

RISK-BASED DECISION MAKING IN THE PETRO-CHEMICAL INDUSTRY

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Abstract

In a changing world new procedures and methods are changing the face of maintenance. With the changes in legislation the maintenance practitioner is left with a wide variety of procedures which can be used to ensure a competitive advantage in a more and more global environment.

This script analyses and describes an option which can be used to ensure the optimal use of scientific procedures to ensure competitiveness in the next century.

Risk-Based-Inspection is analysed into its finest detail to find the scientific base building blocks and recommendations are made to ensure proper implementation of this procedure. A practical example is also given to show the procedure.

Due to the competitive nature of the subject all the necessary information is however not supplied.

Uittreksel

Risiko Gebaseerde Besluitneming in die Petro Chemiese Industrie

In 'n veranderde wêreld is nuwe prosedures en metodes van instandhouding aanhoudend besig om die wetenskap van Instandhoudingsbestuur te verander. Met die verandering in wetgewing is die instandhoudingsbestuurder blootgestel aan 'n aantal verskillende prosedures wat gebruik kan word om 'n voortgesette kompeterende voordeel vir die onderneming te verseker in 'n al hoe meer kompeterende wêreld mark.

Hierdie skripsie analiseer en beskryf die verskillende opsies wat beskikbaar is.

Risiko gebaseerde inspeksie word ge-analiseer in sy fynste detail om die wetenskaplike basis boublokke vas te stel. Aanbevelings word gemaak vir suksesvolle implementering van die prosedure. 'n Praktiese voorbeeld word ook verskaf.

As gevolg van die kompeterende voordeel wat verkry word uit die volg van die prosedure word al die nodige inligting nie weergegee nie.

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Abbreviations

CEO	-	Chief Executive Office
MFD's	-	Manufacturers flow diagrams
MIS	-	Management Information System
MPDS	-	Maintenance Planning and Development System
OHSA	-	Occupational Health and Safety Act
PDR	-	Plan do Review
PFD's	-	Process flow diagrams
PM	-	Preventive Maintenance
POD	-	Probability of detection
RACI	-	Responsibility, Accountability, Consultant, Inform
RBI	-	Risk Based Inspection
RCM	-	Reliability Centered Maintenance
SOP	-	Standard Operating Procedure
SSF	-	Sasol Synthetic Fuels
WG/004	-	Sasol Synthetic Fuels Internal Code

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1.1 INTRODUCTION

At this stage Sasol Synthetic Fuels (SSF) is following the traditional method of doing maintenance on the equipment installed in the plant. This philosophy comprises the following three basic strategies.

a) Time-based maintenance:

This strategy is followed where the process and the equipment concerned are suitable for this type of maintenance. The name states how maintenance is done, namely on a fixed time interval. In our situation this strategy is mostly enforced by statutory requirements.

b) Run to failure:

The run to failure option is mostly followed where failure of certain equipment will not result in significant production losses or injury to staff. In most of the installations there is standby equipment preventing significant delay in production. The equipment will normally not fail catastrophically, and failure of a certain component will normally not result in the failure of other components. *This strategy can best be described as operate to functional failure.*

c) Condition-based maintenance:

Rotating equipment is mostly maintained by using this strategy to determine the condition of the equipment. The equipment is then scheduled for maintenance when a certain alarm level is reached.

From the above it can be seen that all the current strategies are focused on availability and reliability of equipment, which is not necessarily the right focus. The following paragraphs gives an overview of the statutory requirements pertaining to the equipment

1.1.1 STATUTORY REQUIREMENTS

Petrochemical plants are subject to certain statutory inspections on equipment. These inspections are mostly done on an annual basis and the inspection interval can range from one year to ten years, depending on the type of equipment under consideration and the operating conditions. The maintenance frequencies are dictated by internal maintenance systems based on equipment history as required by the Occupational Health and Safety Act (OHSA). This strategy can be seen essentially as a fixed time strategy (time based maintenance).

From these basic requirements and strategies it is clear that the risk for production losses and safety is not taken into account in the decision making process involved. These strategies are also lacking when the economic implication of a certain decision is not clearly evaluated in the process of deciding on which strategy to choose. From the above statements it can be seen that there is a lack of a definitive rule base in the decision making process.

The second problem can be outlined as a lack of standardisation. In practice the maintenance strategies between plants differ due to human considerations and mechanical differences between facilities. This can for example be evaluated when taking into account that the loss of a Gasifier does not compare with the loss of a Synthol train. This can best be described by accounting for the loss of production and real risk. The lack of a standard approach tends to make the maintenance managers over conservative and thus they are over maintaining their equipment (this is due to a lack of fixed procedures for classifying equipment and determining risk).

Thus, it can be seen that most of the benefits can be realized on the statutory equipment, by evaluating the risk involved in the different scenarios.

With this background in mind we can now focus on the statement made in the previous paragraph, and answer the problem statement as is given in the next paragraph.

1.2 BACKGROUND

As highlighted in the previous paragraphs it can be seen that the problem of maintaining equipment in the optimum fashion, both functional and from statutory requirements is becoming a more and more difficult task each day. This can be seen from the pressure that is felt on companies from different outside groups as well as from governments of the day that are insisting more and more on the compliance of companies to certain rules and regulations. This has led to the concept of risk management in facilities. In the following paragraph an outline is given on what the study methodology will be for this script.

1.3 PROBLEM STATEMENT

In this script the following intriguing question will be addressed via different mechanisms, and it will be shown that there is no simple answer to the question, with no clear cut rules.

The question is: How do you produce more and yet spend less or rather, how do you balance the conflicting demands of minimum cost, maximum equipment performance and total safety in a petrochemical plant?

This question will be addressed by realization of the main- and sub-objectives as stipulated in paragraph 1.4 and 1.5.

Out of these two statements the real maintenance problem at hand will be highlighted.

1.4 OBJECTIVES

The main objective of this script is to do a study to find the optimum procedures to maintain mechanical pressurized equipment in a petrochemical plant.

This study addressed the frequency with which these statutory equipment must be inspected and the extent of the inspection.

A comprehensive implementation procedure has been drawn up and a detailed analysis of the implementation of the Risk-Based Decision Making program has been developed.

1.5 RESULTS OF THIS SCRIPT

The Risk Based procedure to be investigated aims to yield the following results;

- The elimination of unnecessary/excess maintenance. (Focus on the critical few).
- Increased plant availability if necessary and increased return on investment.
- Focus more on risk (potential and consequence).
- Lower planned maintenance and service's workload.
- Fewer people doing maintenance to maintain a certain level of plant output.
- Last benefit is optimized maintenance frequencies.

1.6 STUDY METHODOLOGY

The *first section* of this script will be a discussion of information on the topic. The information has been obtained from a comprehensive literature study, as well as from experts and other organizations which are currently doing work on the same subject.

The Second section will include the critical evaluation of the different approaches to handle the different aspects of the subject under discussion. In this section a solution will be described on what the optimum mixes of risk management strategies must be to maintain equipment in given systems or sub-systems according to the agreed on management of risk standards. This will include the evaluation of different procedures to evaluate risk.

Sasol Synthetic Fuels has an extensive history record keeping system on equipment, which will be used to the full potential to assist in classifying equipment, according to

the risk involved in operating the equipment at a certain level of production throughput.

Once a certain risk has been quantified, suitable maintenance strategies and inspection intervals can be applied to effectively manage the risk. Equipment condition monitoring follows to enlarge the knowledge base of the reliability of the equipment identified as high risk equipment.

This leads to a uniform process of measuring and determining maintenance philosophies/strategies for certain groups of equipment.

The *third section* is a decision on the optimum mix of strategies from the literature studies, and the development of a practical model which can be used to implement the risk-based decision logic.

