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MASTER'S THESIS

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Preface

This thesis is submitted in fulfilment of the requirement for a Master's degree in societal safety at the University of Stavanger, Norway. The report is carried out in co-operation with Proactima AS, Stavanger; as a part of the RAMONA project which focuses on regularity and deliverability of the Norwegian gas transport system.

To keep this report as ''Open'', it has been preferred by Proactima AS that all the references which are confidential and related to industry internal documents should have been taken out from this report. Moreover, instead of real names related to those documents, some imaginary names have been used in this report, e.g. 'X' , 'Y' etc.

Quite new to this field, personally I did not have any knowledge about the safety critical valves in hydrocarbon transport system, it is a very comprehensive subject, and the learning curve has been steep. To tackle over this task was pretty hard for me because I came from IT background but I knew that '' for anything in life, to begin, we need three things, a motive, a direction, a dream '' to work with this report has given me a broader understanding of these subject; risk management, operation & maintenance management, condition monitoring and reliability analysis.

The work has been both challenging and rewarding, and I am increasing my knowledge within all above mentioned subjects. Writing this thesis has been hard but in the process of writing I feel, I have learned a lot and my initial conceptions getting better and better.

My sincere thanks go to my parents who always took care of me and prayed for my success in each corner of my life which is unforgettable.

I wish to take this opportunity to express my gratitude to my supervisor Terje Aven for introducing me to the risk management, as well as for lots of great inspiration, ideas, comments and an endless stream of articles. It is a great pleasure for me and I feel proud that I am a student of Professor Terje Aven, a well known personality in risk management, reliability analysis, and societal safety.

I would also like to say my special thanks to Willy Røed, for always encouraging me, giving me quick feed back, motivating me, and on the top his smile, surely I learned a lot from my master thesis but besides that I am very pleased that I have learned many personality development things from Willy Røed,

I would also like to thank Jawad Raza, for providing usefull tips and suggestions during thesis work; finally, lots of thanks are due to my friend Suleman khan, who motivated me through out my thesis.

Stavanger
04.07.2008

CH M. Zahid Nawaz

Summary

In this master thesis, the effects of changing the test interval of the land based safety critical valves have been highlighted. Compliance with the regulations given by the PSAN (Petroleum Safety Authority Norway) requires annual testing of these valves.

The testing of safety critical valves are essential to increase the probability that the valves are able to conduct intended functions, and beneficial to improve safety and regularity. Moreover, "Too often" testing can lead to unnecessary production loss, with major economic consequences, and the danger/risk of test-induced errors. "Too less" testing can lead to the valves failure, which in a result could have major consequences in relation to safety and long downtime during repairs.

There are a number of test methods (differential pressure test, partial stroke testing etc.) used for different safety critical valves, because Valve design, the consequences of downtime, environmental aspects of the testing, etc. varies between different safety critical valves. The choice of inappropriate test regimes can lead to unnecessary downtime and environmental emissions in testing. Thus these different test methods have great influence on the effects of changing the test interval of the safety critical valves.

It is not simple and easy to clarify and conclude, which case of changing the test interval is more appropriate in connection with all the effects related to the change of test interval of these valves. As there are many factors (degradation mechanism, failure modes, testing methods, regularity, production effects) which needs to be deeply analyzed and evaluated for future research.

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Abbreviations

- NPD Norwegian Petroleum Directorate
- ESD Emergency Shut-Down
- ESDV Emergency Shut-Down valve
- SCV Safety Critical Valve
- PSD Process Shut Down
- PSAN Petroleum Safety Authority Norway
- PA Production Assurance
- PSA Probabilistic Safety Assessment
- CORD Coordinated operation and maintenance offshore
- NCS Norwegian continental Shelf
- SIS Safety Instrumented Systems
- MMS Maintenance Management System
- RCM Reliability Centred Maintenance
- RBI Risk Based Inspection
- TPM Team Productivity Management
- PM Planned Maintenance
- PLM Planned Lifetime Management
- LCC Life Cycle Cost
- OEE Overall Equipment Effectiveness
- OLF Norwegian Oil Industry Association
- IEC International Electrotechnical Commission
- ISO International Organization for Standardization
- CMMS Computerized Maintenance Management System
- SAP System Applications and Products
- RNNS Risikonivå på norsk sokkel
- OREDA Offshore Reliability Data

Definitions

Production assurance: Also referred to as regularity, is a term used to describe how capable a system is to meet demand for deliveries or performance [35].

Availability: The ability of an item to be in a state to perform a required function under given conditions at a given instant of time or during a given time interval assuming that the required external resources are provided.

Production Availability: The ratio of production to planned production, or any other reference level, over a specified period of time [35].

Risk: Risk is defined as combination of possible consequences and associated uncertainties (quantified by probabilities)'' [2].

Uncertainty: Lack of knowledge about the performance of a system (the 'World'), and observable quantities in particular

Failure: Termination of the ability of an item to perform a required function.
Note 1: After failure the item has a fault.
Note 2: "Failure" is an event, as distinguished from "fault", which is a state.

Failure mechanism: The physical, chemical or other processes which lead or have led to a failure.

Failure mode: The effect by which a failure is observed on the failed item.

Safety system: A system which realises one or more active safety functions [27].

Safety functions: Physical measures which reduce the probability of a situation of hazard and accident occurring, or which limit the consequences of an accident [27].

1. Introduction

In [27], §7 of the Activities Regulations it is stated that Facilities shall be equipped with necessary safety functions which at all times are able to:

a) Detect abnormal conditions

b) Prevent abnormal conditions from developing into situations of hazard and accident,

c) Limit harm in the event of accidents

Moreover, facilities shall have an emergency shutdown system, e.g. safety critical valve, which would be able to prevent situations of hazard and accident from developing and to limit the consequences of accidents, on safety functions. This system shall be able to perform the intended functions independently of other systems.

According to PSAN (Petroleum Safety Authorities Norway) ‘‘requirements for testing of safety critical valves’’ emphasizes that there should be annual testing of all safety critical valves and intervals for verification have to be established based on; requirements to reliability, knowledge about failure conditions, knowledge about possible consequences from failure conditions, and knowledge about valve characteristics [7].

In testing of safety critical valves means that production must be shut down, the valve must be closed, pressure downstream the valve is bled off, and pressure build-up is measured.

It has been observed that often these tests are carried out during turnarounds, not influencing production downtime, even though test are labour intensive, costs related to such test are limited but sometimes the situation is different. Some oil and gas plants do not perform turnarounds each year and production may have to be shut down for hours because of these tests. In most cases these shut downs are also affecting other installations. This is of course an expensive operation that the operators want to limit to what is needed to maintain the required safety level; not only because of the loss of production and loss of income, but also because a shut down of the process and manual intervention into the hydrocarbon system has a negative effect on the safety level in it self (PSAN, 2004) [7].

For instance, if we focus on the barrier functions of the valves, and if we prove the same safety level with alternative test procedures or risk reducing measures then we could be able to justify an increase of test intervals of safety critical valves; [7]

1.1 Background

Modern production systems are large, complex, automated, and integrated. Failures occur more or less frequently in these complex and large systems. For a production plant, the consequences of failure include high maintenance cost, possible loss of production, and exposure to accidents. It can also lead to annoyance, inconvenience and a lasting customer dissatisfaction that can play havoc with the responsible company's marketplace position [16]. So, it is important for the plant engineers and managers to make decisions that can reduce or eliminate the probability of failures or/and their consequences as well as uncertainties in production processes to get better production assurance.

Production Assurance (PA) is introduced by the Norwegian oil and gas industry, which plays a significant role in supporting the decision-making process for managers and engineers dealing with the challenges of meeting various customer requirements as well as production control needs. Therefore, there has recently been a high degree of interest in use of the production assurance concept [15].

Production assurance (also referred to as regularity) is a term used to describe how capable a system is to meet demand for deliveries or performance [35]. Production assurance may be quantified by various measures like production availability, throughput capacity, deliverability, or demand availability. The PA concept includes several other concepts, such as reliability, maintainability, availability, and maintenance support performance. Some of these concepts, and their relationships, are illustrated in figure 1. In the following section, different concepts, of production assurance are briefly reviewed and discussed.

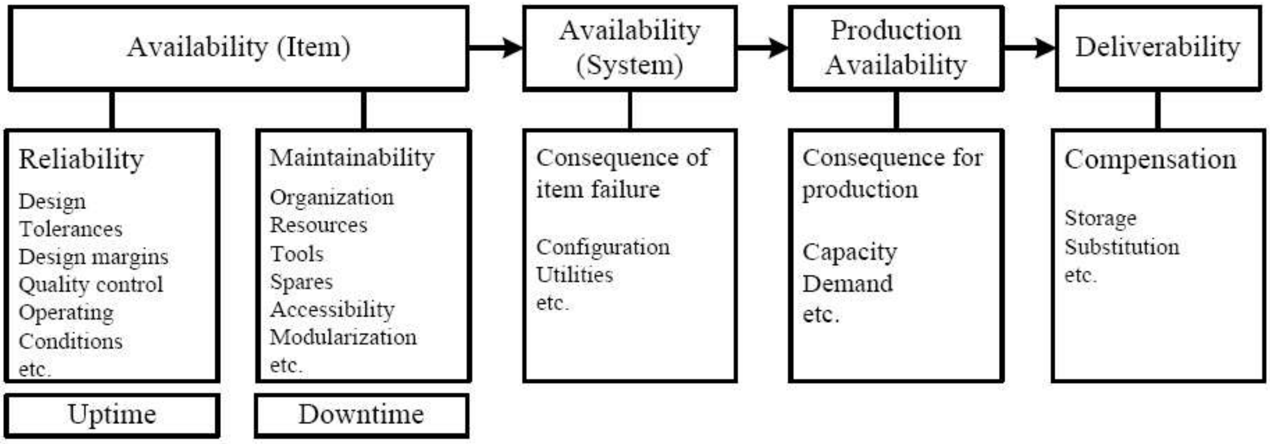

Figure 1, Relationship between production assurance terms [35]

Effective maintenance is necessary to ensure the reliability of plant/equipment. If equipment is unreliable, the profitability of a business can be greatly decreased. Therefore, the benefits of employing the efficient maintenance strategies cannot be underestimated.

Effective equipment maintenance ultimately dictates plant reliability and has great impact on the success and profitability of a business unit. There is an increasing industry focus on safety, risk avoidance and environmental awareness, which emphasises the importance of avoiding failure through successful maintenance. As a consequence, maintenance practices often account for an overwhelming percentage of budget expenditure. The financial and safety benefits of employing efficient and effective maintenance strategies for equipment cannot be underestimated.

The Norwegian safety regulations have two kinds of requirements related to maintenance:

1. High level requirements stating that installations, systems and equipment should be maintained in a prudent manner.
2. Detailed and prescriptive requirements for a system or a piece of equipment to be tested or inspected at certain intervals [22].

Testing and maintenance of the valves is carried out in accordance with the maintenance programme to increase the probability that the valves are going to fulfil their intended functions. Moreover, the testing of safety critical valves are essential because it contributes to improve safety. Therefore, we wish to test these valves "often enough", but not "too often", but what is often enough? This is the one question, which is concerned by both authorities and different players in the current industry.

