frac{\gamma + x}{\alpha + t_n} = \frac{1+9}{5.00 \cdot 10^{5} + 100 \cdot 8 \cdot 8760} = \underline{1.33 \cdot 10^{-6}}$$

The updated failure rate $\ddot{\lambda}_{DU}$ differs only slightly from $\hat{\lambda}_{DU}$. This is because most trust is put in the test results. If the initial failure rate λ_{DU} is assumed less uncertain, i.e. the conservative failure rate λ_{DU-CE} is closer to λ_{DU}, then more trust is put into prior knowledge. $\ddot{\lambda}_{DU}$ would hence become higher in this case since $\lambda_{DU} > \hat{\lambda}_{DU}$. $\lambda_{DU-CE} = 1.5 \cdot \lambda_{DU}$ would for instance give a $\ddot{\lambda}_{DU} = 1.44 \cdot 10^{-6}$ if nothing else is changed.

7.2.1 Discussion

All valves gathered in the test results are as mentioned considered by Gassco as a homogeneous group of valves. One can argue whether the valves in the data collection should be treated as one homogeneous sample or divided into multiple homogeneous samples. The valves are of different types and dimensions. Furthermore some of the similar type of valves might come from different manufacturers and differ slightly in terms of design. Because of this the true failure rate for each specific valve could possibly vary to some extent. However, due to the fact that there is limited amount of data and the fact that more or less all the valves found in the test results operate at different locations, it would not necessarily give a more reliable estimate by splitting the valves into several homogeneous samples of valves. As mentioned earlier, the amount of valves of the different types vary in numbers, and many valves lack information whether they are used as ESD or PSD valves, Some valves are not even registered as to what type they are - whether they are ball, gate or D.E. gate valves. All these uncertainties make it difficult to give a reasonable estimate of each group instead of viewing all the valves as one homogeneous group. The estimates of each sample could easily be more optimistic or pessimistic than if all valves are gathered in one homogeneous sample.

In the analysis it is assumed that the failure rate is constant for all valves by assuming that they all are in the useful life phase of the bathtub curve (see OREDA, 2002). This is of course a simplification as some of the valves in the data collection might be either new or old, and thus should be considered to be in the burn-in phase or wear-out phase respectively. This is an obvious simplification because based on the bathtub curve it is expected that old valves will have a higher probability of failure than valves that are in their useful life phase. Also some brand new valves may fail more often in the burn-in phase. This might help explain why certain valves represented in Gassco’s test results have failed and why others have no registered failures.

There is no information in the test results about the total time in operation for the different valves other than that they have all been in operation since 2007. Also the test results do not give any information about the performance and reliability of the valves before 2007. It is therefore difficult to say with certainty whether the estimated failure rate based on the test results are close to the actual failure rate or not since much of the operational data has not been reported. Possible failures that have occurred in the past (i.e. before 2007) are not documented in the test results. Having access to this information and including it in the basis for the failure rate estimation would have reduced the uncertainty related to the actual failure rate and possibly increased or decreased the value of the estimate.

To compensate for the uncertainty in the failure rate estimate based on the test results it is proposed in the calculations to update the failure rate with prior knowledge in form of an assumed initial failure rate from design. One could also argue whether the assumed initial failure rate from design is realistic or not, as it is derived from a table in OLF 070, though the weight given to the failure rate from design depends on the assumed conservative failure rate which reflects the uncertainty of the initial failure rate from design. Because this is set to be 2 times the failure rate from design, most weight is given to the test results. From the results of the updating of the failure rate we see that the failure rate is only increased slightly from $1.28*10^{-6}$ to $1.33*10^{-6}$. Ideally the expected initial failure rate should be based on e.g. expert judgements and information given by the manufacturers of the different valves. In this way the prior information used to update the failure rate may not be chosen as arbitrary as in this case. It can also be argued, as mentioned in the calculations, if the failure rate should be combined with prior knowledge or if the test results are sufficient enough to estimate the failure rate. If it is decided to combine prior information with the test results it should be considered how much weight should be put on the prior knowledge compared to the test results in order to arrive at a reasonable failure rate estimate.

The failure rate estimate is as mentioned based on calendar time and hence that the valves are assumed to have 100% uptime, which in reality is a simplification. If the failure rate estimate is based on operational time instead of calendar time the result would be a somewhat higher failure rate estimate depending on downtime due to e.g. failures, maintenance and testing.

Two attempts have been given using the OREDA multi sample method to estimate the failure rate based on assumed multiple homogeneous samples. These calculations are shown in detail in appendix B. First the valves were sorted according to valve type (i.e. trunnion ball valves, slab gate valves, and double expanding gate valves). Then the valves were sorted as ESD or PSD. Valves where no information of type or if they are ESD or PSD were not part of the calculations. The results for the first attempt were similar as to the results when valves were viewed as one homogeneous group. The second attempt resulted in a slightly different failure rate estimate, but the upper limit of the 90% uncertainty interval for this failure rate is approximately the same as the upper limit of the 90% confidence interval when assuming one homogeneous group of valves. Despite the uncertainties related to these calculations because of the limited amount of valves included in each group, it still gives an indication of the variation between the valves. It seems that viewing the valves as one homogeneous group will give a fairly reasonable estimate of the mean failure rate of the valves. Due to the limited information given about the valves, the fact that 4 valves are of unknown type and that 20 of them have no information as to what function they have (ESD or PSD) also justifies viewing the valves as one homogeneous group.