The *final section* is a critical evaluation of the benefits that can be obtained. An empirical evaluation of the subject will be made to measure the effect this new philosophy will have on the maintenance budget of Sasol Synthetic Fuels. This measurement will also include an audit which will be compiled to determine the effect the new strategy will have on the overall maintenance efficiency of the strategies which are followed.

1.7 SUMMARY

In this chapter an overview is given on the current situation in Sasol Synthetic Fuels and what the format of this script is. A problem statement was also formulated to capture the essence of the problem at hand. In the following chapter an overview is given on the history of maintenance and how it developed into the present day science at most institutions that are seen as world class in the effective maintenance management of plants or manufacturing facilities.

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2.1 INTRODUCTION

The first step in describing the history of maintenance is to define what maintenance is. From literature the following definitions can be given for maintenance:

- **“to keep equipment etc. in repair” [Oxford : 1982 : p 610]**
- **“Maintenance is the work we do to prevent failures and to correct those failures we cannot prevent.” [Sasol Maintenance Manual]**

Maintenance can therefore be seen as an area of optimization that can help tremendously to enhance the overall performance of any industrial plant. This act of optimization should therefore include the study of the reliability of equipment and the consequent availability of the equipment under observation to be able to deliver or perform a specific function.

Maintenance is linked to the production capacity and the revenue earned by the product that is being produced.

Maintenance is a vital function in any plant that wishes to produce a specific or variety of products and still be profitable over a period of time.

The key objective of maintenance is to maximize our contribution towards long-term profitability by ensuring plant integrity, availability and performance, at minimum life cycle cost.

Keeping the function of maintenance in mind the history of maintenance will be discussed briefly in the following paragraphs.

2.2 HISTORY OF MAINTENANCE

The seven ages of evaluation of maintenance management may be considered to be:

- * The simple age - Maintenance on small/simple plant
- * The dark age - Fire fighting (when it break, fix it)
- * Task age - Fixed Time preventive maintenance (PM)
(Manual planning system)
- * The big brother age - Preventive maintenance (PM) inspection and routines
(Computerized planning)
- * The predictable age - Predictive Maintenance
(Central Maintenance Management System)
- * The team age - Area based maintenance (Multi-skilling)
- * The small team age - Manufacturing Technicians

[ANON : 198? : 2-1-1]

From the above list it can be derived that there has been a definite drive towards the team approach, as the science of maintenance management was studied more and more. It can also be seen from study's that maintenance as a business function became more complex as newer technology become available. This change became even more apparent as the electronic age dawned.

In the modern age of maintenance management and the drive for better quality and cost reductions to ensure survival in the market, it became necessary for the professional maintenance manager to understand all the different tools that are available and to ensure the efficient use of each technique to the advantage of each specific situation.

Next a brief overview is given on the broad categories of maintenance that are currently being accepted as standard for industry and which is also used by Sasol Synthetic Fuels to a more or lesser degree.

2.3 CURRENT MAINTENANCE PRACTICES

Currently, when developing maintenance strategies for a specific area in a plant or more directly for specific equipment in that area, the following action is taken to perform the maintenance task:

Primary action

This is the maintenance activity, which is done first. This may be service or condition monitoring measurement or routine inspection, if a policy of Preventive Maintenance is applied, it can also be the repair activity if an Operate to Failure policy is followed.

From the above it can be seen that the Preventive and Operate to Failure maintenance tasks in the primary action can be further divided into three basic modes of maintenance. These can be identified as:

- * **Condition Based Maintenance (CBM)** is the maintenance policy which relates to any preventive maintenance activity, which includes inspection, testing or measurement on a routine basis to detect the onset of failures and to prevent potential failures.
- * **Time Based Maintenance (TBM)** is the maintenance policy which relates to any preventive maintenance activity. This includes lubrication and greasing etc. or component change-outs and equipment overhauls, etc. carried out on a purely time based frequency irrespective of equipment condition or performance.
- * **Operate to Failure (OTF)** is the maintenance policy which relates to any maintenance activity which is initiated only by equipment failure on equipment for which no corresponding preventive maintenance (CBM or TBM) is done. In the case of “OTF” the primary action is the repair action and there is no secondary action [MPDS: 1995].

Out of the actions described in the primary actions above it can be seen that a secondary action can or will follow, which will be the physical maintenance activity. It must however be kept in mind that all of the processes as discussed must be done to optimized the maintenance process.

This is where Risk Based Inspection comes to play. This is a technique that was developed through scientific methods and is currently being developed and tested to ensure that the full maintenance function is being adhered to. It can be pointed out that Risk Based Inspection (RBI) is a mix of Condition Based Maintenance, Time Based Maintenance and in some instances it can also be operate to failure, depending on the application of the equipment in a specific process and the criticality of the equipment according to the risk ranking. Risk Based Inspections will be defined in Chapter 3.

2.4 SUMMARY

From the above discussion it can be seen that maintenance has become a science in which an invinite number of variables must be taken into account to determine the optimum maintenance strategy for each piece of equipment in a process.

At this stage it must be pointed out that the discussion of the Risk Based Inspection technique in this document will, only focus on pressure vessels in a petrochemical plant, in conjunction with their associated piping systems. The electrical and electronic systems will not be delt with in this script, as they are subjects on their own.

Sasol Synthetic Fuels has an extensive record keeping system on equipment, which will be used to the full potential to assist in classifying equipment, according to the risk involved in operating the equipment at a certain level of production throughput.

Once a certain risk has been quantified, suitable maintenance strategies and inspection intervals can be applied to effectively manage the risk. Equipment condition monitoring follows to enlarge the knowledge base of the reliability of the equipment identified as high risk equipment. This leads to a uniform process of measuring and determining maintenance philosophies/strategies for certain groups of equipment.

RISK BASED MANAGEMENT

In the following paragraphs an overview will be given on what risk is and what the different elements of risk is and why risk is the element that must be managed when looking at an optimum maintenance strategy or philosophy for a given business. Probability theory is also discussed in detail to highlight the most important part of the Risk Based Inspection process.

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3.1 INTRODUCTION

As mentioned in the introduction to this script a large number of larger companies are now realizing that each decision needs to be scrutinized in terms of value-for-money. Thus it can be seen that the old regime of statutory equipment and statutory requirements came under the attention of management because of downtime and high costs.

A few problems, however, arrived when evaluating an item with safety, environmental or other risk impact. The main problem is putting a price to the benefits, this is however, not easy. As can be seen from the following statement.

“There is always a fear of accountability, if a number is put on paper it can be criticized for error” [Woodhouse: 1993 : 11].

It therefore become apparent that improvement in business decision-making relies on a logical approach to risk. Accordingly the basics of probability and risk exposure needs to be thoroughly understood. In the next paragraphs the basics of risk will be discussed.

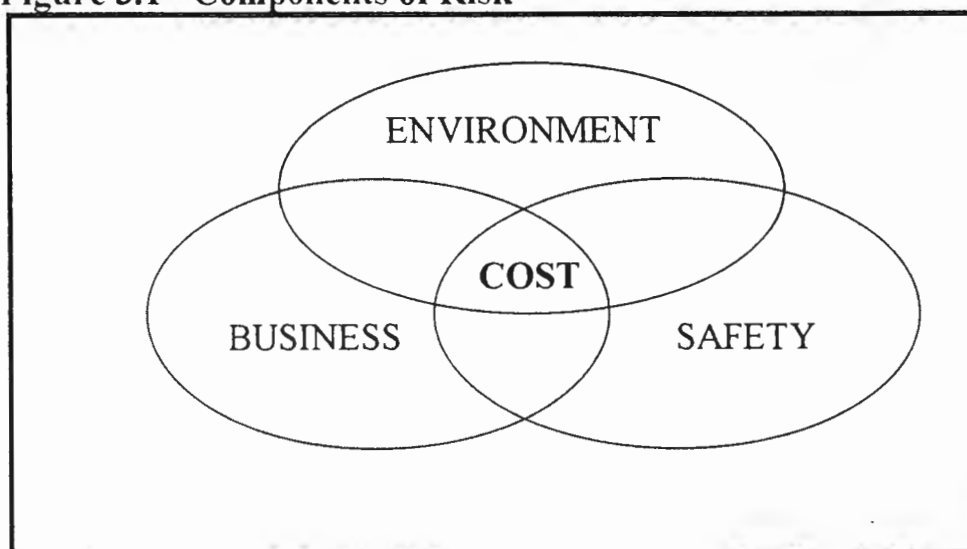
3.2 RISK

First three definition are given on what risk is:

- Webster's (1992) defines risk as, "the possibility of danger, injury or loss"
- Penguin (1985) defines risk as, "to expose to hazard or danger".
- Risk is the likelihood or probability of failure and the consequences resulting from the specific incident or series of incidents [Jones : 1996 : 31].