1.2 Thesis objective/Problem Statement

This thesis is a part of RAMONA project which focuses on regularity and deliverability of the Norwegian gas transport system.

In production plants, generally incidents and events occur from both safety-related and technical integrity-related concerns. “Safety integrity related incidents are those endangering harm to people. Working without Personal Protective Equipment (PPE), personal injuries, and fire and explosions are some of the examples that come under safety integrity-related incidents. Technical integrity-related incidents on the other hand, refers to a wide area of technical incidents arising from day to day operations, and those resulting in the possible reduction or loss of daily production’’; see [17]

The main objective of this thesis is to ‘‘discuss the effects of changing the test interval of land based safety critical valves in hydrocarbons transport systems’’.

Changing test interval means increase or decrease of the interval period compare to current standard test interval (which is one year) followed by industry.

1.3 Contents Of Report

This master thesis consists of seven (7) chapters, in chapter 1, an introduction and background information related to the topic has discussed, and then main problem statement of the thesis has been explained.

The purpose of chapter 2 is to give basic theoretical concepts related to societal safety, risk, risk analysis and risk management including different decision making tools and their pros and cons will be discussed and explained.

Chapter 3 talks about different laws, regulations, standards, guidelines about Risk management, maintenance management, barrier systems, and specifically safety critical components and their maintenance will be discussed.

First part of chapter 4 will give a discussion about basics of valve, valve types and characteristics, performance and pros and cons of these valves. In the 2nd part of this chapter, explains why we need to test valves, different failure mechanisms, failure modes have discussed. In the last part, safety critical valves have been discussed with their testing methods, functions, intervals, etc.

Chapter 5, first discusses industry challenges in connection with changing of test interval of land-based safety critical valves and second part elaborates the effects or consequences of changing the test interval of safety critical valves and discussed with different dilemmas in section 5.3

In chapter 6, a case study is described, which is based upon chapter 4 and chapter 5 of this report. This case study is about one land-based gas process plant, among others, regularity of production and equipment is main objective of the operator, moreover, safety critical valves have been used as en emergency shutdown valve (ESDV) in this case study. The main theme is to discuss effects of changing the test interval of the safety critical valves used in this processing plant.

Lastly, chapter 7 will summarise the whole discussion of this report and makes some fine conclusions.

2. Risk Management

In this chapter, firstly societal safety is defined and then there are some concepts which needs to bee understood for having good picture of Risk management has been discussed.

2.1 Societal Safety

As a student of Master program in ‘‘Societal safety’’, It is first necessary to briefly discuss about societal safety .According to [24], it is defined as:

> *“The ability society has to maintain critical societal functions, protect the life and health of the citizens and meet their basic requirements in a variety of stress situations”*

Societal safety is a systematic process of applying scientific principles in dealing with threats, dangers, risk, losses and other dynamic side effects of modern society.

One can say that the state is a key actor and ultimately responsible for the societal safety. In addition, the state needs ability to establish and maintain public confidence in critical social institutions and finally the state build mutual trust among different groups within the population.

2.2 Risk Analysis

Risk can be defined as ’combination of possible consequences and associated uncertainties (quantified by probabilities)’’ [2]

Similarly another way of defining risk can be a combination of the probability of occurrence of harm and the severity of that harm. Risk may be expressed qualitatively as well as quantitatively.

The definition implies that risk aversion (i.e. an evaluation of risk which places more importance on certain accidental consequences than on others, where risk acceptance is concerned) should not be included in the quantitative expression of risk. It may be relevant to consider on a qualitative basis certain aspects of risk aversion in relation to assessment of risk and its tolerability. [3]

The implication of the definition is further that perceived risk (i.e. subjectively evaluated risk performed by individuals) should not be included in the expression of risk [34].

When accident consequences are considered, these may be related to personnel, to the environment, and to the assets and the production capacity. These are sometimes called “dimensions of risk” [3].

Risk is also expressed as ‘’uncertainty of the performance of a system, quantified by probabilities of observable quantities’’ [1].

It is very necessary and prerequisite for discussing risk analysis and risk management that there should be clear perspective about risk. There exists many definitions of risk, but this thesis will use following definition of risk by [2]:

‘’Combination of possible consequences and associated uncertainties (quantified by probabilities)’’

Moreover, this definition can be observed as an extension of the ISO standard (ISO, 2002) definition; combination of the probability of an event and its consequences, and in this manner uncertainties are expressed by probabilities. One can not necessarily say that low uncertainty means low risk or high uncertainty means high risk. For example in a specific diving activity in offshore involves two possible outcomes say (0, 1) and similarly two fatalities (0,1), have two alternatives A &B. It has uncertainty (probability) distribution (0.6, 0.4) and (0,1) respectively. Hence for alternative ‘A’ there is higher uncertainty and lower risk to initiate activity while alternative ‘B’ shows highest risk because of certain fact that if a person start this activity he/she will get accident. So as a result we can say that for understanding clear perspective about risk, it is necessary to see both dimensions [1].

Normally a risk analysis is a systematic evaluation of risk connected to an installation, system, subsystem, project, job etc. Risk analysis search to identify incidents which potentially could develop into accidents and then mapping both the consequences and probabilities of a such an accident.

The main objective of performing risk analyses is to support decision-making processes. Risk analysis enables us to take both certain and uncertain quantities into account and calculate to what extent specific events or scenarios can be expected to occur in the future. Thus risk analysis provides a basis for comparing alternative concepts, actions or system configurations under uncertainty [12].

Among other objectives, risk analysis are useful to:
To ensure adequate safety, value adding and cost effectiveness for existing and future

petroleum industry developments.
To prevent all events or chain of events that may cause loss of life, or damage to health, the environment or assets.

A model below see figure 2, presenting the process of executing risk analysis and getting the results. This model performs risk acceptance criteria and therefore is in accordance with the management regulations and is a common way of performing risk analysis and the use of risk acceptance criteria [34].

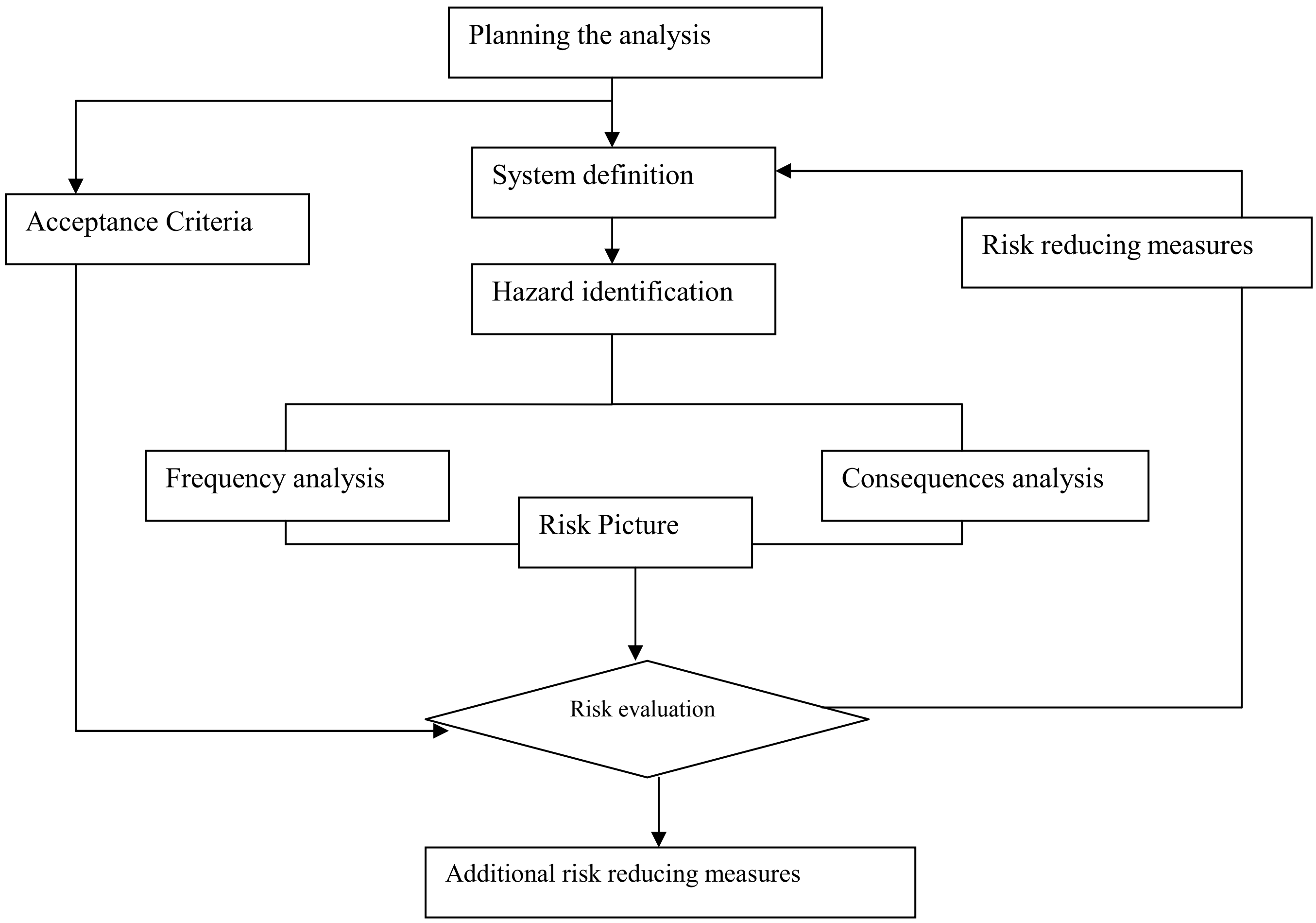

Figure 2: Risk estimation, analysis and evaluation [34]

2.3 Risk Management

The purpose of risk management is to ensure that adequate measures are taken to protect people, the environment and assets from harmful consequences of the activities being undertaken, as well as balancing different concerns, in particular HES (Health, Environment and Safety) and costs. Risk management includes measures both to avoid the occurrence of hazards and reduce their potential harms [2].

It is acknowledged that the ability to define what may happen in the future, assessment of risk and associated uncertainties, and to select best alternative lies at the heart of the risk management system, which helps in many range of decision-making, from allocating wealth to safeguarding public health, from exploring new reservoirs to decommissioning/disposal of a project, from paying insurance premiums to wearing a seat belt etc. Risk management has the following set of goals:

• Identify, assess and control risks that threaten the achievement of the defined project objectives, like regularity, schedule, cost targets and performance of project delivery. These risk management activities should support the day-to-day management of the project as well as contribute to efficient decision making at important decision points.

• Develop and implement a framework, processes and procedures that ensure the initiation and execution of risk management activities throughout the project.

• Adapt the framework, processes and procedures so that the interaction with other project processes flow in a seamless and logical manner.

For instance, exploring and producing oil and gas involves risky investments. When petroleum executives make investment decisions on petroleum projects, they face several uncertainties including future oil and gas prices, reserves, efficient maintenance, environment, petroleum prospective-ness, fiscal terms, current degree of exploration and operational peculiarities. How can the petroleum and gas industry cope to these and other challenges, and making decision on the allocation of capital among competing projects in diverse geographical areas.