7.3 Determining PFD

The estimated failure rate $\ddot{\lambda}_{DU} = \underline{1.33 \cdot 10^{-6}}$ is then used to determine the average probability of demand, PFD_{Avg}, of the valves in the test results. The minimum accepted value of $PFD_{Avg} = 1.0 \cdot 10^{-2}$ is set as the overall performance target for the valves. Annual FST and leak tests are carried out for the valves and therefore $\tau_{FST} = 8760$ hours. All valves are for simplicity assumed non-redundant, and FST is assumed to detect all DU failures during testing. From equation 7 we get:

$$PFD_{Avg} \approx \lambda_{DU} \cdot \frac{\tau}{2} = 1.33 \cdot 10^{-6} \cdot \frac{8760}{2} = \underline{5.83 \cdot 10^{-3}} < 1.0 \cdot 10^{-2}$$

From the calculation above we see that the overall performance of the valves based on annual FST and leak tests is adequate to meet the performance target. The next step is to determine PFD_{Avg} when taking into account that PST is carried out every 6 months in addition to the annual FST. This gives $\tau_{PST} = 6$ months $= 4380$ hours. Furthermore the PST coverage of DU failures is assumed to be $\theta_{PST} = 60\%$ as mentioned in section 6.2.3. When using equation 8 to calculate the PFD_{Avg} we get:

$$PFD_{Avg} \approx PFD_{FST} + PFD_{PST} = (1 - \theta_{PST}) \cdot \lambda_{DU} \cdot \frac{\tau_{FST}}{2} + \theta_{PST} \cdot \lambda_{DU} \cdot \frac{\tau_{PST}}{2}$$

$$= (1 - 0.60) \cdot 1.33 \cdot 10^{-6} \cdot \frac{8760}{2} + 0.60 \cdot 1.33 \cdot 10^{-6} \cdot \frac{4380}{2} = \underline{4.08 \cdot 10^{-3}}$$

From the calculation above we have that PST has a positive contribution to the PFD_{Avg} as the estimated is lower than if only FST is taken into consideration.

This is however if all failures are detected, and SIL2 is covered by the valves alone. Systematic failures and MTTR have not been taken into account.

Here only the contribution to PFD_{Avg} by the safety critical valve is estimated. However, to meet the SIL2 criteria the total PFD_{Avg} for the SIF must be estimated and be lower than of $1.0 \cdot 10^{-2}$. Under the assumption that the other components of the ESD system are redundant the total PFD_{Avg} could still be lower than $1.0 \cdot 10^{-2}$ and meet SIL2.

7.3.1 Discussion

It is assumed in the calculations that all valves are non-redundant (1oo1 voted) and alone cover the PFD target equal to 1% which corresponds to the SIL2 criteria. In reality the sum of the PFD contributions of all the subsystems of a SIF must be lower than the PFD target for SIL2, as mentioned in section 2.5. Also the different valves represented in the test results could potentially be part of SIFs and ESD systems with different designs, configurations, and redundancies. Some of the valves could be redundant (e.g. 1oo2 voted). However, by assuming non-redundant valves and that all DU failures are valve failures in the PFD calculations, the results are conservative. If redundant components were included in the PFD calculations then the resulting PFD would typically be lower than in this case where only non-redundant valves are included.

In the PFD calculations only valves have been considered because the purpose was to evaluate the overall performance of the valves in this thesis. Also, too little information is given in the test results to consider other components in the ESD systems. However, the number of failures that are assumed to be caused by the valves are probably exaggerated and too conservative. Some of these failures might in reality be caused by other components in the ESD system, but since these are often redundant the PFD calculations based solely on non-redundant valves can be considered conservative when all DU failures are assumed valve failures.

Furthermore it is assumed in the PFD calculations that all DU failures are detected through FST and internal leak testing, and that 60% of the DU failures are detected through PST. However, in reality FST and internal leak testing are not necessarily perfect tests. Some DU failures may remain undetected and are only detected during overhauls. (Rausand, 2014) By assuming for instance a DU failure coverage factor for FST equal to 90% and that the remaining 10% of DU failures are not detected before 20 years have passed, then the resulting

PFD becomes much higher than for a comparable perfect test with 100% coverage. Also systematic failures and possible downtime periods due to e.g. testing, maintenance or overhauling are not taken into account in the calculations, but would normally affect the safety and the availability of the valves.

Tests that have not been reported in the test results or possibly have been skipped have not been considered in the calculations. The reason why some tests are missing are not known and are therefore not a part of the analysis.

7.4 Determining test interval

Based on the results of the PFD calculations in section 7.3 alone it seems adequate with an annual test interval for FST and leak testing of the valves. The next step is to check whether the test interval should be changed or not.

The two approaches mentioned in section 6.2.4 are used. In the first approach the failure rate estimate based on test results $\hat{\lambda}_{DU}$ and 90% confidence interval is compared to the assumed initial failure rate λ_{DU} to consider doubling or halving of the test interval. From the results in section 7.2 we have that:

- $\hat{\lambda}_{DU} = 1.28 \cdot 10^{-6}$ is lower than $2 \cdot \lambda_{DU} = 4.00 \cdot 10^{-6}$ and higher than $\lambda_{DU}/2 = 1.00 \cdot 10^{-6}$
- $\lambda_{DU} = 2.00 \cdot 10^{-6}$ is within the estimated 90% confidence interval $[6.70 \cdot 10^{-7}, 2.24 \cdot 10^{-6}]$

Based on this approach the test interval should not be changed. Since the test interval should not be doubled according to the first approach the second approach is used to check if the test interval can be increased from 12 to 18 months. Equation 9 is used to calculate the proposed test interval. With the input parameters $\ddot{\lambda}_{DU} = 1.33 \cdot 10^{-6}$, $\tau = 12$ months, and $\lambda_{DU} = 2.00 \cdot 10^{-6}$ the proposed test interval becomes:

$\ddot{\tau} = \frac{\lambda_{DU}}{\ddot{\lambda}_{DU}} \cdot \tau = \frac{2.00 \cdot 10^{-6}}{1.33 \cdot 10^{-6}} \cdot 12 \approx$ <u>18 months</u> (this value has been rounded down to first allowed test interval)

Based on this calculation isolated it can be considered to increase the test interval from 12 months to 18 months for Gassco's valves. However, if the true failure rate for a valve is in the upper half of the 90% confidence interval the PFD value will exceed the PFD target of 0.01. 10 DU failures among the 100 safety critical valves leaving everything else unchanged the

Bayes estimated failure rate $\ddot{\lambda}_{DU}$ would be $1.47 \cdot 10^{-6}$ and hence the calculated test interval ratio $\ddot{\tau}$ would be approximately 16 months. When rounding $\ddot{\tau}$ down to the first allowed test interval the updated test interval would be 12 months, i.e. no change.