Risk is present in all business sectors. These are risks to safety, risk to environment and risk to the commercial success of the business. The most common risk is the financial risk, with which all managers are familiar. The common element of all the risks mentioned, however, is the cost of the risk under investigation. This argument can be graphically depicted as in the following figure.

Figure 3.1 Components of Risk



[Author : 1997]

In the context of maintenance we are not trying to eliminate risk, indeed the existence of most businesses is based on the exploitation of risk [Jones : 1996 : 31]. The greater the risk that can be accepted the greater the potential for profit. However, the consequence for not managing the risk effectively can be very high, or even devastating not only for the business, but also for the environment and the individuals. As can be seen from the numerous incidents where risk was not managed effectively. Businesses also know of many near misses that could easily have led to catastrophic failures or incidents as mentioned.

From the definition of risk as given by [Jones : 1996 : 31] two factors needs to be considered. These factors are likelihood and consequence. The likelihood of an incident occurring depends on the combination of the following factors, namely technical, human and environmental. Consequences include direct cost associated with loss of business and the repair of the equipment, but also include more direct costs associated with plant degradation, loss of prestige, fines, penalties, potential legislation and increased insurance.

3.2.1 RISK MANAGEMENT

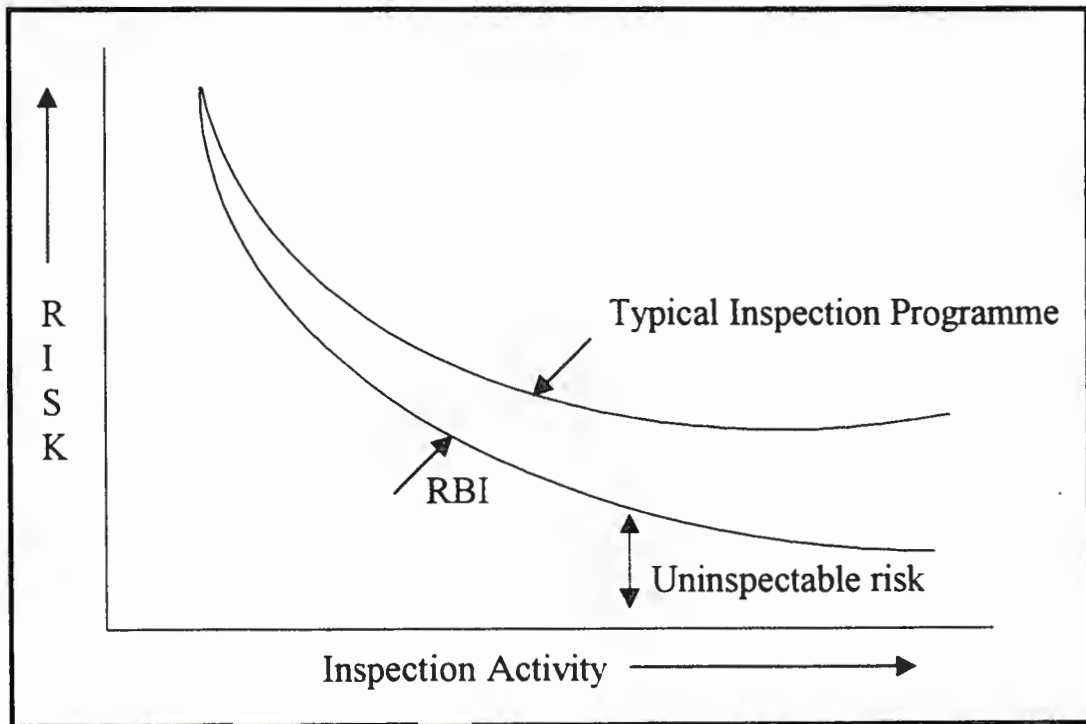
The basis for risk management processes is to set targets for safety, business and environment and to identify the hazards that could be threats to these targets. Business units must determine the relative risk for each unit/division and this information can then be used to manage the risk, according to the agreed upon management standard and targets as highlighted. The relative risk (likelihood and consequence) presents a prioritization of where the available resources must be focused to give the optimum risk management philosophy for a specific business.

There are different measures that can be adopted to manage risk. The risk can simply be accepted and through training it can be ensured that personnel are able to manage the incident effectively, or ways can be sought to eliminating the risk by redesign, change of operation or gold plating. The likelihood of occurrence can also be reduced through increased inherent reliability, reducing operations or a

more benign environment. Consequence of the incident can be reduced by acquiring advanced warning or introducing protective systems. Or the risk can be transferred through insurance or subcontracts, or by inspecting for a given anticipated damage mechanism.

In figure 3.7 the effect of Risk Based Inspection is illustrated by applying a risk evaluation approach to a standard inspection program.

Figure 3.2 Effect of RBI on Risk



[Miller : 1996 : 21]

From the figure it can be seen that a given level of inspection activity can reduce the overall operating asset risk level. Alternatively for a given level of risk a substantial saving can be made by reducing inspection activities if an RBI approach is applied.

Maintenance has many definitions, but one of the popular definitions is that maintenance is a cost that does not contribute to the bottom line of a company. This is related to the technical maintenance process itself. However the only reason for conducting maintenance is due to the perception that it would be more

costly if maintenance is not done. Maintenance perse is a measure taken to eliminate or reduce the consequence of failure, in other words it has always been a risk management measure. As such the concept of risk management must be applied to maintenance in a controlled and scientific manner. There are many risk management philosophies that can be used to determine risk and to predict the risk that is involved in operating a certain piece of equipment for a certain given time under certain conditions. These methodologies such as Baye's theory and CHAOS theory will be discussed in the next two paragraphs, to show where the stochastic risk is derived from. There is, however, some more recent developments that are also suitable to determine how to manage a specific risk involved when operating specific equipment. It is therefore clear that an effective risk management or risk control philosophy must be followed by a company to ensure continued existence of the company. Without such a controlled approach a business is not effectively controlling safety or its environmental impact (risk). What is more important, if it is not in control of its risked cost it therefore places the entire commercial viability of the business in jeopardy.

In today's competitive climate the risks are higher and the consequences are even more visible. Businesses that succeed in this climate will be businesses that know and have effective control over their risks. The development of a risk-based maintenance regime is thus not simply desirable but is now an essential part of the management of business.

In the following paragraph an outline is given on how risk can be analyzed.

3.3 NATURE OF RISK

First the basic definition of risk will be given in mathematical form, 1 [Jones : 1996 : 31].

- Risk exposure = probability x consequence 3.