Suppose we can take an example of oil and gas company which has to choose between two types of area (just assuming North sea and Barent sea) for their new project related to Oil and gas field. To support the decision making ,the company evaluates the concepts with respect to a number of factors i.e. investment costs, operational costs, schedules, market deliveries and regularity, technology development, reservoir recovery, environmental aspects, safety aspects, external factors. After evaluation and measuring these factors qualitative and quantitatively, an alternative will be chosen. The best alternative is one which is acceptable for all stake-holders and considered to be the one giving highest profitability, almost no fatal accidents and no environmental damage. Since it is impossible to know with certainty which alternative is the best as there are risks and uncertainties involved. So the decision of choosing a specific alternative has to be based on predictions of costs and other key performance measures, and assessments of risk and uncertainties.

Similarly when we discuss the effects of changing the test interval of safety critical valves, then one have to consider the factors like the economic cost, maintenance cost, production loss, regularity, process shut downs, maintainability and availability.
Leakage acceptance criteria, testing methods, testing cost etc. After evaluating and measuring these factors, one of the best alternatives could be choose, which would be acceptable to all stake-holders.

2.4 Decision Making and Risk Management

Now a days, there is a great need and importance for the implementation of risk management in various industries and in society. We all agreed that risk cannot be eliminated but must be reduced and managed. It seems to be high expectations, that risk management is the proper framework for obtaining the proper balance between benefits and burdens, i.e. exploring opportunities on the one hand and avoidance of accidents and catastrophes on the other.

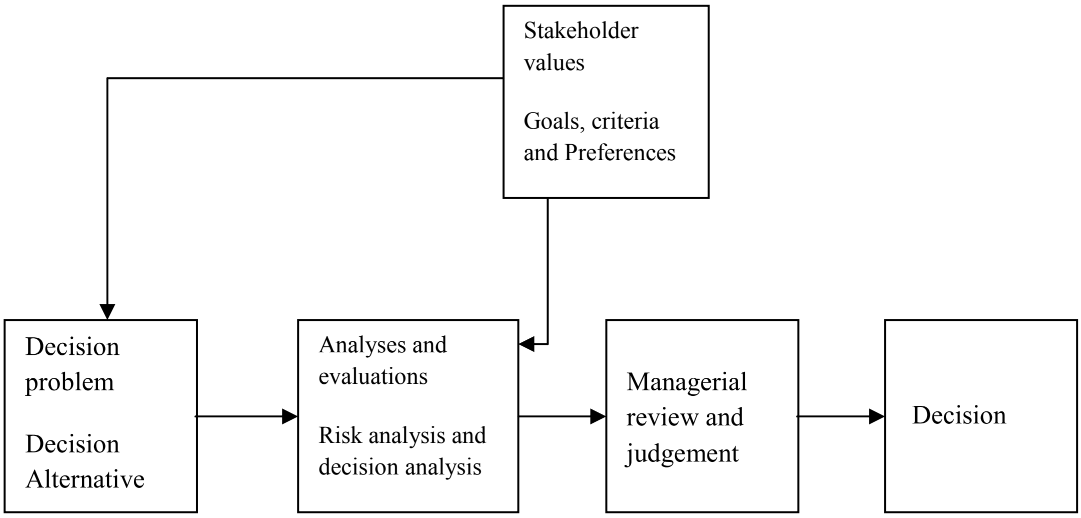

Figure 3: Basic structure of the decision-making process [1]

In figure 3: illustrates a decision-making process described by [1]. In this process, decision alternatives should be generated, analysis and evaluations should be carried out, the alternatives should be generated, analysis and evaluations should be carried out (which provides important background information to decision), the alternatives should be reviewed, and finally, a decision should be made. Both the analysis and the review process are affected by the stakeholders' values, goals, criteria and preferences [10].

Decision making is obviously not only about making decisions, but making good decisions. Risk management involves decision making in situations involving high risks and large uncertainties, and such decision-making is difficult as it is hard to predict what would be the consequences (outcomes) of the decisions. A number of tools are available to support decision making in such situations, such as cost-benefit analyses, cost-effectiveness analyses, Bayesian decision analysis, risk and uncertainty analyses and risk acceptance criteria. [1]

2.4.1 Decision Supporting Tools

There are several different views regarding decision making and all have their pros and cons. Here I would like to give brief overview of some of the approaches based on [1]:

<u>Expected utility paradigm:</u>

In expected utility paradigm, suppose if a person is coherent in his preferences among consequences and his opinions about uncertainty quantities, then expected utility approach is attractive as it provides recommendations based on a logical basis. On the other hand in expected utility approach preferences have to be specified for all consequences, which is a difficult task in practice, moreover, almost no role of management in this case.

Cost-Benefit Analysis:

The economical aspects of a project, plant, system etc. are of most importance, and usually one will have to document that the benefit of solutions and efforts is higher than the associated cost. Cost benefit analysis is a way to evaluate the advantages and disadvantages between different efforts .The main advantage with the use of cost benefit analysis is that it forms basis for prioritizing between alternative solutions. In connection with risk analysis where different risk reducing measures are identified, cost benefit is of great value. There is only one thing, i.e. money that prevents all risk reducing measures to be implemented. If one should reach a risk level as low as possible regardless of the connected cost, every identified risk reducing measure should of course be implemented but however there is rarely the case.

By performing a cost benefit analysis, one will get a good decision support for choosing between alternative risk reducing measures. The method will search to assign monetary values to each benefit, thus making the decision between the alternative solutions easier. There are several ways to perform such an analysis.

Common ways to perform such analysis is to assign monetary values for future investments, cost of testing, cost of poor reputation, and cost of a human life and so on. These are all parts of what one call cost benefit factors, all contributing to visualize possible effects of a project at a certain point.

However when we see cost benefit analysis, it requires us to indicate the value of a statistical life, not the value of a life. As we acknowledge that a life has in principle an infinite value. So, there should be no amount of money that a person would find sufficient to compensate the loss of life. While a statistical life has a finite value, considering that point; decisions need to be taken that balance benefits and risks for loss of life. It means we are willing to accept the value of loss, given that this benefit is present.

Multi-attribute Analysis

In many cases, we perform a multi-attribute analysis without any explicit trade-offs and is rather easy to conduct and works in practice. After assessing the various attributes, costs, production loss, regularity, safety, environment, political aspects, etc., separately then it is a management task to make a decision by balancing the costs and benefits and thus we gain flexibility in situations involving many stakeholders. But again in some cases it lacks coherency in decision making.

For making a good decision, focus should be on situations characterized by a potential of rather large consequences and large associated uncertainties which relate to economic performance, possible accidents leading to loss of lives or environmental damage, etc. Risk and decision analyses plays very important role to support good decision making.

ALARP –principle

It is abbreviation for ‘As Low as Reasonable Practicable’ being used to make decision concerning risk. In Norwegian oil and gas industry, traditionally predefined risk acceptance criteria is used. Those criteria are made with basis in both internal/external regulations and objectives for the company. But when the ALARP principle is used, one do not stop when the estimated risk level is within the limits of risk acceptance rather one has to keep searching for other risk reducing measures and implementing them as long as it is reasonably practicable. Therefore, obviously cost efficiency and the ALARP principle has a strong relation in principle. The concept of cost efficiency is to evaluate the benefit of implementing further risk reducing measures. If the expected cost for implementing a new risk reducing measure is lower than the expected benefit, this risk reducing measure will be implemented. The ALARP principle could be followed when no more risk measures are regarded beneficial to implement, it means that the cost of further implementation is grossly disproportional with the expected benefit. The remaining risk level is then considered acceptable.

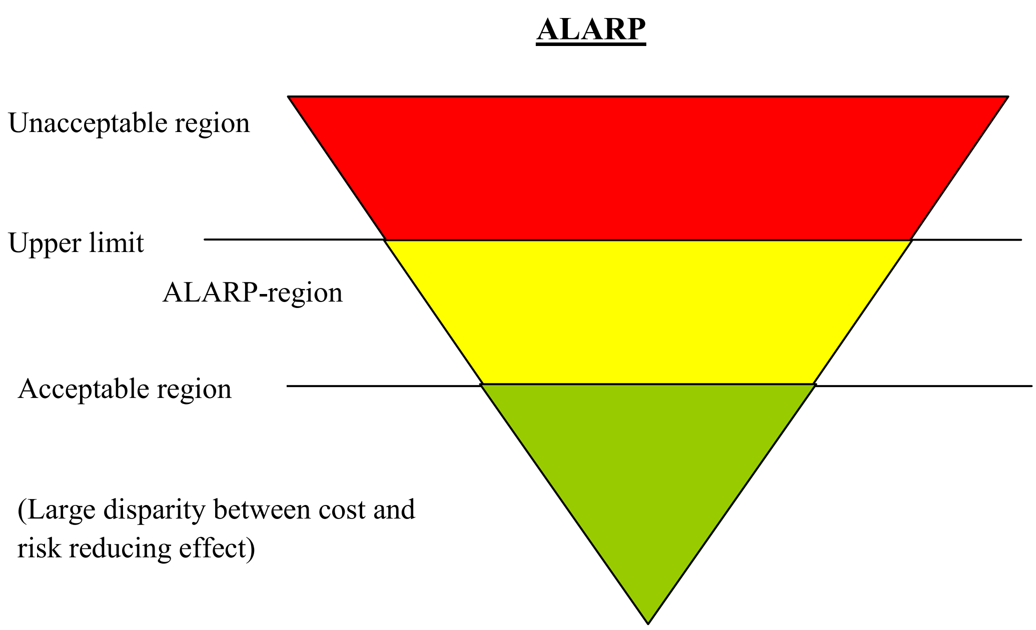

Figure 4: The ALARP principle is described according to [34]

One of best way to visualize the ALARP region is perhaps through matrix which is described below:

Risk Matrix

		Consequence			
		Catastrophic	**Severe**	**Moderate**	**Minimal**
Probability	**Often**				**ALARP**
	Probable			**ALARP**	
	Rare		**ALARP**		
	Unlikely	**ALARP**			

=Acceptable =ALARP Area = Unacceptable

Figure 5: Risk Matrix

The yellow part of the risk matrix represents the ALARP region, where further risk reducing measures have to be implemented if it is presumed to be cost effective .The red area represents a risk level unacceptable while the green area represents a risk level as an acceptable.

3. Regulations/ Standards

This chapter is about different regulations/standards presented by the authority of the Norwegian Petroleum Directorate (NPD) and the Petroleum Safety Authority Norway (PSAN) related to maintenance program and further related to safety critical systems.

The legislation consists of a two parts; resource management or ‘‘resource hierarchic’’ part and a health, environment and safety (HES) or ‘‘HES hierarchic’’ part; which further display different legislation levels.