7.4.1 Discussion

From the estimation of the updated test interval we see that the test interval may be considered increased from 12 months to 18 months. However, this is only true if the actual failure rate is equal to the mean estimated failure rate. If for instance the actual failure rate for a valve proves to be in the upper half of the 90% confidence interval then the PFD value may very well exceed the PFD target of 0.01 when using a test interval equal to 18 months.

Similarly if we assume that the number of DU failures is increased by 1 unit to 10 DU failures among the 100 safety critical valves and leaving everything else unchanged, then the estimated failure rate combining test results with prior knowledge $_{DU}$ would be $1.47 \cdot 10^{-6}$. The resulting test interval using equation 9 would then be approximately 16 months. When rounding down to the first allowed test interval the updated test interval would be 12 months, i.e. no change.

7.5 Uncertainties and possible sources of error related to the reported measurements

There are many possible sources of error and uncertainties related to the measured closing times and internal leak rates in the test results. This is discussed in this section.

7.5.1 Measured closing times

There is a potential sources of error related to the accuracy and validity of the reported closing times in the test results. How the test results are measured could possibly be one such source of error. This could possibly vary from one valve to another and may also differ from one installation to another. If for instance the closing times of certain valves are measured manually by observing the valve movement and using a stopwatch, the measured time could be inaccurate. Manually measured closing times could possibly deviate from the true closing time of the valve due to e.g. delays to when the operator registers that the valve starts moving and when it stops. Therefore measures done automatically by monitoring should be preferred since they are most likely more accurate than manual measures. Due to this it should always be documented in the test results how the closing times have been measured. This may reduce the uncertainty related to accuracy and validity of each measurement, and may also give a more correct evaluation of the closing times.

Another possible source of error related to the measured closing times might be possible delays in the response time from when the ESD button is pushed until the valve is closed. It could be difficult to tell by only looking at the reported closing times whether the delays are caused by the valves themselves or if they are caused by other components in the ESD loop (such as ESD logic, solenoid valves, actuator, HPU etc.). Delays caused by other components of the ESD system might therefore erroneously be reported as valve failures. It should therefore be indicated in the test results what component causes each delay. By monitoring the forces on e.g. the actuator and stem it may be easier to find out what component the delayed closing time is caused by.

7.5.2 Measured internal leak rates

There are also possible sources of errors related to the accuracy and validity of the reported internal leak rates. Different methods have been used to measure the internal leak rates of the valves represented in the test results. The internal leak testing methods vary from pressure testing methods (full valve leak tests or cavity leak tests) to AE measurements as discussed in section 4.4. There could possibly also be variations of each leak testing method used for the different valves in terms of e.g. specific measuring equipment (different types of sensors, gauges, and measuring devices). The accuracy and validity of the different methods and measuring equipment used may vary and might possibly arrive at different results for internal leak rate values for the same valves.

In cavity leak tests for instance there are two possible ways in which gas can leak into cavity – either from the upstream side and the downstream side of the given valve since both sides are pressurized. Therefore the internal leak rate is measured based on internal gas leakages from both the upstream and downstream side into cavity. It could be difficult to tell which of the two sides that contribute the most to the internal leak rate measured in a cavity leak test. Internal leakages into cavity from the downstream side of the valve are of less interest to

Gassco since the gas will flow in the opposite direction during normal operation (Hoff, 2015). Hence what is important is that the valve is able to prevent internal gas leakages from the upstream side (i.e. the gas flow direction) when emergency situations occur. Internal leak rate values reported in the test results that are measured through cavity leak tests might give a wrong impression of the internal leak rate through the valve. As an example one might erroneously get the impression that the internal leakage through the valve is too high from the upstream side when in fact most of the internal leakage into cavity during testing comes from the downstream side. It should therefore be documented in the test results how the internal leak rate is measured for each valve.

There are also uncertainties related to the timing of the internal leak rate measurement. As mentioned in section 4.4 Gassco requires that one must wait a minimum of 15 minutes after the valve has closed and the pressure is lowered before measuring the internal leak rate. At this time the internal leak rate is considered to have stabilized at a level that indicates the true leak rate through the valve – the internal leak rate is typically high the first minutes (Hoff, 2015). This could possibly be a source of error because it is not possible to know based on the test results alone if the internal leak measurement in each situation is initiated after waiting 15 minutes or not. As an example the measured average internal leak rate for a valve might be reported to be 0.058 kg/s when the measurement is initiated without waiting the required 15 minutes, while the true, stabilized leak rate value if one had waited might be 0.035 kg/s. Based on this it is possible that some of the high internal leak rate values reported in the test results erroneously have been counted as failures in the results. Therefore it should be reported in the test results exactly how the internal leak tests are done.

7.5.3 Repeatability of testing routines

A possible source of error related to the tests is the repeatability and routines used for testing. The closing times and internal leak rates of each valve might not be measured using exactly the same routines. For instance the instructions given for leak testing for a certain valve each year might vary. The differential pressure over the valve is usually set, but the instructions given each year to the limits for lowering of the pressure during testing could vary (Hoff, 2015). Therefore the same routine should be used for each valve every time it is tested. This would make it easier to compare test results since all tests are done exactly the same way each time.

8. Test routines for safe performance of production- and safety critical valves

The purpose of this thesis was to verify if the testing routines and overall performance of production- and safety critical valves operated by Gassco are good enough. When working with this thesis the test results provided by Gassco are too limited to give an accurate analysis based on these results. The results have a span of 8 years, starting in 2007. However, the test results do not provide any information about the possible valve failures detected prior to 2007, even though many of the valves have been in operation even longer.