From this definition it can be seen that nearly every improvement in business decision-making relies on a logical approach to risk as can be seen from the

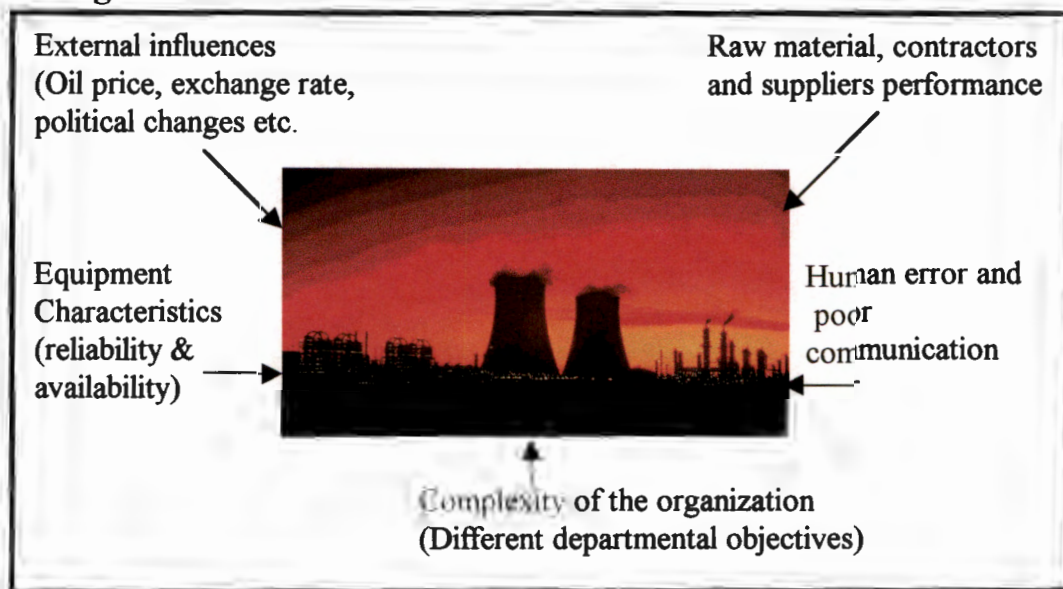
previous paragraph. This is true for the financial as well as the statutory implications.

[Woodhouse : 1993 : 12] also makes the following statement:

“Almost everything that is done or decision taken involves probabilities and consequences. The future is never certain and there are many factors that contribute to the unpredictability of risk”. We can therefore see that there are many factors contributing to the decision making process when risk is considered.

These factors are shown in the next figure.

Figure 3.3 Risk Factors



[Woodhouse : 1995 : 12].

From the figure it can easily be seen that each of the factors shown does have an impact on the total risk situation within a specific area of responsibility. It can be seen that to get the optimum risk philosophy and strategy for a given organization one of the key factors is total alignment of the work force and interdepartmental co-operation, towards common objectives. This risk can be seen as a complex factor, but fortunately it is possible to transfer some of the methods from familiar areas of risk and probability to their industrial counterparts. Also there are a wealth of knowledge and skills in the specialist fields of safety assessment and reliability engineering, which can be utilized [Woodhouse : 1995 : 12].

It is well known that the relative value of risk exposure can be used for assessing project viability, ranking investment options, comparing alternative operating strategies, optimizing maintenance and stores strategies and a host of other risk-related management decisions.

Out of the formula for risk exposure it can be seen that as the potential consequence becomes greater, a new consideration begins to appear : if the event was to occur, could the company survive the legal and financial implications?

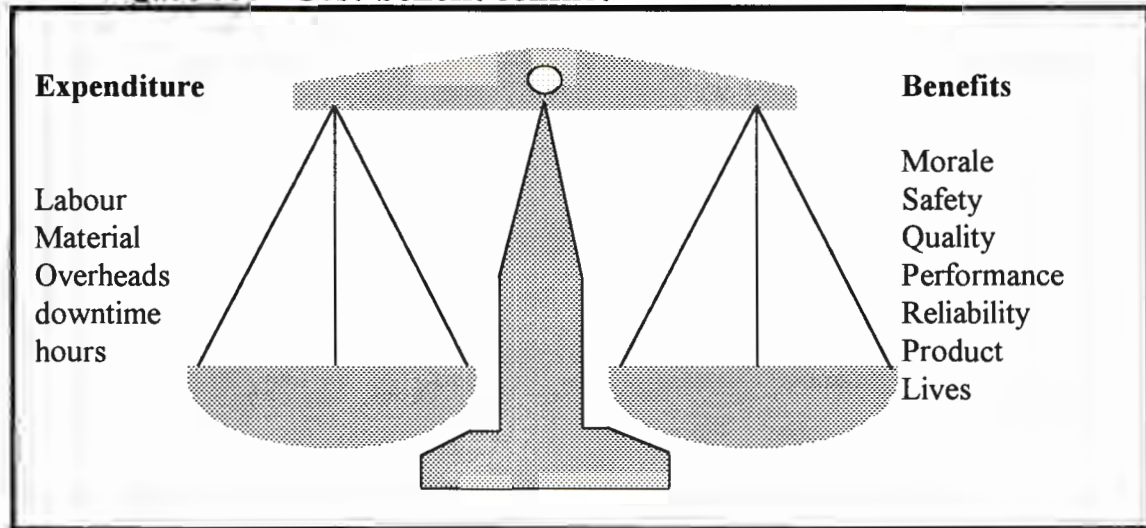
For example, if the business was run on purely financial grounds, then efforts to improve conveyor reliability would be given the same priority as the safety improvement offered by better gas detection.

The differences between the two issues as described above lies in:

- The quality of data available
- The “added value” of safety and security, over and above the pure economic incentive (confidence, moral, public duty etc.) [Woodhouse : 1995 :14].

The lack of data and the presence of intangibles or “added value” factors do not prevent a logical, numerical basis for estimating risk exposure.

We therefore say that we have a cost-benefit conflict, which can be demonstrated visually as in the next figure.

Figure 3.4 Cost-benefit conflict

[Woodhouse : 1995 : 15]

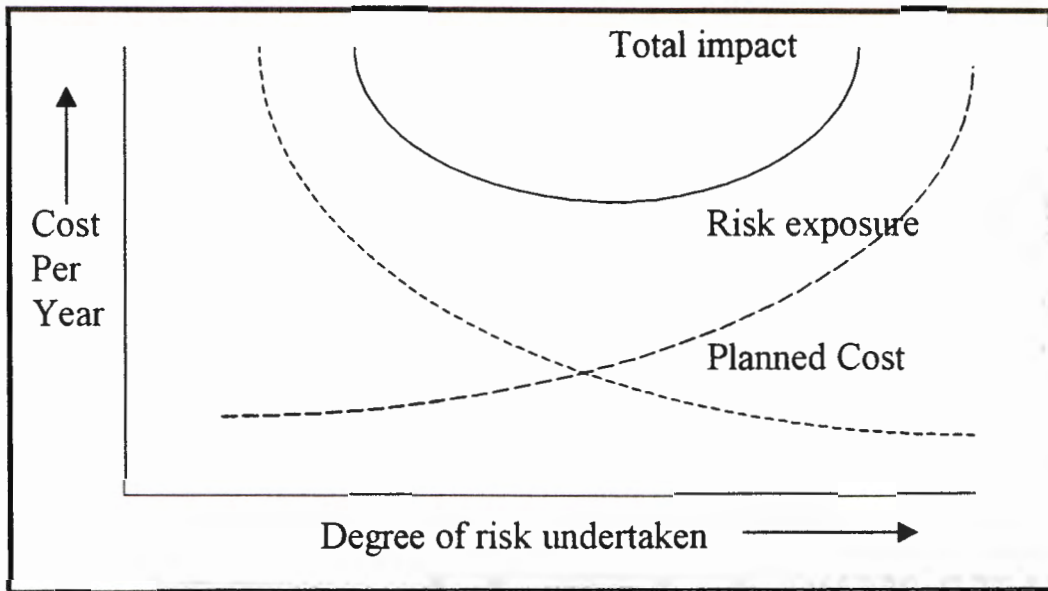
A total impact is achieved by recognizing that nearly all problems or decisions are characterized by a cost-benefit trade off.