In the HES area, the Norwegian Pollution Control Authority, the Norwegian Social and Health Directorate and the PSA (former NPD) co-operate on joint, total regulations relating to health, environment and safety on the Norwegian continental shelf. Hence, the HES regulations are issued in pursuance of the Petroleum Act, the Pollution Act, the Product Control Act, the Health Personnel Act, The Patients' Rights Act, The Communicable Diseases Control Act and Health related and Social Preparedness Act. The regulations are the framework regulations (Royal Decree), the management regulations, the information duty regulations, the facilities regulations and the activities regulations. Guidelines to the regulations have been prepared by [27]:

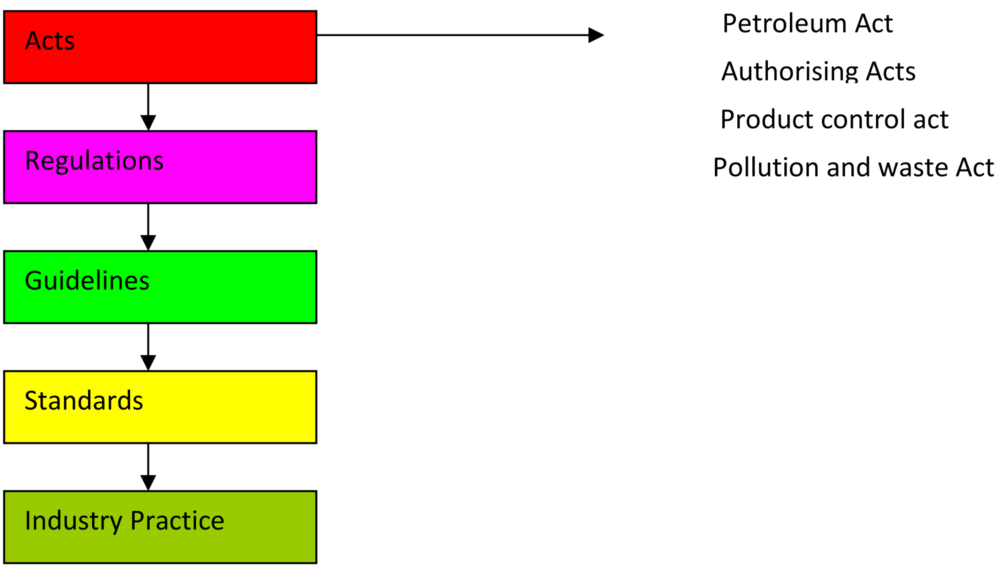

Figure 6: Hierarchical description of Acts/Regulations/Standards:

Regulations are connected together as shown in figure 6; Some points related to figure 6 is explained below.

Acts and regulations come on the first and second level in hierarchy. Then are the guidelines to regulations for detail explanation and similarly these guidelines showed some specific requirement which is called standards.

->*Petroleum Activities Legislation* (Acts and Regulations)

For example, Petroleum activities Act § 9-1 says ''The petroleum activities shall be conducted in such manner as to enable a high level of safety to be maintained and further developed in accordance with the technological development''

->*Guidelines to Regulations*

These are guidelines to different regulations relating to management, information duty, facilities and activities under the ''Joint regulations''. E.g. OLF (Norwegian Oil Industry Association)g recommended guidelines for the application of IEC (International Electrotechnical Commission) 61508 and IEC 61511 in the petroleum activities on the Norwegian Continental Shelf,

->*Standards:* The guidelines to the regulations often refer to recognized standards as a way to fulfil the functional requirements in the regulations. International Standards like ISO, API, IEC, OLF guidelines, EN and NORSOK standards are often used.

->*Industry internal governing documents like* ''Testing of safety critical valves in gas/condensate pipeline system''.

In NORSOK standards Z – 008, maintenance defined as –

> *"The combination of all technical, administrative and managerial actions, including supervision actions, during life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function"*

Maintenance includes activities such as monitoring, inspection, testing and repairing. This means that is all what is required to keep or to get the item or system back into desired operating condition.

According to §7 of the Activities Regulations; the safety functions at all times will be able to provide functions and should be designed so that they can be tested and maintained without impairing the performance of the function.

Similarly under the §32 of the Activities Regulations, it says that ‘’facilities shall have an emergency shutdown system which is able to prevent situations of hazard and accident from developing and to limit the consequences of accidents, on safety functions. The system shall be able to perform the intended functions independently of other systems’’. Moreover, the emergency shutdown system shall be designed so that it will go to or remain in a safe condition in the event of a failure which may prevent the functioning of the system.

More specifically, ‘’emergency shutdown valves shall be installed which are capable of stopping streams of hydrocarbons and chemicals to and from the facility, and which isolate the fire areas on the facility’’

In §44 (maintenance programme) under the Activities regulations states that the emergency shutdown system should be verified in accordance with the safety integrity levels stipulated on the basis of the IEC 61508 standard and OLF's Guidelines 070. In addition to that plants which are not included by this standard and these guidelines, the operability should be verified through a full-scale function test at least once each year. The test should cover all parts of the safety function, including closing of valves. The test should also include measurement of interior leakage through closed valves. Recording of the plant's or equipment's functionality in situations where the function is triggered or put to use may replace testing of the plant or the equipment,

The OLF (Norwegian Oil Industry Association) recommended guidelines for the application of IEC 61508 and IEC 61511 in the petroleum activities on the Norwegian continental Shelf, says that periodical functional tests shall be conducted using a documented procedure to detect covert faults that prevent the SIS (Safety Instrumented Systems) from operating according to the safety requirement specifications. The entire SIS shall be tested including the sensor(s), the logic solver, and the final element(s) (e.g., shutdown valves, motors) [36].

In addition, It is recommended to record and analyse activation of SIS functions to include the activation as part of the functional testing. If proper operation and documentation thereof exist for a period, the manual proof test for that period may be omitted. Observe that the spurious activation of an ESV due to a PSD, does not test the entire function of the same valve during an ESD action.

Moreover, In OLF guidelines it is mentioned that, some periodic interval (determined by the user), the frequency(s) of testing for the SIS or portions of the SIS shall be reevaluated based on historical data, installation experience, hardware degradation, software reliability, etc. Change of interval is handled as a modification. Any change to the application logic requires full functional testing, and shall be treated as a modification. Exceptions to this are allowed if appropriate review and partial testing of changes are done to ensure that the SIL has not been compromised.

4. Valves

Valves are mechanical devices specifically designed to direct, start, stop, mix, or regulate the flow, pressure, or temperature of a process fluid. Valves can be handle either liquid or gas applications [5].

Valves are used in pipeline systems to control the flow rate, the pressure, or the flow direction of a fluid. They can turn on, turn off, regulate, modulate or isolate the fluid.

4.1 Valve Types

4.1.1 Gate valves

Gate valves are used when straight-line, laminar fluid flow and minimum restrictions are needed. These valves use a wedge-shaped sliding plate in the valve body to stop, throttle or permit full flow of fluids through the valve. When the valve is wide open, the gate is completely inside the valve bonnet. This leaves the flow passage through the valve fully open with no flow restrictions allowing little or no pressure drop through the valve [19].

Gate valves are designed to operate fully open or fully closed; when fully opened, there is very little pressure drop across a gate valve, and when fully closed there is good sealing against pressure.

With the proper mating of a disk to the seat ring, very little or no leakage occurs across the disk when the gate valve is closed. However, some leakage may occur under very low back pressures. Another positive feature of gate valves is that they usually open or close slowly, which prevents fluid hammer and subsequent damage to the piping system.

The main limitation of gate valves is that they are not suitable for throttling applications. When gate valves are used in throttling applications, the flow tends to have high speeds near the gate seat, which leads to erosion. Also, in the partially open state, the valve is prone to vibrate, which can lead to damage. In general gate valves are more subject to seat and disk wear than globe valves, and repairs, such as lapping and grinding, are more difficult to accomplish.

4.1.2 Ball valves

Ball valves are simple shutoff devices that use a ball to stop and start the flow of fluid downstream of the valve. As the valve stem turns to the open position, the ball rotates to a point where part or the entire hole machined through the ball is in line with the valve-body inlet and outlet. This allows fluid to pass through the valve. When the ball rotates so that the hole is perpendicular to the flow path the flow stops [19].

This rotational-motion valve uses a ball-shaped disk with a hole bored through to stop or start fluid flow. When the valve handle is turned to the open position, the ball is rotated so that the hole lines up with the valve body's inlet and outlet. When the ball is rotated so the hole is perpendicular to flow, the valve is closed.

Advantage of ball valve is ease of operation, high flow capacity, and a high pressure and temperature tolerance. In addition, they have the ability to provide fire-safe protection, and they can handle severe service chemicals. Ball valves typically have lower cost and weight, and provide tight shutoff and low stem leakage. They can be adapted to for use in multiple port configurations.

4.1.3 Check valves

The purpose of a check valve is to allow fluid flow in one preferred direction and to prevent back flow or flow in the opposite direction. Ideally, a check valve will begin to close as the pressure drops in a pipeline and the fluid momentum slows. When the flow direction reverses, the check valve should close completely. Check valves can be of the following types: swing, lift and tilting disk.

4.2 Failure modes

A failure mode is a description of a fault. To identify the failure modes it is necessary to study the outputs of various functions. Some functions may have several outputs. Some outputs may be given a very strict definition, such that it is easy to determine whether the output requirements are fulfilled or not. In other cases the output may be specified as a target value with an acceptable deviation [20] . See Figure 7:

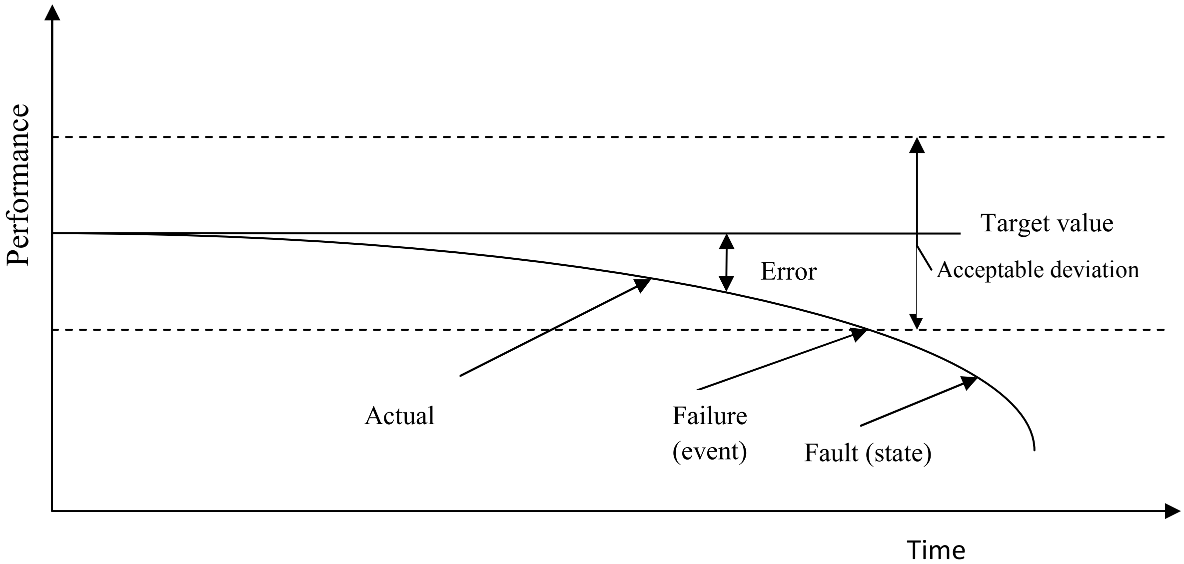

Figure 7: Illustration of the difference between failure, fault and error

When considering a process shutdown valve, it should be designed a specified closing time, for example, 10 seconds. If the valve closes too slowly, it will not function as safety barrier. On the other hand, if the valve closes too fast, it can probably cause pressure shock destroying the valve or the valve flanges. Closing time between 6 and 14 seconds may, for example, be acceptable, and it can be stated that the valve is functioning as long as the closing time is within the interval. The criticality of the failure will obviously increase with the deviation from the target value [20].