As mentioned earlier some valves lack results for some of the years, and the results do not reveal the age of the different valves. We do not know the reasons why some valves have not been tested some of the years, or what the actual causes of the failures are for all the valves. The fact that so much essential information is missing makes it difficult to analyse the performance of the valves and verify if the testing and maintenance routines are good enough. Therefore the provided calculations are based on quite a few simplifications and assumptions. However, the calculations based on the test results provided and simplifications made show that Gassco seem to have adequate testing routines and satisfactory valve performance. Nevertheless, there seems to be room for improvement of the testing routines and more detailed information could be reported to ensure more accurate measurements in the future. In this way it could be possible to conduct a more reliable analysis based on less uncertain measurements.

To ensure proper testing a set of routines are suggested. Routines should be established when performing tests of valves. Based on the test results and related analysis routines should be in place that make sure that:

- The test routines are done in the same way every year for the valves.
- The test routines are preferably done in the same way for the same type of valves.
- Personnel are properly trained to do the tests.
- All required test results are reported.
- All deviating results are properly explained (high measurements, faulty tests, causes etc.).
- The test methods and procedures used for testing are reported.

The reported test results used for analysis should include the following information for each valve:

- Total time in operation
- Valve size
- Valve type
- Safety critical function (ESD or PSD)
- Location (operational and environmental conditions)
- Reported failures (causes) and repair history
- Testing methods and procedures (closing function, closing times, and internal leak rates)
- Results from FST, leak testing, and PST

As discussed in section 4.5 valve condition monitoring systems can be used to support FST and internal leak testing. The implementation of such systems could potentially reduce uncertainties related to measurements of closing times and internal leak rates. Closing times and internal leak rates could be measured with less need for human interaction, and it also gives the possibility to trend the measurements. Furthermore, by trending the measurements one might indicate possible degradation of valves. The use of condition monitoring systems can be especially useful for deciding when testing or maintenance is needed, as possible dangerous failures could be detected at an early stage. However, valve condition monitoring systems are not always reliable as mentioned in section 4.5, and should therefore not fully replace manual testing but be used as a supplement.

PST can also be used to detect failures in the closing function of valves, but internal leakages are not discovered since the valve only closes partially. PST is especially useful for detecting failures in the closing mechanisms of the valves that otherwise would remain hidden for a longer period of time if only FST was performed. The results from the calculations in section 7.3 indicate that the contribution of PST as a supplement to FST is positive. However, PST should not be performed at too short intervals as this may result in damage to the valves.

9. Conclusion and further studies

9.1 Conclusion

The work on this thesis has been done to verify if the performance of the production- and safety critical valves in the gas transport system is good enough. The different valves have been studied in order to get a better understanding of how they are built and how they function. Literature has been used to find a good way to evaluate the true performance of the valves, the testing methods and the test results provided by Gassco.

Based on the test results it seems to indicate that the overall performance of the valves is within the criteria set by Gassco if the valves are viewed as a homogeneous group. The valves also seem to perform well if an average failure rate is estimate based on multiple homogeneous groups (either based valve type or ESD and PSD) as shown in appendix B, given the limited information available. It is proposed that the test interval for FST and internal leak testing should not be changed when taking the calculations and uncertainties into account – hence the valves should be tested every 12 months.

It has been of great importance for Gassco to verify/stress that very few ESD valves fail to close, as these valves are the most critical if they fail. The ESD valves prove to be highly reliable, as only a fraction of them fail to close.

The test results provided by Gassco are however not sufficient enough to give a thorough analysis of the valves. The information about the valves is too limited for the calculations to give any clear answers to the research questions posed in these studies. The test results are only shown for the last 8 years, some valves also lack results for some of these years, and some valves have not been reported tested each year. The reasons why quite a few results are missing are not known from the test results. In chapter 8 suggestions are given for possible improvements of the test routines. Condition monitoring and PST can in general improve the testing of the valves.

To conclude it is fair to say that Gassco seems to be a safe operator and provider of gas pipeline systems based on the test results provided.

9.2 Further studies

For further studies more information should be gathered of the production- and safety critical valves. The information needed for further studies can be found in chapter 8. If this information had been available more precise evaluations of the true performances and calculations of the valves could have been given. It would possibly also have been easier to verify if the performance of the production- and safety critical valves operated by Gassco is safe and meet the SIL criteria.