“The first pleasant surprise is that every single industrial task or investment can be broken down into a combination of just five possible objectives, or reasons for spending money.

- reliability and risk impact
- improved operating efficiency
- extended plant life / determent of capital cost
- compliance with external (legal / safety) requirements
- “shine”, customer impression, morale and other intangibles

[Woodhouse : 1995 :15].

Whatever number crunching is involved, the outcome can best be described as the total impact of the problem. The total impact can be shown as in the next figure.

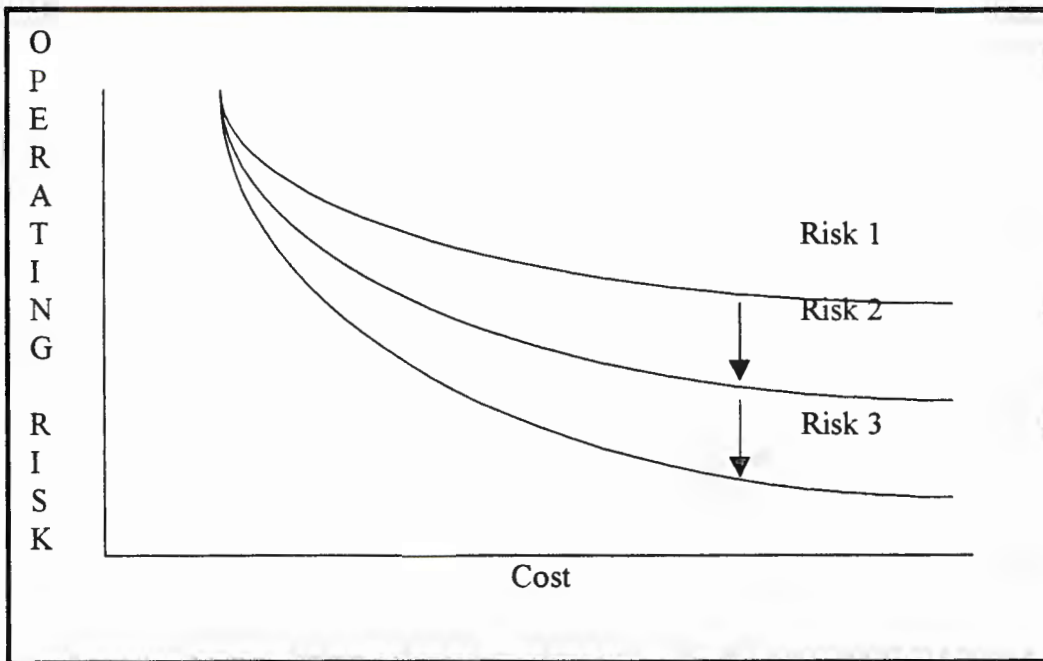
Figure 3.5 Total impact curves

[Woodhouse : 1995 : 16]

This total impact combines the “hard” cost of labour and materials with risk exposures, inefficiencies and constraints. It is a measure of both what is spent, and of what is not achieved. Short falls in reliability (breakdown risks), losses of efficiency, safety risks and other constraints all contribute to this total impact.

From figure 3.5 the planned cost can also be shown to have different relative risk values associated to the maintenance philosophies.

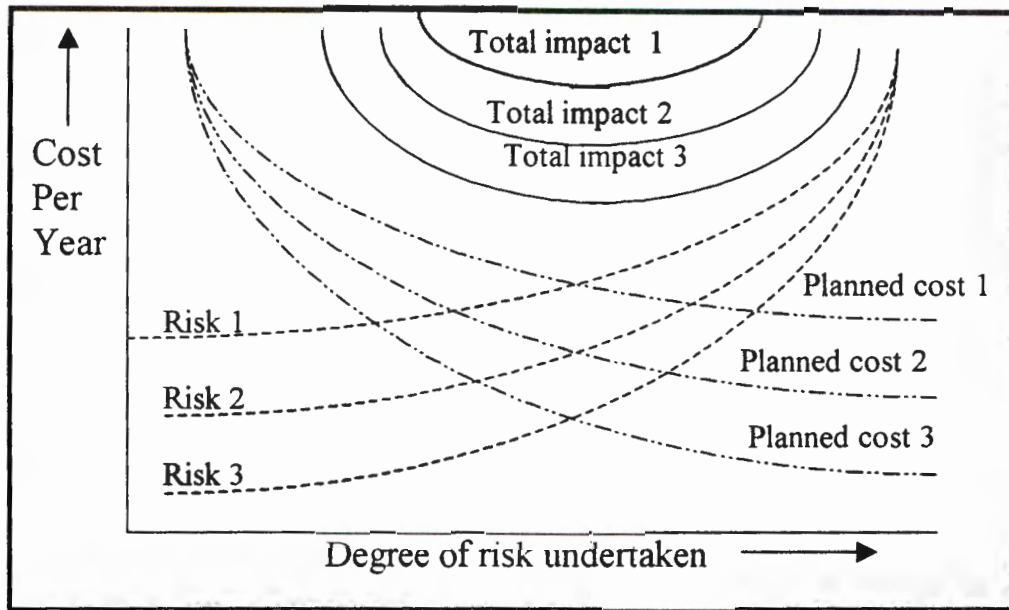
The next figure shows how the risk can vary with different levels of cost and external influences.

Figure 3.6 Risk / Cost Dependability

[MPDS : 1995]

From the figure it can be seen that if the risk can be lowered by for instance inspecting for and focussing on a specific defect. The figure proves that the specific risk can not be lowered by adding more resources and money, as depicted by the virtual parallel line to the horizontal axes at the end of the risk graph. If the risk cost dependability graph is combined with the total impact curve the following graph is derived.

Figure 3.7 Total Cost Impact Curve



[Author : 1997]

From the figure it can be seen that with a specific inspection program, for example level one and a specific cost involved a level one total impact curve will be derived which will have a specific optimum point at which the equipment will perform. If strategies are changed to do a more optimum inspection strategy by focussing the resources at the right problems a situation as in the graph where a lower expenditure level as is shown in level three total impact curve will be achieved. For this strategy there would also be a optimum point of operation.

From the graph it can be seen that the total cost impact for a given facility can thus be lowered by managing the risk from the total risk line 1 to line 2 or three in figure 3.7. Prioritizing of work can also be done by taking the risk into account. This aspect will be highlighted in more detail in the following chapters.

Quantifying the factors pertaining for the specific risk is the next step in managing risk of equipment (see Chapter 4). This is the most important step in the risk management process and is handled in Appendix B. Quantifying risk can be seen as a risk ranking according to agreed criteria and can be done qualitatively or

quantitatively depending on the initial criticality of the equipment (See **Appendix B for more detail**).

In the next paragraph a theoretical background is given on risk, and how and why statistical methods can be used to assist in developing risk based decision making criteria to develop inspection and maintenance strategies for equipment.

3.4 RISK

3.4.1 BAYE'S THEOREM

3.4.1.1 BACKGROUND

“Probabilistic analysis and reliability updating have been used for a number of applications in offshore, civil, aerospace and process engineering; however, implementation of these methods are cumbersome and complicated and hard to justify for many refinery and process plant problems”. [Conley : 1994 : 1].

The concept of risk based inspection combines the probabilities of failure with consequences of failure for the many components in a petrochemical plant to evaluate and rank equipment with respect to safety and reliability. The goal of this ranking is to prioritize inspection and maintenance needs as part of a program that distributes the available resources to maximize safety and reliability. And in this regard minimize risk at the same time.

Because a typical risk based inspection program involves many pieces of equipment, the methods for assessing any individual piece of equipment must be easy to implement.