In OREDA (Offshore Reliability Data) project, although it's only related to offshore activities, but failure modes listed below are almost occurs in onshore valves also:

DOP	Delayed operation
EXL	External leakage to environment
FID	Faulty indication
FTC	Failed to close (Actuator failure)
FTO	Failed to open (Actuator failure)
INL	Internal leakage in closed position
LCP	Leakage in closed position
OVH	Overhaul
PLU	Plugged

SPO Spurious operation

OTH Other

UNK Unknown

It is important to understand that a failure mode is a expression of the failures as seen from the outside, that is, the termination of one or more functions. “Internal leakage” is thus a failure mode of shutdown valve, since the valve looses its required function to “close flow”. Wear of the valve seal, however, represents a cause of failure and is hence not a failure mode of the valve.

A classification scheme for failure modes has been suggested by [21]:

1) *Intermittent failures:* Failures that result in lack of some function only for a very short period of time.

2) *Extended failures:* Failures that result in lack of some function that will continue until some part of the functional block is replaced or repaired. Extended failures may be further divided into:

    a) *Complete failures:* Failures that cause complete lack of a required function

    b) *Partial failures:* Failures that lead to a lack of some function, but do not cause a complete lack of a required function.

    Both the complete and partial failures may be further classified:

    a) *Sudden failures:* Failures that could not be forecast by prior testing.

    b) *Gradual failures:* Failures that could be forecast by testing. A gradual failure will represent a gradual “wearing out” of the specified range of performance values.

    The extended failures are split into four categories; two of these are given specific names:

    a) *Catastrophic failures:* A failure that is both sudden and complete.

    b) *Degraded failure:* A failure that is both partial and gradual.

    The failure classification described above is illustrated in Figure 8, which is adapted from Blanche and Shrivastava (1994), [20]:

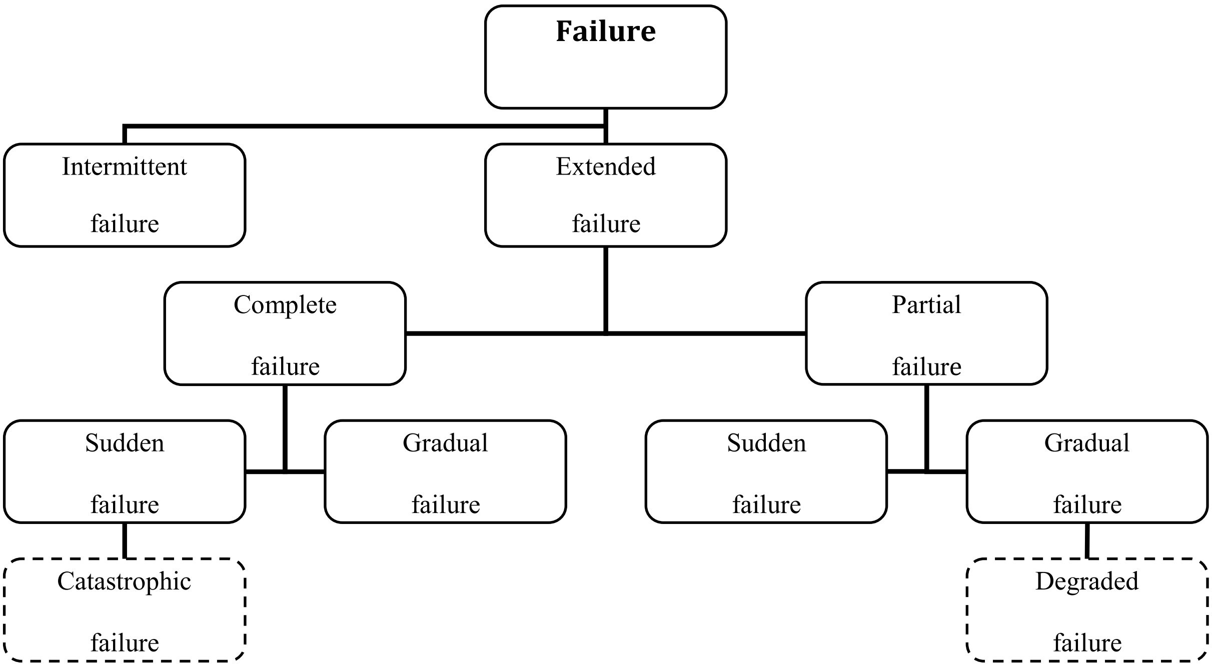

Figure 8: Failure classification [21]

4.3 Failure causes and failure effects

The function of a system usually consists of several sub functions. Failure modes at one level in the hierarchy will often be caused by failure modes on the next lower level. It is important to link failure modes on lower levels to the main top level responses, in order to provide traceability to the essential system responses as the functional structure is refined. This is illustrated in Figure 9, for a hardware structure breakdown [20].

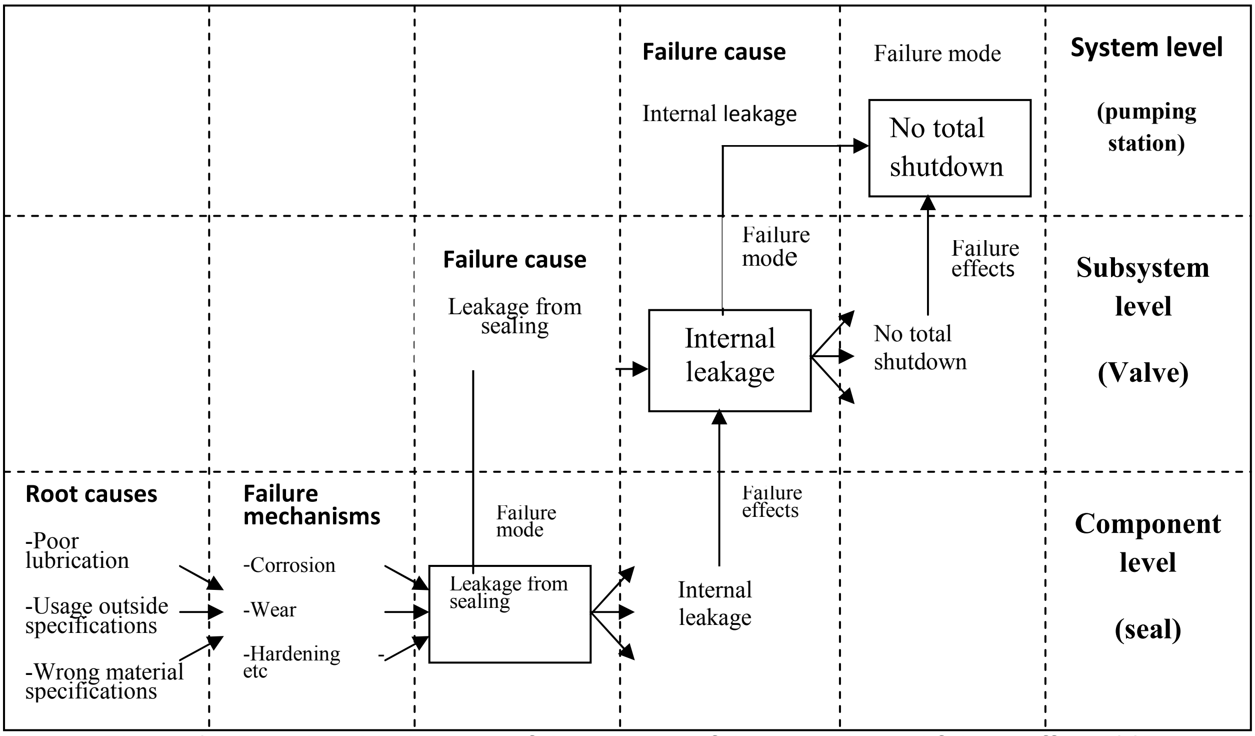

Figure 9 - Relationship between failure cause, failure mode and failure effect [20]

According to IEC (International Electrotechnical Commission) failure cause is "the circumstances during design, manufacture or use that has led to a failure." The failure cause is necessary information in order to avoid failures or reoccurrence of failures.

Failure causes may be classified in relation to the life cycle of a functional block as illustrated in figure 10, where the different failure causes are defined as:

1. *Design failure:* A failure due to inadequate design of a functional block.
2. *Weakness failure:* A failure due to a weakness in the functional block itself when subjected to stress within the stated capabilities of the functional block.
3. *Manufacturing failure:* A failure due to nonconformity during manufacture to the design of a functional block or to specified manufacturing processes.
4. *Ageing failure:* A failure whose probability of occurrence increases with the passage of time, as a result of processes inherent in the functional block.

Misuse failure: A failure due to the application of stresses during use that exceed the stated capabilities of the functional block.

5. *Mishandling failure:* A failure caused by incorrect handling or lack of care of the functional block [20].

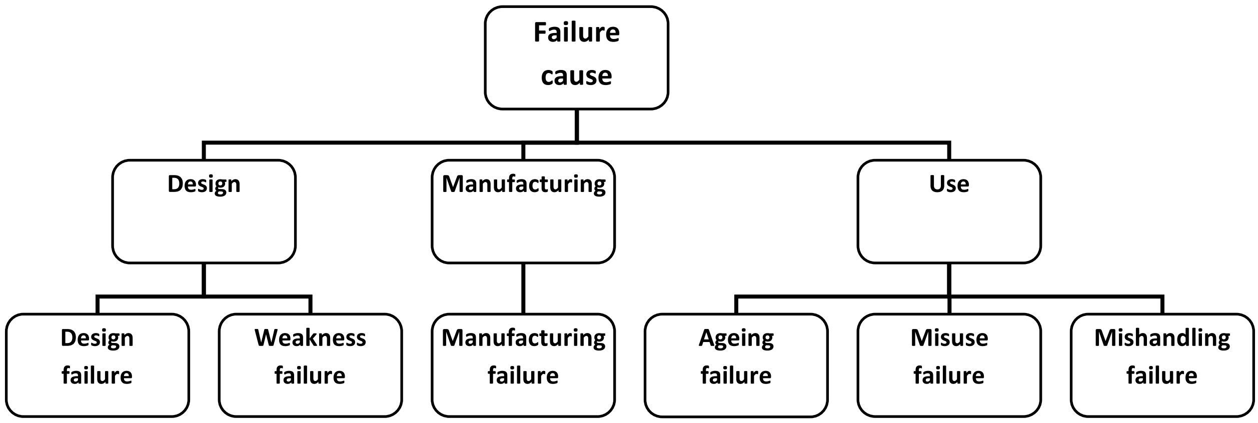

Figure 10: Failure cause classification [20]

These various failure causes are not necessarily separate; there could be overlap between some of them. For example, there is an obvious overlap between “weakness” failures and “design” and “manufacturing” failures.