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Appendices

Appendix A: Test results of safety critical valves

SAFETY CRITICAL VALVES	Function test (ability to close on demand)								
	2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**ΣTOTAL**
A. Number of closing tests that are successful	**33**	**90**	**92**	**97**	**96**	**99**	**98**	**98**	**703**
A.1. Ball valves	27	67	70	72	70	72	71	71	520
A.1.1. dimensions 30"-42"	26	44	47	49	47	49	48	48	358
A.1.2. dimensions 20"-28"	0	10	10	10	10	10	10	10	70
A.1.3. dimensions 12"-19"	0	10	10	10	10	10	10	10	70
A.1.4. dimensions < 10"	1	3	3	3	3	3	3	3	22
A.2. Gate valves	3	18	18	18	18	18	18	18	129
A.2.1. dimensions 30"-42"	3	14	14	14	14	13	14	14	100
A.2.2. dimensions 20"-28"	0	2	2	2	2	2	2	2	14
A.2.3. dimensions 12"-19"	0	2	2	2	2	2	2	2	14
A.2.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
A.3. D.E. valves	3	5	4	5	4	5	5	5	36
A.3.1. dimensions 30"-42"	3	5	4	5	4	5	5	5	36
A.3.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
A.3.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
A.3.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
A.4. Unknown type	0	0	0	2	4	4	4	4	18
A.6.1. dimensions 30"-42"	0	0	0	0	0	0	0	0	0
A.6.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
A.6.3. dimensions 12"-19"	0	0	0	2	2	2	2	2	10
A.6.4. dimensions < 10"	0	0	0	0	2	2	2	2	8
B. Number of closing tests that have failed	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**1**	**3**
B.1. Ball valves	0	0	0	0	1	0	0	1	2
B.1.1. dimensions 30"-42"	0	0	0	0	1	0	0	1	2
B.1.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
B.1.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
B.1.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
B.2. Gate valves	0	0	0	0	0	0	0	0	0
B.2.1. dimensions 30"-42"	0	0	0	0	0	1	0	0	1
B.2.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
B.2.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
B.2.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
B.3. D.E. valves	0	0	0	0	1	0	0	0	1
B.3.1. dimensions 30"-42"	0	0	0	0	1	0	0	0	1
B.3.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
B.3.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
B.3.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
B.4. Unknown type	0	0	0	0	0	0	0	0	0
B.6.1. dimensions 30"-42"	0	0	0	0	0	0	0	0	0
B.6.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
B.6.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
B.6.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
C. Number of closing tests not reported or skipped ("-")	**67**	**10**	**8**	**3**	**2**	**1**	**2**	**1**	**94**
C.1. Ball valves	46	6	3	1	2	1	2	1	62
C.1.1. dimensions 30"-42"	24	6	3	1	2	1	2	1	40
C.1.2. dimensions 20"-28"	10	0	0	0	0	0	0	0	10
C.1.3. dimensions 12"-19"	10	0	0	0	0	0	0	0	10
C.1.4. dimensions < 10"	2	0	0	0	0	0	0	0	2
C.2. Gate valves	15	0	0	0	0	0	0	0	15
C.2.1. dimensions 30"-42"	11	0	0	0	0	0	0	0	11
C.2.2. dimensions 20"-28"	2	0	0	0	0	0	0	0	2
C.2.3. dimensions 12"-19"	2	0	0	0	0	0	0	0	2
C.2.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
C.3. D.E. valves	2	0	1	0	0	0	0	0	3
C.3.1. dimensions 30"-42"	2	0	1	0	0	0	0	0	3
C.3.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
C.3.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
C.3.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
C.4. Unknown type	4	4	4	2	0	0	0	0	14
C.6.1. dimensions 30"-42"	0	0	0	0	0	0	0	0	0
C.6.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
C.6.3. dimensions 12"-19"	2	2	2	0	0	0	0	0	6
C.6.4. dimensions < 10"	2	2	2	2	0	0	0	0	8

SAFETY CRITICAL VALVES	Closing times compared with risk acceptance criteria*								
	2007	2008	2009	2010	2011	2012	2013	2014	ΣTOTAL
A. Number of normal closing times with acceptable risk	**31**	**84**	**87**	**94**	**95**	**93**	**91**	**93**	**668**
A.1. Ball valves	27	63	67	69	69	68	65	67	495
A.1.1. dimensions 30"-42"	26	42	45	46	46	45	43	44	337
A.1.2. dimensions 20"-28"	0	9	9	10	10	10	10	10	68
A.1.3. dimensions 12"-19"	0	9	10	10	10	10	9	10	68
A.1.4. dimensions < 10"	1	3	3	3	3	3	3	3	22
A.2. Gate valves	1	16	16	18	17	16	17	17	118
A.2.1. dimensions 30"-42"	1	13	13	14	13	12	13	13	92
A.2.2. dimensions 20"-28"	0	2	2	2	2	2	2	2	14
A.2.3. dimensions 12"-19"	0	1	1	2	2	2	2	2	12
A.2.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
A.3. D.E. valves	3	5	4	5	5	5	5	5	37
A.3.1. dimensions 30"-42"	3	5	4	5	5	5	5	5	37
A.3.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
A.3.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
A.3.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
A.4. Unknown type	0	0	0	2	4	4	4	4	18
A.6.1. dimensions 30"-42"	0	0	0	0	0	0	0	0	0
A.6.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
A.6.3. dimensions 12"-19"	0	0	0	2	2	2	2	2	10
A.6.4. dimensions < 10"	0	0	0	0	2	2	2	2	8
B. Number of closing times with tolerable or unacceptable risk	**0**	**0**	**0**	**0**	**1**	**2**	**2**	**1**	**6**
B.1. Ball valves	0	0	0	0	0	0	1	0	1
B.1.1. dimensions 30"-42"	0	0	0	0	0	0	0	0	0
B.1.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
B.1.3. dimensions 12"-19"	0	0	0	0	0	0	1	0	1
B.1.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
B.2. Gate valves	0	0	0	0	1	2	1	1	5
B.2.1. dimensions 30"-42"	0	0	0	0	1	2	1	1	5
B.2.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
B.2.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
B.2.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
B.3. D.E. valves	0	0	0	0	0	0	0	0	0
B.3.1. dimensions 30"-42"	0	0	0	0	0	0	0	0	0
B.3.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
B.3.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
B.3.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
B.4. Unknown type	0	0	0	0	0	0	0	0	0
B.6.1. dimensions 30"-42"	0	0	0	0	0	0	0	0	0
B.6.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
B.6.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
B.6.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
C. Number of closing times not measured or reported ("-")	**69**	**16**	**13**	**6**	**4**	**5**	**7**	**6**	**126**
C.1. Ball valves	46	10	6	4	4	5	7	6	88
C.1.1. dimensions 30"-42"	24	8	5	4	4	5	7	6	63
C.1.2. dimensions 20"-28"	10	1	1	0	0	0	0	0	12
C.1.3. dimensions 12"-19"	10	1	0	0	0	0	0	0	11
C.1.4. dimensions < 10"	2	0	0	0	0	0	0	0	2
C.2. Gate valves	17	2	2	0	0	0	0	0	21
C.2.1. dimensions 30"-42"	13	1	1	0	0	0	0	0	15
C.2.2. dimensions 20"-28"	2	0	0	0	0	0	0	0	2
C.2.3. dimensions 12"-19"	2	1	1	0	0	0	0	0	4
C.2.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
C.3. D.E. valves	2	0	1	0	0	0	0	0	3
C.3.1. dimensions 30"-42"	2	0	1	0	0	0	0	0	3
C.3.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
C.3.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
C.3.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
C.4. Unknown type	4	4	4	2	0	0	0	0	14
C.6.1. dimensions 30"-42"	0	0	0	0	0	0	0	0	0
C.6.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
C.6.3. dimensions 12"-19"	2	2	2	0	0	0	0	0	6
C.6.4. dimensions < 10"	2	2	2	2	0	0	0	0	8

*For most of the ESD valves the acceptable limit is ≤ 2 sec per inch valve + 10% and tolerable limit is ≤ 2 sec per inch valve + 20%, though a few valves have other acceptable limits and tolerable limits. The general risk acceptance criteria referred to here are presented in chapter 7.2.