A qualitative method is the easiest to implement for a large system. A quantitative or semi-quantitative system may be preferable for a number of reasons, such as the desire to use better physical models for some pieces of equipment, or to investigate the sensitivity of the results to changes in assumptions. This is however too

computational intensive, the use of Baye's Theorem retrains many of the features of more complex methods while being easy to implement.

In the next chapter it will be demonstrated how Baye's Theorem in its simplest form can be used to update the estimated reliability of process equipment. Chapter 3.4.1.2 is an abstract out of Conley and Tallin to explain Baye's theorem, this is done to give the reader of this script a better understanding of the concepts as the explanation of the subject is handled in an excellent and conclusive style. Their abstract also shows directly how Baye's theory can be used to apply Risk Based Inspection to a specific piece of equipment by using conditional probability as the starting point.

3.4.1.2 ASSESSING INSPECTION RESULTS USING BAYE'S THEOREM

“In the application of the theorem to assessing a refinery or petrochemical plant components, it is assumed that the condition of a component with respect to some mode of failure or damage mechanism can be described by a set of states $A_1 A_2 \dots A_4$. For example, the fraction of life of a piece of equipment that has been consumed could be described by four discrete states:

- A_1 - less than 25% of the life has been consumed.
- A_2 - 25% to 50% of the life has been consumed
- A_3 - 50% to 75% of the life has been consumed, and
- A_4 - more than 75% of the life has been consumed.

These states are mutually exclusive and exhaustive, that is if the equipment is in state A_1 it cannot also be in any of the states $A_2 A_3$ or A_4 and the equipment must be in one of the four states. Because the states $A_1 A_2 \dots A_4$ are exhaustive the sum of their probabilities $\sum p [A_i] = 1$.

In addition, to states A_i , it is assumed that there exists a method of observation that indicates in which state the equipment is in. While the equipment tube will

definitely be in one of the states, A_i it is not possible to observe with certainty the state the equipment is actually in. As a result, four different inspection results can occur.

- B_1 - favors A_1
- B_2 - favors A_2
- B_3 - favors A_3 and
- B_4 - favors A_4

The inspection results B_i are, like the actual states, A_i , mutually exclusive and exhaustive. The uncertainty associated with an inspection program is described by a set of conditional probabilities. Given that the state of the equipment is known these probabilities quantify the likelihood that the inspection will rank it in the correct state or in other states. Formally these are the conditional probabilities, $\rho[B_k/A_i]$, the probability of ranking B_k given the tube is actually an A_i . Because the B_i are mutually exclusive and exhaustive, these probabilities satisfy the relation:

$$\sum_{k=1}^{k=n} \rho[B_k \setminus A_i] = 1 \quad [3.2]$$

For example, given that the equipment is in state A_2 , the probability that the inspection method shows that the equipment is in state A_2 is $\rho[B_2 \setminus A_2]$. For an uncertain inspection, $\rho[B_2 \setminus A_2]$ is less than one, and at least one of the probabilities $\rho[B_1 \setminus A_2]$, $\rho[B_3 \setminus A_2]$, and $\rho[B_4 \setminus A_2]$ is greater than 0.

Baye's theorem combines the probabilities $\rho[A_i]$, call the *prior* probabilities with the conditional probabilities, $\rho[B_k \setminus A_i]$ to yield an expression for the probability that the equipment is in any state A_i , given that the equipment was observed to be in state A_k which results in observation B_k .

$$\rho[A_i \setminus B_k] = \frac{\rho[B_k \setminus A_i] \rho[A_i]}{\sum_{j=1}^{j=n} \rho[B_k \setminus A_j] \rho[A_j]} \quad [3.3]$$

The probabilities, $\rho[A_i \setminus B_k]$ are call *posterior* probabilities.

The power of theorem is that it provides a formal means of incorporating an uncertain inspection result, B with information on the expected condition based on an analysis or opinion. For example, an analysis of the equipment based on mean and minimum material properties and a conservative estimate of mean operating conditions can be used to estimate the probability that the equipment is in each of the assumed states, A_i . An inspection or test will result in a result that favors membership on one of the states. By applying the theorem, the probability of being in any one of the states is changed from the prior probability, $\rho[A_i]$ to the posterior probability $\rho[A_i|B_k]$ through the application of Equation 2". [Conley, 1994 : 2-4].

From the above paragraphs it can be seen that Baye's theorem is exceptionally suitable for determining the optimum inspection frequency and method for a specific certainty of degradation mechanisms present and a certainty of locating a defect in time. It is also clear that the risk will be lowest in reliable data is available and can be used to perform the risk ranking.

This concept will be discussed in more detail in Chapter 4. Next an other possibility of determining the inspection frequency and the extent of the inspections is discussed under the heading Chaos Theory.

3.4.2 CHAOS THEORY

3.4.2.1 BACKGROUND

Chaos theory is a basic control system with a cause and effect equation. For this equation the variables that depict the state of the system must be known. We can therefore determine dynamic behaviour overtime. In other words in the long run the state of a system will change to some known state, this is known as the attractor and the theory is based on this known future state.

Deterministic chaos theory has been used to determine:

- Weather pattern simulation

- Brain waves
- Fluid turbulence
- Oil rig vibration
- Chemical reaction
- Computer networks
- Market currency exchangers

It must be noted that a measure of a 10% pattern can be used to develop a predictive process.

Chaos theory can be used to develop complex dynamic systems.

- Only one variable is needed to develop a chaos system
- If a underlying pattern can be determined a system model can be developed

Chaos theory is characterized by the following:

- Non-linearity in system
- Irregular behaviour
- Long-term unpredictability
- Strange attractors
- Divergent projections

Keeping this in mind we can see that his method of predicting the future can at present only be used up to a point in the future with certainty, after which it becomes unreliable.

Next the applications for Chaos theory is discussed.

3.4.2.2 APPLICATIONS

Chaos theory can be used where:

- History is available
- Reliable data is available

- ≥ 300 Data points are available
- Assess if the pattern is linear or irregular
[Walters : 1995 : 3-5].

From the many applications listed and the information given above it can be seen that Chaos theory can not be applied to pressure vessels because of the limited amount of information available. It may however be possible to use this theory to determine the behaviour of equipment up to a point in time.

More work must however be done on the subject and it could be the future of determining maintenance and inspection practices for specific pieces of equipment in our process industry.

3.5 RELIABILITY AND RISK

When history of failures are available it is easy to determine meantime between failures and to determine the real risk to the business as a consequence of this failure rate or consequence of failure. This is however not available for most of the statutory equipment in our chemical facilities. Mean time to failure is available for less than one percent of the equipment under consideration. It was therefore necessary to develop a method to quantify the risk of degradation. The rate of material degradation is then linked to an inspection program which in turn will determine the risk of operating a given system or piece of equipment under specific conditions. This problem will be discussed in the next chapters by showing how the different scientific methods available today can be used to minimize the risk that is taken in the maintenance strategy process.

3.6 SUMMARY

In this chapter an overview was given on risk and the factors that influence it. Risk was also linked to cost and the premium that must be paid to safety and legal constraints. An overview was also given on Baye's theory and Chaos theory to give a better understanding of why we can use statistical methods to determine the most effective maintenance and inspection program for a specific piece of equipment. In the next chapter a process will be shown that can be used to

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manage the risk in statutory pressurized equipment by categorizing equipment in specific risk groups due to probability and consequence as discussed.