Failure mechanisms are, according to IEC, the “physical, chemical or other processes that has led to a failure.” These processes can, for example, be wear, corrosion, hardening, pitting, oxidation etc.

This level of failure cause description is, however, not sufficient to evaluate possible remedies. Wear can, for instance, be result of wrong material specification (design failure), usage outside specification limits (misuse failure), poor maintenance (mishandling failure), and so forth. These fundamental causes are referred to as *root causes* (see figure 10), the causes upon which remedial actions can be decided.

A general picture of the relationship between cause and effect is that each failure mode can be caused by several different failure causes, leading to several different failure effects. To get a broader understanding of the relationship between these terms, the different levels of see figure 9, should be brought into account.

Figure 9, shows that failure mode on the lowest level is one of the failure causes on the next higher level and the failure effect on the lowest level equals the failure mode on the next higher level. The failure mode “leakage from sealing” for the seal component is, for example, one of the possible failure causes for the failure mode “internal leakage” for the valve, and the failure effect on the next higher level “internal leakage” resulting from “leakage from sealing” is the same as the failure mode “internal leakage” of the valve **[20].**

4.4 Why Testing of Valves/equipment

In NORSOK standards Z – 008, maintenance defined as –

> *"a combination of all technical, administrative and managerial actions, including supervision actions, during life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function"*

According to above definition, that is all what is required to keep or to get the item or system back into desired operating condition.
In §7 of the activities regulations it is stated that facilities shall be equipped with necessary safety functions which at all times are able to:

a) Detect abnormal conditions,

b) Prevent abnormal conditions from developing into situations of hazard and accident,

c) Limit harm in the event of accidents.

Similarly under the §32 of the activities regulations, it says that ''facilities shall have an emergency shutdown system which is able to prevent situations of hazard and accident from developing and to limit the consequences of accidents, on safety functions. The system shall be able to perform the intended functions independently of other systems''

More specifically, ''emergency shutdown valves shall be installed which are capable of stopping streams of hydrocarbons and chemicals to and from the facility, and which isolate the fire areas on the facility''

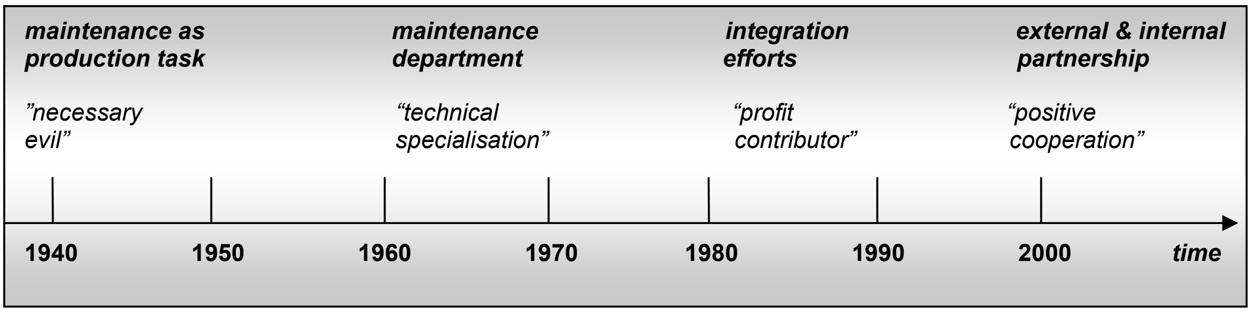

Figure 11: Maintenance management in a time perspective [22]

From figure 11, No more than a few decades ago, maintenance function was considered as an unwanted necessity, which is almost impossible to manage. This vision changed with time and maintenance became a separate service that had the centre attention on technical aspects, with the weight on specialization and efficient working methods. More recently, the progress was the realization that there were more efficient ways in terms of optimizing use of the means and more effective ways in terms of achieving the desired results and it was positive cooperation with other operating functions (Internal partnership) [22]:

In [41], it is stated that the purposes of monitoring, testing and other preventive maintenance actions are the detection of the degradation and prevention from the failure of the safety functions of systems and equipment and the assurance of prompt correction and restoration of these safety functions.

In order to optimize the level of inspection and maintenance activities, equipment/valves are inspected and tested to:

- To evaluate ageing effects of an equipment
- Check corrosion
- To prevent accidental events and damage
- To analyse dynamic degradation and failure mechanism.
- To estimate the probabilities of degradation.
- To access the consequences of different degradation cases and evaluate their severity according to the probabilities of the worst consequences due degradation.
- To perform the risk ranking for each component.
- To make appropriate recommendations, based on results in order to improve the operation and maintenance.
- To keep regularity flow constant, we need to test valves and other equipment periodically.
- To check the reliability and availability of the valve/equipment.

4.5 Safety Critical valves

In this report we, by the term Safety critical valves refer to emergency shut down system(ESD).

The emergency shut down system (ESD system) is a safety system that constitutes an important barrier (the ESD barrier). Fundamental tasks for the ESD barrier are to stop streams of hydrocarbons and chemicals to and from the facility, and isolate the fire areas on the facility. To manage to do this the ESD barrier are depending by the functionality of ESD valves [18].

Based on company interpretations [23], to define whether or not a valve is safety-critical is determined on an evaluation of the safety importance, i.e. how important it is for safety point of view. Therefore an analysis/assessment is needed to demonstrate how the risk level could be affected to the following failure modes:

- Valve fails to close on demand
- Valve fails to close within the specified time
- That it leaks

To identify safety critical valves; the required analysis/assessment is performed in to three steps:

1 – To Identify and illustrate the functions of the valve

Valve functions that are important to safety should be identified, i.e. the functions whose failure could result in an unacceptable risk, e.g. failure to close, leakage through closed valve.

A safety critical valve normally has more than one function, these are as follows:

- Does it have an ESD or PSD function?
- Is the valve part of an overpressure protection system?
- Is it designed to close/seal off the flow in both directions?
- Is the valve part of a double block and bleed setup?
- Other functions.

2 – To explain the effects on safety of the above failure modes

3 – To classify critical/unacceptable leakage rate through the valve

In the onshore plants, acceptable leakage rates generally set higher than for an offshore installation, the main reason for this is due to lower human risk exposure in onshore plants.

The acceptance criteria shown in Table 1, is determined on the basis of whether the contribution to risk of a leakage through the valve is acceptable, required some measures or not acceptable. According to the performed analysis of some onshore terminals and gas transportation systems [23], recommended reference values for leakage rates are established in table:

Table 1: Acceptance criteria for leakage through closed valves

Leak rate [kg/s]	Action
< 0.05	Acceptable
0.05 – 1.0	Perform specific evaluations, Plan for repair.
> 1.0	Not acceptable - repair

The wide range between the lower and upper limits, i.e. from 0.05 kg/s to 1.0 kg/s, is calculated and mainly based on practical considerations. Current industry experience shows that most valves (>99 of 100) satisfy the lower limit requirement i.e. <0.05 kg/s.

4.5.1 Testing Methods

There are a number of test methods have been used, such as measurement of the differential pressure over the closed valve, testing by depressurise cavity on the valve, partial stroke testing, microphone testing of the closed valve and microphone testing on open valve. Testing of safety critical valves can also be testing of function (close) or testing of leakage (including interior leakage or leakage through closed valve). The various testing methods are different with respect to the required performance in real shut-down situations.

- Testing of the function (close) with real shut-down case
- Testing of the function (close) with plant shut down

According to the company interpretations [23], this test is not considered complete since the forces acting on the valve body and valve internals are different from the real case. Thus the test does not disclose all relevant failure mechanisms.

- Partial stroke testing
  The main advantage with this test is that one can avoid shut-down of the plant, therefore it is only relevant while the plant is in normal operation; but this test is not considered complete because the test does not demonstrate full closure of the valve. Thus the test does not disclose all relevant failure mechanisms.

It is preferred that, a test should reflect the intended function in a real situation. According to company interpretations [23]; for an emergency shutdown (ESD) valve, this sort of testing should normally be complete closing of the valve with the system under pressure and in operation.

However, in some cases there may occur unwanted effects of these ideal tests, like economic consequences related to lost production, but also sometimes negative effects on safety and environment.

Based on the industry experience [23], the optimal system for testing therefore may well be one that applies different test methods, and combinations of tests, in a consistent program, individually tailored to the specific safety critical valve.

Testing methods of leakage through valve

Different testing methods are used to observe the leakage through the safety critical valve:

- Leakage test through closed valve with full pressure differential across the valve.
- Leakage test through closed valve with different pressure levels up- and downstream of the valve
- Leakage test through closed valve, by measurement of leak rates into the valve body/cavity.
- Leakage test with valve in open position

When we talk about testing of leakage rate through a closed valve; acceptance criteria for leakage rates through the valve at normal full differential pressure across the valve should be defined.

5. Challenges By Changing The Test-Interval

This chapter firstly in section 5.1, discusses the current industry challenges related to the testing of land-based safety critical valves. The testing of safety valves are beneficial in a way that they increase the chances that the valves are going to conduct intended functions but unfortunately, testing of safety critical valves also lead to some disadvantages. Such disadvantages can be for example, that a process must be shut down, which gives a disadvantage both in relation to the production loss and in relation to safety.

Moreover, section 5.2 and 5.3 describes the effects of changing the test interval of these valves, focusing on specifically two different dilemmas i.e. 'if test-interval is greater than one year' and 'if test-interval is less than year'.

5.1 Industry Challenges

Petroleum Safety Authority (PSA) took over regulatory responsibility for the supervision of technical and operational safety, as well as the working environment to the land-based plants i.e. Kårstø, Kollsnes, Sture, Tjeldbergodden, Mongstad, Melkøya and Slagentangen 1. January 2004. In this connection, they have introduced requirements for the testing of safety critical valves in the pipeline system.

Safety critical valves are used to perform one or several important functions, such as closing or opening to provide over-pressure protection, in order to minimize emissions to the external environment through the external leak and to isolate the maintenance activities. Testing and maintenance of the valves is carried out in accordance with the maintenance programme to increase the probability that the valves are going to fulfil their intended functions. A positive test results in practice gives increased belief that the valve will be able to carry out the intended function as needed. A negative test results indicate that something is not efficient as it should be, and therefore for example could followed up with more frequent testing and possible repairs, which in turn leads to increased belief that the valve will be able to carry out the intended function as needed.

We conclude that the testing of safety valves are positive in that they increase the chances that the valves are going to be able to conduct intended functions.

Unfortunately, testing of safety critical valves also lead to some disadvantages. Such disadvantages can be for example, that a process must be stopped (shut down); when the test will be carried out. This provides a disadvantage both in relation to the delayed production (downtime) and in relation to safety, in this case a large amount of hydrocarbon leaks occurs in connection with the up and down driving of processing. Moreover, it is also noted that work on the equipment itself is a risk, in a manner that a high percentage of hydrocarbon leaks can occur just by doing maintenance work on the equipment.

From above, we see that the testing of safety critical valves are desirable because it contributes to improve safety. At the same time, it is important to ensure that no tests are conducted too frequently. Therefore, we wish to test these valves "often enough", but not "too often", but what is often enough? This is the one question, which is concerned by both authorities and different players in the current industry.