PRODUCTION- AND SAFETY CRITICAL VALVES	**Internal leak rates compared with risk acceptance criteria***								
	2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**ΣTOTAL**
A. Number of int. leak rates with acceptable risk	**27**	**86**	**90**	**90**	**97**	**95**	**91**	**90**	**666**
A.1. Ball valves	24	66	68	66	70	68	65	67	494
A.1.1. dimensions 30"-42"	23	44	47	43	47	45	43	44	336
A.1.2. dimensions 20"-28"	0	9	9	10	10	10	10	10	68
A.1.3. dimensions 12"-19"	0	10	10	10	10	10	9	10	69
A.1.4. dimensions < 10"	1	3	2	3	3	3	3	3	21
A.2. Gate valves	1	15	18	17	18	18	17	14	118
A.2.1. dimensions 30"-42"	1	13	14	14	14	14	13	10	93
A.2.2. dimensions 20"-28"	0	0	2	1	2	2	2	2	11
A.2.3. dimensions 12"-19"	0	2	2	2	2	2	2	2	14
A.2.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
A.3. D.E. valves	2	5	4	5	5	5	5	5	36
A.3.1. dimensions 30"-42"	2	5	4	5	5	5	5	5	36
A.3.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
A.3.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
A.3.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
A.4. Unknown type	0	0	0	2	4	4	4	4	18
A.6.1. dimensions 30"-42"	0	0	0	0	0	0	0	0	0
A.6.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
A.6.3. dimensions 12"-19"	0	0	0	2	2	2	2	2	10
A.6.4. dimensions < 10"	0	0	0	0	2	2	2	2	8
B. Number of int. leak rates with tolerable or unacceptable risk	**2**	**1**	**1**	**3**	**2**	**0**	**2**	**4**	**15**
B.1. Ball valves	2	0	1	3	2	0	1	0	9
B.1.1. dimensions 30"-42"	2	0	1	3	2	0	0	0	8
B.1.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
B.1.3. dimensions 12"-19"	0	0	0	0	0	0	1	0	1
B.1.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
B.2. Gate valves	0	1	0	0	0	0	1	4	6
B.2.1. dimensions 30"-42"	0	0	0	0	0	0	1	4	5
B.2.2. dimensions 20"-28"	0	1	0	0	0	0	0	0	1
B.2.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
B.2.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
B.3. D.E. valves	0	0	0	0	0	0	0	0	0
B.3.1. dimensions 30"-42"	0	0	0	0	0	0	0	0	0
B.3.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
B.3.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
B.3.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
B.4. Unknown type	0	0	0	0	0	0	0	0	0
B.6.1. dimensions 30"-42"	0	0	0	0	0	0	0	0	0
B.6.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
B.6.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
B.6.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
C. Number of int. l leak rates not measured or reported ("-")	**71**	**13**	**9**	**7**	**1**	**5**	**7**	**6**	**119**
C.1. Ball valves	47	7	4	4	1	5	7	6	81
C.1.1. dimensions 30"-42"	25	6	2	4	1	5	7	6	56
C.1.2. dimensions 20"-28"	10	1	1	0	0	0	0	0	12
C.1.3. dimensions 12"-19"	10	0	0	0	0	0	0	0	10
C.1.4. dimensions < 10"	2	0	1	0	0	0	0	0	3
C.2. Gate valves	17	2	0	1	0	0	0	0	20
C.2.1. dimensions 30"-42"	13	1	0	0	0	0	0	0	14
C.2.2. dimensions 20"-28"	2	1	0	1	0	0	0	0	4
C.2.3. dimensions 12"-19"	2	0	0	0	0	0	0	0	2
C.2.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
C.3. D.E. valves	3	0	1	0	0	0	0	0	4
C.3.1. dimensions 30"-42"	3	0	1	0	0	0	0	0	4
C.3.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
C.3.3. dimensions 12"-19"	0	0	0	0	0	0	0	0	0
C.3.4. dimensions < 10"	0	0	0	0	0	0	0	0	0
C.4. Unknown type	4	4	4	2	0	0	0	0	14
C.6.1. dimensions 30"-42"	0	0	0	0	0	0	0	0	0
C.6.2. dimensions 20"-28"	0	0	0	0	0	0	0	0	0
C.6.3. dimensions 12"-19"	2	2	2	0	0	0	0	0	6
C.6.4. dimensions < 10"	2	2	2	2	0	0	0	0	8

*For most of the ESD valves the acceptable limit is ≤ 0.05kg/s and tolerable limit is ≤ 0.2kg/s, though a few valves have other acceptable limits and tolerable limits. The general risk acceptance criteria referred to here are presented in chapter 7.2.

Based on the overall test results of all the safety critical valves the following failures are considered DU failures:

Number of DU failures related to 'Fail to close on demand' and ‘Delayed operation’:	4
Number of DU failures related to 'Internal leakage in closed position':	5
Number of DU failures in total:	9

These results are based on the following considerations done by Gassco (Hoff, 2015):

- Both the ESD valves and PSD valves are considered dangerous with respect to the failure mode ‘Fail to close on demand’
- Only the ESD valves have been considered dangerous with respect to the failure modes ‘Delayed operation’ and ‘Internal leakage in closed position’.
- Closing times of ESD valves exceeding 20% of the general acceptance criteria of 2 seconds per inch could be considered as dangerous failures.
- Internal leak rates of ESD valves measured to be higher than 0.2 kg/s can generally be considered as dangerous failures. For a few of the ESD valves a higher or lower internal leak rate limit than 0.2 kg/s is considered dangerous.