MAINTENANCE STRATEGY PROCESS FOR STATUTORY / PRESSURIZED EQUIPMENT – MANAGING THE RISK

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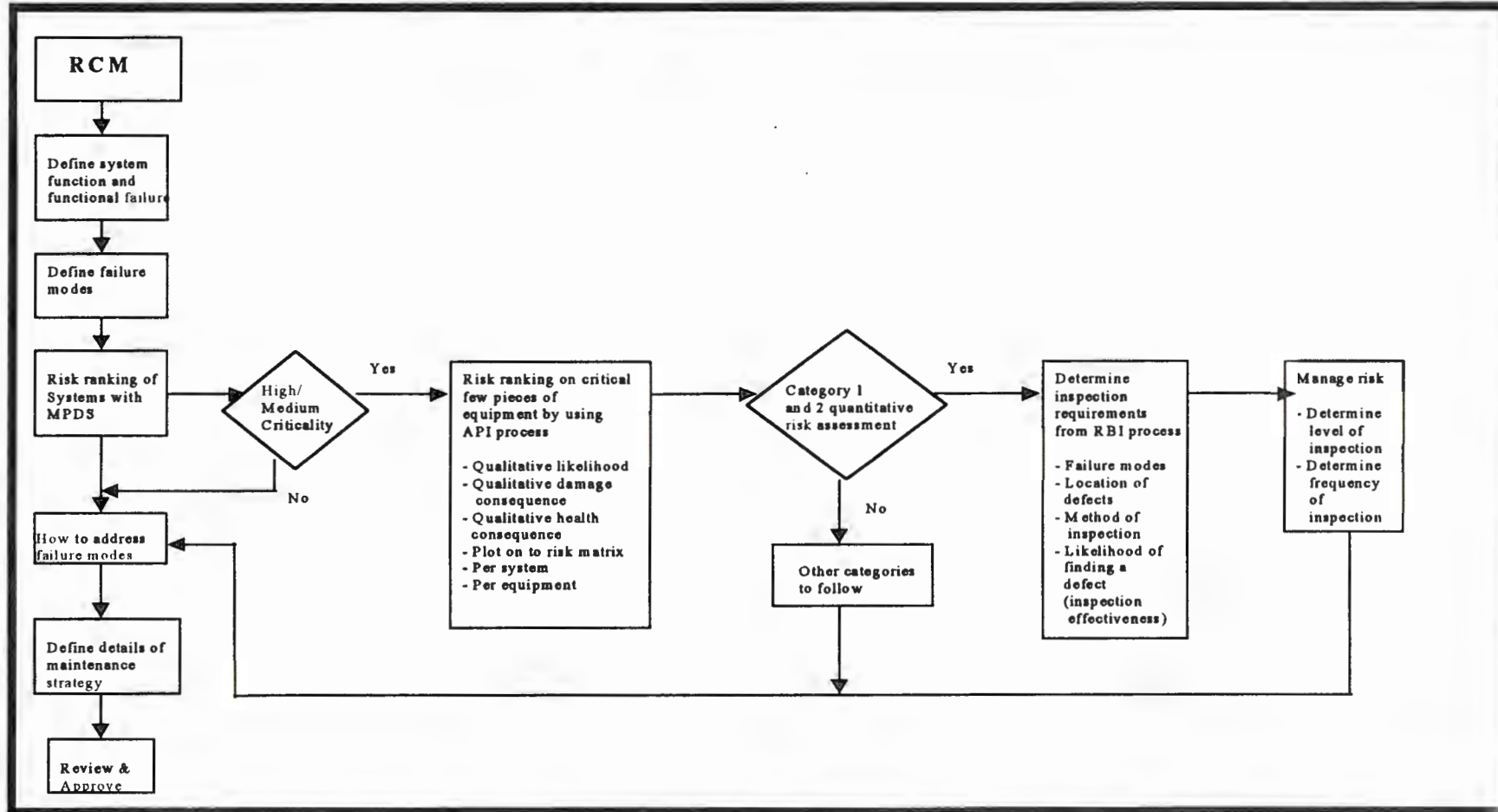
4.1 INTRODUCTION

In this chapter background is given on how the maintenance strategy process at Sasol Synthetic Fuels (SSF) is composed. A short description is given on the exact steps that are followed in the strategy process while incorporating the API Risk Based Inspection concepts into the Reliability Centered Maintenance Strategy Process.

The Reliability Centered Maintenance (RCM) process, as it is being applied in the maintenance strategy process at SSF is suitable for any type of equipment. For pressurized equipment the Risk Based Inspection (RBI) route is followed, however, additional inputs and information is required in order to arrive at an optimum strategy. The RBI process, as proposed by American Petroleum Institute (API), is supplementary to the RCM process and was developed as a tool in order to manage risk in a scientific way and focus resources where they are really needed. Due to the fact that no mean time between failures statistics are available for pressurized equipment, the RBI approach has to be followed to determine optimal levels of inspections and inspections frequencies. In general, code WG/004 (internal Sasol code) allows enough freedom to extend inspection frequencies to an optimum, except if frequencies of more than 96 months are required. The following figure gives an overview of the process and where RBI is applied on the maintenance strategy process.

THE RBI LOOP IN THE STRATEGY PROCESS

Figure 4.1 Maintenance Strategy Process



In order to effectively managed the risk on statutory/pressurized equipment it is advised that the RBI route as proposed by API be followed. Next an overview is given on Risk Based Inspection.

4.2 RISK BASED INSPECTION

4.2.1 DEFINITION

Risk Based Inspection (RBI) is a method for prioritizing and managing the efforts of an inspection program.

4.2.2 RISK RANKING

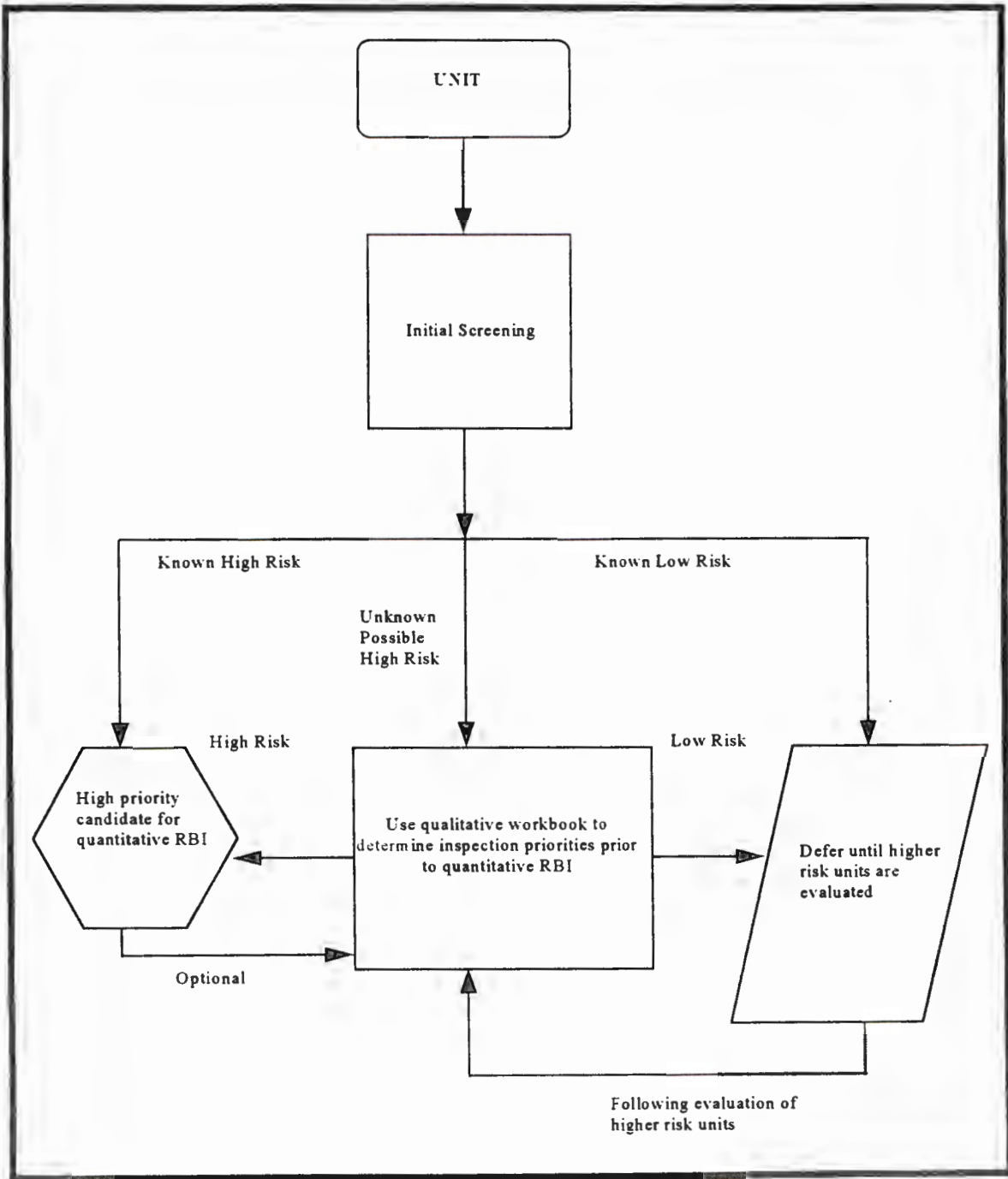
The first step in the development of a risk based inspection program is the risk ranking of the equipment. This step involves the categorizing of equipment into different risk categories determined by certain physical factors which will determine the consequence and the likelihood of certain failures.