There are a number of test methods, such as measurement of the differential pressure over the closed valve, partial stroke testing, microphone testing of the closed valve and microphone testing on open valve. The question of how often the safety critical valves should be tested can not be answered without having to consider which test methods that will be used; how often it is appropriate to test the valves are connected to test-methods. Microphone testing of open valve can for example, in principle be carried out continuously (every second), similarly more frequent testing obviously would not be appropriate in the case of the partial stroke testing. In principle, we do not need to restrict a test regime to just one test method. One can, if it is considered to be appropriate, combine different test methods with different test frequencies to test regimes. Thus the question is: which test regime is appropriate to use in safety-critical valves?

In addition, we can say that one test regime is not necessarily appropriate for all safety-critical valves. Valve design, the consequences of downtime, environmental aspects of the testing, etc. varies between different safety critical valves. Such variations mean that test regime for one valve does not necessarily should be the same as for another valve. In principle it can be carried out detailed studies for every safety critical valve. But it's not necessarily appropriate. Presumably it will be best to first categorize safety critical valves and then do individual evaluation for certain categories of safety critical valves and other categories can have the more standardized maintenance program. But which valves should be in which category?

In conclusion, we can say that the consequences of weak/fail maintenance programme for safety critical valves could be serious: "Too often" testing can lead to unnecessary production loss, with major economic consequences, and the danger/risk of test-induced errors. "Too less" testing can lead to the valves failure, which in a result could have major consequences in relation to safety and long downtime during repairs. The choice of inappropriate test regimes can lead to unnecessary downtime and environmental emissions in testing. For small variation in test regimes can cause the individual differences between the valves which could not taken good enough into considerations, and for the large variety of test regimes could lead to a complex system for planning and carrying out tests. It is obvious that the "good" test regime can be found by balancing all of the above considerations against each other. But to find such a balance is difficult, and is a challenge for all companies to have safety critical valves.

5.2 Effects of changing the test interval of safety critical valves

Changing test interval means increase or decrease of the interval period compare to current standard test interval (which is one year) followed by industry. In usual practical applications testing and inspection is the most relevant and effective means of deterioration control.

The observed failure frequency, together with a criticality evaluation, will be a basis for prioritizing the maintenance work and optimization of test intervals [2];

When one talks about effects of changing the test interval of safety critical valves, one should be very clear that every scenario of changing test interval has advantages and disadvantages, therefore some times ideal is not achieved in a simple way.

In fact cost, the level of risk and the benefits from risk control are closely linked see figure 12, we can say any expected increase in benefit from a decision may increase the risk if cost are kept constant or any reduction in risk may reduce the benefits as cost may increase.

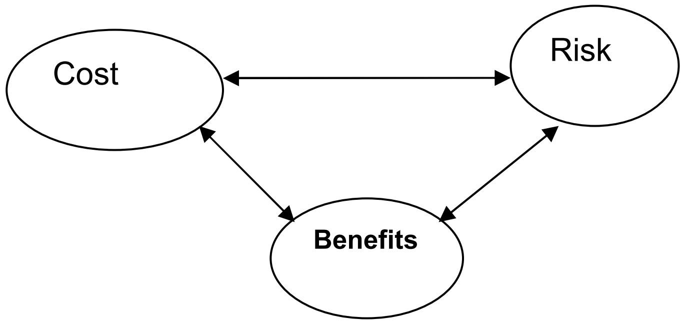

Figure 12: Relationship between risk, cost and benefit [22]

From figure 12, suppose one increases the test interval from 1 year to 2 years, then there would be some benefits like increase uptime of processing plant, avoidance of production loss, however this may also increase the risk related to probability of failure of a valve, degradation mechanism of valves like, corrosion, erosion, scaling etc.; and lastly cost remain constant. Thus, one of above these (cost, benefits, risk) can not be changed with out affecting the others.

5.3 Different dilemmas of changing test interval of Safety Critical Valve

There are different dilemmas that can be analyzed to see the effects of changing the test interval. In table 2, among others, specifically two dilemmas are illustrated i.e. in first dilemma, we set test interval greater than one year which mean 'not often' testing. Similarly in the other case, one can set test interval less than one year, which means 'too often' testing of these safety critical valves.

Many factors like safety, production loss, economic aspects, reliability, and probability of failures related to these two dilemmas will be discussed in section 5.3.1.

In company's internal document [23], it is mentioned that ''reference value for test-interval is 1 year, the program can deviates if satisfactory documentation is justified''.

Table 2: Different dilemmas of changing test interval of Safety Critical Valve

Test interval> 1 year		**Test interval < 1 year**	
Positive effects	*Negative effects*	*Positive effects*	*Negative effects*
▪ Save economic cost ▪ Reduction in maintenance cost ▪ Avoidance of production loss ▪ Less number of process shut downs ▪ Improve regularity	▪ May cause higher risk related to safety level ▪ Performance issues ▪ May cause higher frequency of occurrence of failure	▪ High reliability and functionality of equipment ▪ Improved safety level ▪ Higher maintainability and availability	▪ May increase leakage ▪ Maintenance cost increased ▪ More production shut downs may affects other installations ▪ Labour intensive

5.3.1 Discussion

There are some advantages and disadvantages related to each dilemma; see table 2. Firstly, we see that current company interpretations about testing of safety critical valve which is once a year; is quiet satisfactory. In the company's internal document [23]; is mentioned about safety critical valve that: ''the reference value for test interval is 1 year. The program may deviate from this, provided that adequate and documented grounds for this are stated''

There are many critical factors involve in each dilemma. Followings are the some ''critical factors and their impacts'' involved in changing the test interval of ESV. table 3:

Table 3: Critical factors (assumed) and their impacts, effecting on changing the test-interval

Critical Factors	**Impacts**		
	Interval <1 year	**Interval =1 year**	**Interval >1 year**
Failure Probability	Very Low	Low	Relatively high
Reliability	Very high	High	No big effects
Maintenance Cost	High	Relatively high	lower
Pigging	Little effects	Minimum Effects	May be relatively high effects
Safety	Maximum	OK	OK

Aging/Life	Ok	OK	OK
Corrosion	No effects	Minimum Effects	Relatively High eff.

Secondly, if we set test interval test interval greater than one year then what would be the effects, in this scenario most important factor which is probability of failure, may increase gradually by the passage of time, according to table 3; there would be relatively high probability of failure in this case; as compare to other dilemmas. One can also observe the probability of failure from the table 4, which shows different parameter to observe probability of valve i.e. valve type (including valve design, flow characteristics, performance, etc.), failure mode (e.g. leakage across the valve), testing method applied (e.g. function close testing with plant shut down, partial stroke testing) and age of valve on the time of valve failure.

Table 4: valve failure (assumed) history

Valve type	Date of Failure	Failure Modes	Testing method applied	Date of Valve installation or last recondition	Age at Failure x
1					
.					
.					
N					

When we analyse reliability, in terms of availability of safety critical valve, we can see from table 3, there are not so big effects on the equipment.

As we know land based critical safety valves are installed in corrosive environment, so this is also one of the important factor to analyse whether the effects of corrosion is ‘minimum’ or ‘relatively high’ in each dilemma. In this dilemma (test interval > 1 year) , we can say effects related to corrosive would become relatively high.

Another factor is the maintenance cost, if after analysis we see that the maintenance cost is almost same after increasing the test interval, then we can say there would be lower maintenance cost (as a whole) needed ; so it means this factor gives support to increase test interval.

Besides other factors , safety is also very important factor, in current practice there are no concerns related to safety issues, but if we set test interval less one year; then there are chances to have more internal leakage because of more process shut downs; as compare to other dilemmas. Safety issues of having test interval greater than one year supports longer test interval, in a way that according to [40]:

Twelve hydrocarbon leaks larger than 0.1 kg/s were reported at the land-based plants in 2007. However, these were only minor gas escapes, and all the incidents were categorised as small fires. Among other failures related to safety, leakage is the main failure mode in these safety critical valves. According to [23], In onshore plants, acceptable leakage rates (see table 5) generally set to higher than for an offshore installation, among others; due to lower human risk exposure etc. Industry experience also shows that most valves (>99 of 100) normally satisfy the lower limit requirement <0.05 kg/s. It means there would not be high consequences or risk related to safety point of view, if we increase the test interval as compared to today's practice.

Table 5: Acceptance criteria for leakage through closed safety critical valves

Leak rate [kg/s]	Action
< 0.05 kg/s	Acceptable
0.05 – 1.0 kg/s	Perform specific evaluations. Plan for repair.
> 1.0 kg/s	Not acceptable - repair

The main advantage of having test interval greater than one year is the reduction in maintenance cost and besides that regularity is also one of the most important benefits in this scenario. Because not in all plants, testing or inspection work is done during turnarounds. there are some plants and facilities, where production may have to be shut down for hours because of these tests. In many cases these shut downs are also affecting negatively to other installations. Therefore, this is obviously an expensive operation. In this scenario due to shut downs, we loose production assurance and equipment availability and similarly there is a loss of production and also loss of cost. In short by increasing test interval, on the one hand; we can avoid shutdowns/downtime and hence can improve regularity and on the other hand we can avoid negative effects on the safety level caused by shut down of the process and manual interference into the hydrocarbon transport system.

According to API Specification 6D ''the purchaser should examine the valve design for compatibility with pigging operations when ordering valves for use in pipelines requiring pigging.''

From company governing document [23], It is mentioned that events that could change the condition of valve are:

- Pigging operations
- Too often testing of function close

Pigging is now the most widely accepted term for any device which is inserted into a pipeline and which travels freely through it, driven by the product flow.

Pipelines need cleaning to remove fine solids that may have settled from the product as it traversed the pipeline. Also, some foreign material such as water may have separated from the product and are collected in low points in the pipeline water which can cause corrosion so it is important to remove it. Effects of changing the test interval of safety critical valves also depends on the periodic pigging operations, because excessive use of pigging also damage the valve sealing and valve body and thus cause valve degradation. If pigging operations interval decreases, then it could be a advantage for valve to avoid scaling, seal damage and hence, improve performance of safety critical valve for longer test interval than normal.

Effects of production-loss related to the safety critical valves:

Production is also a very important factor for changing the test-interval of these valves. If we test valves 'too often' , one can see due to process shut down and downtime of the processing plant there is large of production loss can be evaluated. In one processing plant , say production is assumed to be 440 million cubic feet per day, which off course is a very large production quantity..

According to company interpretations[23], it takes 6 hours to complete testing of valves and also cause down time for one day.

From this, we can calculate the One day production loss by:

Assume average gas price is 65 NOK (Norwegian krone) per thousand cubic feet. By multiplying gas price with production per day, we get

One day production loss = 440 x 65 x 1000 = 28,600000 NOK (28 million and 600000 NOK)

Moreover, it is mentioned in company's internal documents that normally 3 ton gas releases during testing of these safety critical valves. Thus, one can say testing too often can cause lot of production loss, economic loss and also risk to the other equipment connected with valve, and also risk to the environment.

6. Case Study

In this chapter, a case study is represented that is related to current industry practice. The case study presented is not based upon a real project. However, the decision-making problems in the case study are representative for a typical Norwegian oil and gas plants or facilities. This case study helps putting focus on some practical issues, and visualizes the arguments of this thesis title.