Appendix B: Failure rate estimation based on multiple homogeneous samples

The following calculations are done using the OREDA multi sample method, as described in OREDA (2002), to estimate the mean failure rate of the production- and safety critical valves operated by Gassco based on the assumption that the valves are not homogeneous. Two cases are presented. In the case 1 the valves are sorted into homogeneous groups based on valve type, while in case 2 the valves are sorted into homogeneous groups based on whether the valves are used as ESD valves or PSD valves.

Explanation of important parameters in the calculations (see OREDA, 2002):

k = number of different samples

n_i = number of failures in sample i

τ_i = total time in operation in sample i

$\hat{\theta}_1$ = mean failure rate for pooled (for homogeneous sample)

$\hat{\sigma}^2$ = variation between the k samples

θ^* = mean failure rate of multiple samples

<u>Case 1 – Mean failure rate estimation based on assumption of variation between valve types:</u>

The valves represented in Gassco's test results are sorted into k = 3 homogeneous samples based on valve type; ball, gate, and double expanding gate. There are 4 valves reported in the test results that are of unidentified valve type. These have not been included in the calculations.

Step 1:

$k = 3$

$\sum_{i=1}^{k} n_i = 6 + 2 + 1 = \underline{9}$

$\sum_{i=1}^{k} \tau_i = 5115840 + 1261440 + 350400 = \underline{6727680}$

$\hat{\theta}_1 = \frac{\sum_{i=1}^{k} n_i}{\sum_{i=1}^{k} \tau_i} = \frac{9}{6727680} = \underline{1.34\text{E-}06}$

Step 2:

$S_1 = \sum_{i=1}^{k} \tau_i = \underline{6727680}$

$S_2 = \sum_{i=1}^{k} \tau_i{}^2 = 5115840^2 + 1261440^2 + 350400^2 = \underline{2.79E+13}$

$\sum_{i=1}^{k} \frac{n_i^2}{\tau_i} = \frac{6^2}{5115840} + \frac{2^2}{1261440} + \frac{1^2}{350400} = \underline{1.31E\text{-}05}$

$V = \sum_{i=1}^{k} \frac{n_i^2}{\tau_i} - \hat{\theta}_1^2 \cdot S_1 = 1.31E\text{-}05 – 1.34E\text{-}06^2 \cdot 6727680 = \underline{1.02E\text{-}06}$

Step 3:

$\hat{\sigma}^2 = \frac{V-(k-1)\hat{\theta}_1}{S_1^2 - S_2} \cdot S_1 = \frac{1.02E-06 - (3-1)1.34E-06}{6727680^2 - 2.79E+13} \cdot 6727680 \approx \underline{0}$ (equal to 0 due to negative value)

Step 4:

$$\theta^* = \frac{1}{\sum_{i=1}^{k} \frac{1}{\frac{\hat{\theta}_1}{\tau_1} + \hat{\sigma}^2}} \cdot \sum_{i=1}^{k} \left[\frac{1}{\frac{\hat{\theta}_1}{\tau_1} + \hat{\sigma}^2} \cdot \frac{n_i}{\tau_i} \right] = \frac{\sum_{i=1}^{k} ni}{\sum_{i=1}^{k} \tau i} = \frac{9}{6727680} = \underline{1.34E\text{-}06} = \hat{\theta}_1$$

Because the calculations indicate no variation $\hat{\sigma}^2$ between the assumed homogeneous samples, the mean failure rate of multiple samples θ^* becomes equal to the mean failure rate of a homogeneous sample $\hat{\theta}_1$.

Case 2 – Mean failure rate estimation based on assumption of variation between ESD and PSD valves:

The valves represented in Gassco's test results are sorted into k = 2 homogeneous samples; ESD valves and PSD valves. For 20 valves reported in the test results there it is unknown based on the information in the reported test results whether they are used as ESD valves or PSD valves. These have not been included in the calculations.

Step 1:

$k = 2$

$\sum_{i=1}^{k} n_i = 5 + 3 = \underline{8}$

$\sum_{i=1}^{k} \tau_i = 4415040 + 1191360 = \underline{5606400}$

$\hat{\theta}_1 = \frac{\sum_{i=1}^{k} n_i}{\sum_{i=1}^{k} \tau_i} = \frac{8}{5606400} = \underline{1.43E\text{-}06}$

Step 2:

$S_1 = \sum_{i=1}^{k} \tau_i = \underline{5606400}$

$S_2 = \sum_{i=1}^{k} {\tau_i}^2 = 4415040^2 + 1191360^2 = \underline{2.09\text{E}+13}$

$\sum_{i=1}^{k} \frac{n_i^2}{\tau_i} = \frac{5^2}{4415040} + \frac{3^2}{1191360} = \underline{1.32\text{E-}05}$

$V = \sum_{i=1}^{k} \frac{n_i^2}{\tau_i} - \hat{\theta}_1^2 \cdot S_1 = 1.32\text{E-}05 - 1.43\text{E-}06^2 \cdot 5606400 = \underline{1.80\text{E-}06}$

Step 3:

$\hat{\sigma}^2 = \frac{V-(k-1)\hat{\theta}_1}{S_1^2 - S_2} \cdot S_1 = \frac{1.80E-06\ -(2-1)1.43E-06}{5606400^2-2.09E+13} \cdot 5606400 = \underline{2.00\text{E-}13}$