Description:

Case study is related to Norwegian gas transport system assumed name; 'X' Transport and main focus of this 'X' is on ''A'' gas processing plant in Norway. ''Y'' is the operator for the 'X' processing plant. This processing plant is assumed to play a key role in the transport and treatment of gas and condensate from important areas on the Norwegian continental shelf.

Operator of this plant wants to set the overall maintenance strategy in a way that they control maintenance activities so that the company's main business objective is achieved in an efficient manner. Following objectives should also be achieved:

Health, safety and environment (HSE):

The Processing plant will be operated and held up in a way that eliminate or decrease the HSE-related risks for the entire operation.

Regularity:

Maintenance of plant is to be managed in such way that ensures the requirements for optimal regularity for production and equipment.

Economy:

Maintenance is to be done with the best possible utilization of resources, which prevent or limit the equipment failure that lead to production loss or high repair / replacement cost.

Safety Systems:

It is indeed essential to prevent accidents in order to achieve the overall goals. Therefore safety systems are considered very important in connection with maintenance strategy and optimum maintenance strategy is always focused.
In this case study, safety critical valves are used as a main barrier system; these valves are also named as emergency shutdown valves (ESDV).

These critical safety valves are tested once a year, and now operator wants to make analysis and evaluation that if one changes the test-interval of these valves then what would be the effects on the overall company's goals and policies.

Discussion

There are number of factors, one have to consider while analysing and evaluating the effects and consequences of changing the test interval of these safety critical valves:

- Degradation mechanism
- Failure modes
- Testing methods
- Regularity
- Cost of testing
- Production effects
- Economic aspects
- Maintenance issues (reliability, availability)

Most of the onshore/off-shore process plants perform periodic scheduling of maintenance, which is called preventive maintenance. E.g. valves are taken out for service even if no signs of fault are detected.

In one case, during a maintenance shutdown about 600 valves were received for periodic maintenance. Out of these, only about 30% of them needed repair. For the remaining 42 valves it was not necessary to take them out of the plant for maintenance. These schedules are deliberately conservative because unscheduled out-ages are expensive [14].

Thus we say optimum maintenance strategy can effects on the changing of the safety critical valves

In addition, it means effects of changing the test interval of these valves can depend on selection of maintenance strategy. In this case study, we assumed that condition-monitoring is used to monitor a state of the machine, using the measuring parameters that observes something about the changes in the machine's technical condition. Following advantages can be achieved by doing proper condition-monitoring of these valves:

- May increase test interval instead of periodic scheduling
- Lower maintenance costs
- Repair equipment in the right time
- Reduce repair time
- Minimize the degree of future failure rate
- Better utilization of equipment / availability
- Increased security

Degradation mechanism

The reason that a valve degrades, can often be a combination of several sub causes, and can therefore is rather a very complex nature. The combined effects of several degradation mechanisms can higher than effects of each individual degradation mechanisms. For example combined effects of corrosion and fatigue, and the corrosion and wear. These synergy effects can be difficult to explain properly. To predict the effects of degradation mechanisms in an environment that is constantly in flux makes it even more difficult to predict the effects of the current degradation mechanisms that affect the processing plants/facilities.

When we analyse current degradation mechanism of these valves with respect to changing of the test interval, one can see that safety critical valves in the ‘‘A’’ processing plant are located in corrosive environment. Therefore, it could be possible that it gives negative effects to the performance and the reliability of the valve. On the other hand if we set test interval less than one year, than one can minimize the degradation effects of corrosion, erosion, scaling, dehydration of valve body etc.

Failure Modes

In this case study, we assumed following failure modes connected to safety critical valves:

- Valve fails to close on demand
- Valve fails to close within the specified time
- That it leaks

Among other failures, leakage (see table 6) is the main failure mode in these safety critical valves. By changing test interval what will be the effect on leakage, we have analyze this leakage acceptance criteria.

Table 6: Acceptance criteria for leakage through closed valves in process plant "A"

Leak rate [kg/s]	Action
< 0.05 kg/s	Acceptable
0.05 – 1.0 kg/s	Perform specific evaluations. Plan for repair.
> 1.0 kg/s	Not acceptable - repair

According to the company interpretations [23], in onshore plants, acceptable leakage rates (see table 6) generally set to higher than for an offshore installation, among others due to lower human risk exposure etc. Industry experience also shows that most valves (>99 of 100) normally satisfy the lower limit requirement <0.05 kg/s.

Now if we see [40]; twelve hydrocarbon leaks larger than 0.1 kg/s were reported at the land-based plants in 2007. However, these were only minor gas escapes, and all the incidents were categorised as small fires.

From above, one can say that if we set the test interval of safety critical valves greater than one year in this processing plant 'A' we can achieve many benefits including, regularity, reduction in maintenance cost, may avoid damage to valve etc.

History of Failure events

Here, one can use the history (assumed) of failure events related to these safety critical valves, which can be essential to analyze the clear picture and effects of changing the test interval.

Table 7: History (Assumed) of failure events related to failure modes of safety critical valves

Failure Mode	Events 2004	Events 2005	Events 2006	Events 2007
Valve leaks in the closed position	5	5	3	1
Valve fails to close on demand	1	2		
Valve fails to close within the specified time	3	2		1
External leakage in process liquid	2	2	1	1
Internal leakage in actuator	1	2	1	2

From table 7, one can evaluate that number of failure events related to those failure modes are almost decreasing every year, so this is also the good sign to set the test interval of safety critical valves greater than one year**.**

Testing Methods

There are a number of test methods used in this processing plant ''A'', such as measurement of the differential pressure over the closed valve, partial stroke testing, microphone testing of the closed valve and microphone testing on open valve.

According to industry internal document [23]; it is essential that, as possible, a test should reflect the intended function in a real situation. For an emergency shutdown (ESD) valve, this would normally be complete closing of the valve with the system under pressure and in operation.

The complete/ideal test may sometimes be difficult to perform in practice, because it may in itself represent a risk or a direct loss of economic value or can be harmful to the environment. So in this case study, one analyse different testing methods (not all) and their effect on changing of the test interval.

Table 8: Different ways of testing methods and their effects on changing test interval

Testing Method	**Test interval > 1 year**	**Test interval < 1 year**
Testing with plant shut-down	Less down time Improve regularity Probability failure may increase	More system shutdowns Valve can be damage Production loss More maintenance cost
Partial stroke testing	Avoid shut-downs Not full closure of valve Not complete Test	Not full closure of valve Not complete Test
Microphone testing	Continuous testing Could be expensive	Continuous Testing Could be expensive

From table 8, only three types of testing methods are illustrated; these methods have some pros and cons like if we test valves too often by testing with plant shut down case, we can get benefits in ‘‘A’’ processing plant in term of less number of down times and production capacity by improving regularity. This way of doing testing, on the other hand may cause high probability of failure as result of corrosion, erosion, wear etc.

If safety critical valves tested often then, on could have an advantage with partial stroke testing, that one can avoid shut-down of the plant, but this test is not considered complete since the test does not demonstrate full closure of the valve. So we can say test could not demonstrate all relevant failure mechanisms.

In the current Oil and Gas industry, some companies wants to increase test interval up to 2 years, for them, Microphone testing or ‘‘lyttetesting’’ could give a strong argument and suggestion except that this way of doing testing could be expensive because it needs almost continuous testing, we can assume say every 10 seconds.

Costs associated with the valve-maintenance

Cost of testing safety critical valves in this processing plant is assumed to be 5 million NOK on every year.

Table 9: Cost (assumed) related to testing of safety critical valves.

Cost	Cost of testing if test-interval > 1 year	Cost of testing if test-interval < 1 year
Cost related to testing to SCV	5 million NOK	5 million NOK

From Table 9, it shows that if one change the test interval of these valves, then cost of testing remain the same. However, In case of increasing test interval there could be possibility of some extra maintenance cost due to corrosion, erosion, cavitations, slug effects etc.

Effects of production-loss related to the valves

Production of processing plant 'A' is approximately 440 million cubic feet per day, which off course is a very large production quantity. Now, through analysis, one can say that if we set the test interval less than one year, it could have big effects.

In this processing plant it takes 6 hours to complete testing of valves and also cause down time for one day.

From this, we can calculate the One day production loss by:

Assume average gas price is 65 NOK (Norwegian krone) per thousand cubic feet. By multiplying gas price with production per day, we get

One day production loss = 440 x 65 x 1000 = 28,600000 NOK (28 million and 600000 NOK)

Moreover, normally 3 ton gas releases during testing of these safety critical valves. Thus, one can say testing too often can cause lot of production loss, economic loss and also risk to the other equipment connected with valve, and also risk to the environment as mentioned before, 3 ton gas releases during the testing.

Conclusion

Sometimes ideal solution is difficult to implement or t o achieve. Effects of changing the test interval of safety critical valves in this case study indeed have some advantages and also disadvantages in each aspect. The regularity and economical aspects of a processing plant are of most importance, and usually one will have to document that the benefit of solutions and efforts is higher than the associated cost. .The main advantage with the use of cost benefit analysis is that it forms basis for prioritizing between alternative solutions.. Moreover, many factors relevant to cost, safety, regularity, economic aspects, environment, political issues, etc need to be analyzed and evaluated specially benefits generated by different alternatives/activities for the company, society and for the individuals. Off course, generating alternatives and predicting their burdens and benefits is a basis for good decision making. From above case study, one can suggest that, instead of increasing test interval up to one year, if we increase the test interval up to six months, which means new test interval would be every 18 months. In this way, after evaluating the risk related to safety, health and environment, we can achieve optimum regularity, avoid production loss, avoid economic loss etc.

7. Conclusion

Testing and maintenance of the valves is carried out in accordance with the maintenance programme to increase the probability that the valves are going to fulfil their intended functions.

It is acknowledged that the ability to define what may happen in the future (e.g. what can be the effects of changing the test interval), assessment of risk and associated uncertainties, and to select best alternative lies at the heart of the risk management system.

We can say that the consequences of weak/fail maintenance programme for safety critical valves could be serious. "Too often" testing can lead to unnecessary production loss, with major economic consequences, and the danger/risk of test-induced errors. "Too less" testing can lead to the valves failure, which in a result could have major consequences in relation to safety and long downtime during repairs.

Of course, generating alternatives and predicting their burdens and benefits is a basis for good decision making, but when we have many factors like safety, production assurance, economic aspects, and etc. then sometimes ideal solution to the given problem is not achieved. When we talk about effects of changing the test interval of land-based safety critical valves, then one should realise that every scenario (increasing or decreasing or have a current test interval) has both advantages and some disadvantages related to safety, regularity, production loss, economic aspects etc.

Due to different valves (having different performance criteria, capacity rating, flow characteristics, response characteristics) use as a safety critical valves (e.g. ball , gate and check valve are normally used) different testing methods (like some needs plant shut down, others do not, e.g. partial stroke testing) applied to different safety critical valves, different testing criteria applied, so in this situation it is not easy to evaluate which testing method is best suitable, which type of safety critical valve to be best suited for different testing methods. As a result it is not easy to find one test-interval which is most appropriate in connection with related effects.

In the end, there should be a detailed study regarding selection of valves, individual evaluation of each testing method for certain categories of safety critical valves and testing criteria needs to be deeply analyzed and evaluated for future research on this problem.

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