Step 4:

$$\sum_{i=1}^{k} \frac{1}{\frac{\hat{\theta}_1}{\tau_i}+\hat{\sigma}^2} = \frac{1}{\frac{1.43E-06}{4415040}+2.00\text{E}-13} + \frac{1}{\frac{1.43E-06}{1191360}+2.00\text{E}-13} = \underline{2.63\text{E}+12}$$

$$\sum_{i=1}^{k} \left[\frac{1}{\frac{\hat{\theta}_1}{\tau_i}+\hat{\sigma}^2} \cdot \frac{n_i}{\tau_i}\right] = \frac{1}{\frac{1.43E-06}{4415040}+2.00\text{E}-13} \cdot \frac{5}{4415040} + \frac{1}{\frac{1.43E-06}{1191360}+2.00\text{E}-13} \cdot \frac{3}{1191360} = \underline{3968697}$$

$$\theta^* = \frac{1}{\sum_{i=1}^{k} \frac{1}{\frac{\hat{\theta}_1}{\tau_i}+\hat{\sigma}^2}} \cdot \sum_{i=1}^{k} \left[\frac{1}{\frac{\hat{\theta}_1}{\tau_i}+\hat{\sigma}^2} \cdot \frac{n_i}{\tau_i}\right] = \frac{1}{2.63\text{E}+12} \cdot 3968697 = \underline{1.51\text{E-}06}$$

Step 5:

$\hat{\beta} = \frac{\theta^*}{\hat{\sigma}^2} = \frac{1.51E-06}{2.00E-13} = \underline{7566629}$

$\hat{\alpha} = \hat{\beta} \cdot \theta^* = 7566629 \cdot 1.51\text{E-}06 = \underline{11.42}$

$\left[\frac{1}{2\hat{\beta}} z_{0.95,2\hat{\alpha}} , \frac{1}{2\hat{\beta}} z_{0.05,2\hat{\alpha}}\right]$ = [8.15E-07 , 2.24E-06]

where $z_{0.95,11.42} = 12.34$ and $z_{0.05,11.42} = 33.92$

From step 4 we see that the failure rate estimate is somewhat higher than the estimated failure rate based on a homogeneous sample of valves from section 7.2. However, the 90% uncertainty interval of the estimate has approximately the same upper limit as the 90% confidence interval given for one homogeneous sample of valves in section 7.2.

Appendix C: The impact of the number of DU failures and PST on the valve performance and required test interval

The impact of the number of DU failures on the estimated PFD$_{Avg}$ and updating of function test interval:

x (DU failures)	t_n (hours)	$\widehat{\lambda_{DU}}$	λ_{DU}	$\ddot{\lambda}_{DU}$	τ (months)	PFD_{Avg}	$\ddot{\tau}$ (months)	Updated τ (months)
9	7008000	1.28E-06	2.00E-06	1.33E-06	12	5.83E-03	18.02	18
10	7008000	1.43E-06	2.00E-06	1.47E-06	12	6.42E-03	16.38	12
11	7008000	1.57E-06	2.00E-06	1.60E-06	12	7.00E-03	15.02	12
12	7008000	1.71E-06	2.00E-06	1.73E-06	12	7.58E-03	13.86	12
13	7008000	1.86E-06	2.00E-06	1.86E-06	12	8.17E-03	12.87	12
14	7008000	2.00E-06	2.00E-06	2.00E-06	12	8.75E-03	12.01	12
15	7008000	2.14E-06	2.00E-06	2.13E-06	12	9.33E-03	11.26	9
16	7008000	2.28E-06	2.00E-06	2.26E-06	12	9.92E-03	10.60	9

The impact of PST on the estimated PFD$_{Avg}$ and updating of the function test interval:

The PST coverage of DU failures is conservatively assumed to be 60%. The failure mode 'Internal leakage in closed position' cannot be detected by PST, whereas 'Fail to close on demand' and 'Delayed operation' can be detected.

The PFD equation used below is derived from Lundteigen and Rausand (2007). The calculations are based on the assumption of 9 DU failures in total among the 100 safety critical valves.

PST interval τ_{PST}	FST interval τ_{FST}	$PFD \approx PFD_{FST} + PFD_{PST} = (1-\theta_{PST})\cdot\lambda_{DU}\cdot\frac{\tau_{FST}}{2} + \theta_{PST}\cdot\lambda_{DU}\cdot\frac{\tau_{PST}}{2}$	PFD if annual FST only	Contribution to PFD by PST compared to annual FST only:
2 weeks	12 months	2.47E-03	5.83E-03	58 %
1 month	12 months	2.63E-03	5.83E-03	55 %
2 months	12 months	2.92E-03	5.83E-03	50 %
3 months	12 months	3.21E-03	5.83E-03	45 %
6 months	12 months	4.08E-03	5.83E-03	30 %

PST interval τ_{PST}	FST interval τ_{FST}	$PFD \approx PFD_{FST} + PFD_{PST} = (1 - \theta_{PST}) \cdot \lambda_{DU} \cdot \frac{\tau_{FST}}{2} + \theta_{PST} \cdot \lambda_{DU} \cdot \frac{\tau_{PST}}{2}$	PFD if annual FST only	Contribution to PFD by PST compared to annual FST only:
2 weeks	18 months	3.63E-03	5.83E-03	38 %
1 month	18 months	3.94E-03	5.83E-03	33 %
2 months	18 months	4.38E-03	5.83E-03	25 %
3 months	18 months	4.81E-03	5.83E-03	18 %
6 months	18 months	6.13E-03	5.83E-03	-5 %

PST interval τ_{PST}	FST interval τ_{FST}	$PFD \approx PFD_{FST} + PFD_{PST} = (1 - \theta_{PST}) \cdot \lambda_{DU} \cdot \frac{\tau_{FST}}{2} + \theta_{PST} \cdot \lambda_{DU} \cdot \frac{\tau_{PST}}{2}$	PFD if annual FST only	Contribution to PFD by PST compared to annual FST only:
2 weeks	24 months	4.80E-03	5.83E-03	18 %
1 month	24 months	5.25E-03	5.83E-03	10 %
2 months	24 months	5.83E-03	5.83E-03	0 %
3 months	24 months	6.42E-03	5.83E-03	-10 %
6 months	24 months	8.17E-03	5.83E-03	-40 %