In the maintenance strategy process the first step is a risk ranking with MPDS which will categorize the medium high risk equipment from level one to level eight. The next step is to review all the risk rankings for correctness by using the API risk ranking.

Step number three is to do a qualitative risk analysis to rank the equipment into a five-by-five matrix, according to the API process. This step will determine the relative criticality of each piece of equipment.

In the next figure an overview is given on the RBI screening process:

Figure 4.2 Initial screening

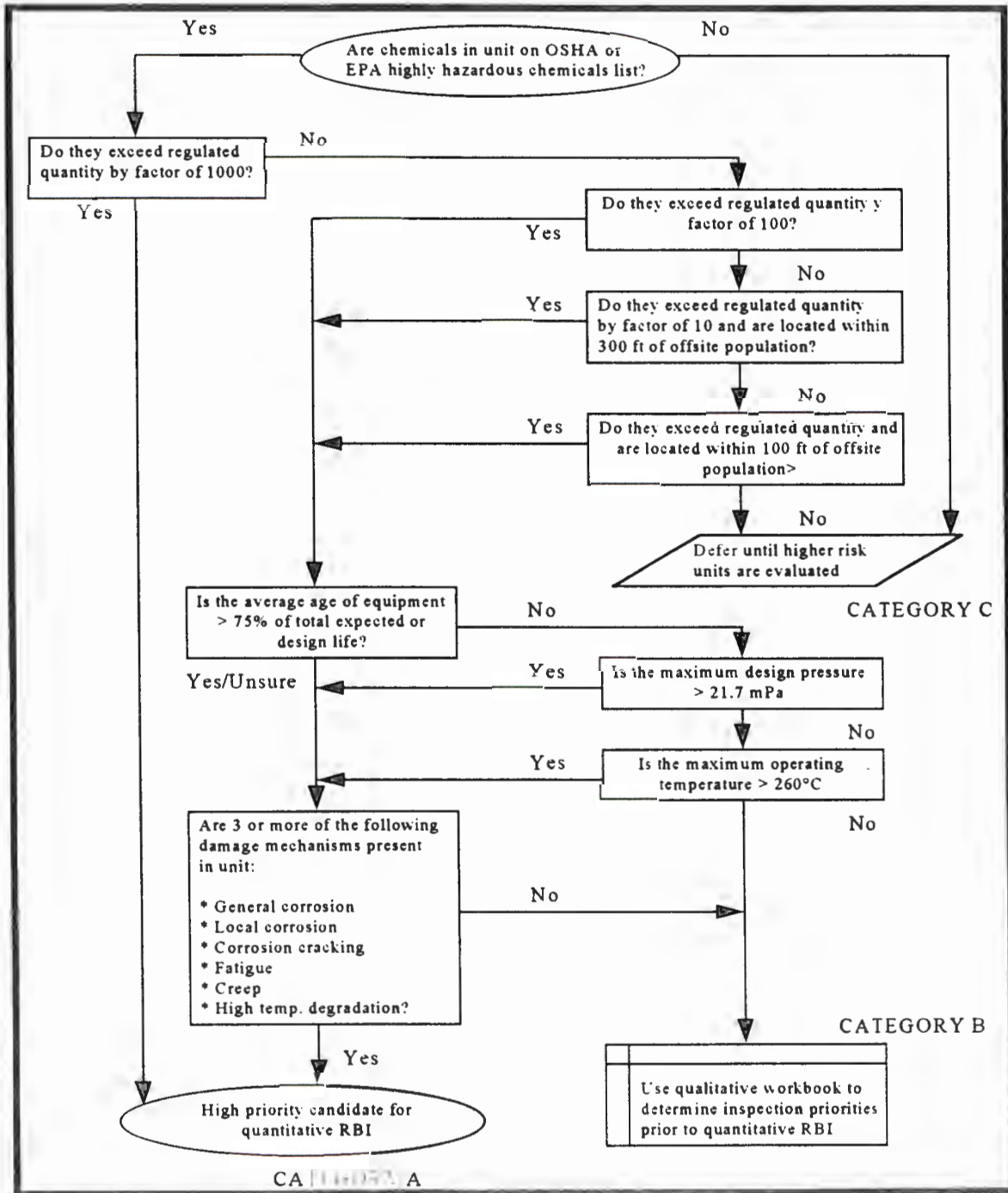


[API : 1995 : 5]

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From the initial screening procedure the next step is to do a more detail screening of the equipment under consideration. This process is illustrated in the following figure.

Figure 4.3 Detail screening



[API : 1995 : 6]

From this figure it can be seen that a ranking can be done according to a qualitative or a quantitative procedure. The qualitative procedure will be discussed first.

4.2.3 QUALITATIVE RISK RANKING

The qualitative process has three basic functions:

- 1 Screening the units within the site to select the level of analysis needed and to ascertain the benefits of further analysis (quantitative RBI or some other technique).
- 2 Rating the degree of risk within the units and assigning them to a position within a risk matrix.
- 3 Identifying areas of potential concern at the plant, which may merit enhanced inspection programs.

In appendix B (part A) the questions that must be asked are outlined as given by API. The first part of the examination is the determining of the **qualitative likelihood** of a certain incident or scenario of happening. This analysis can also be done on different levels, plant, unit and system level.

There are six different sub-factors that make up the likelihood category:

- Amount of equipment (Equipment factor, EF)
- Damage mechanisms (Damage factor, DF)
- Appropriateness of inspection (Inspection factor, IF)
- Current equipment condition, (Current Condition Factor, CCF)
- Nature of process (Process factor, PF)
- Equipment design (Mechanical design factor, MDF)

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Each of these sub-factors are given a rating due to certain criteria, as can be seen from appendix (B). According to the rating given in each category the likelihood can be derived from point 30 of appendix B, this can be used to plot on the risk matrix.

Next the qualitative **consequence** category (appendix B, part B and C) is done, this analysis is derived from a combination of elements that determine the magnitude of a fire and/or explosion hazard:

Part B: Determining of damage consequence category

- Inherent tendency to ignite (Chemical factor, CF)
- Quantity that can be released (Quantity factor, QF)
- Ability to flash to a vapor (State factor, SF)
- Possibility of auto-ignition (Auto-ignition factor, AF)
- Effect of higher pressure operations (Pressure factor, PRF)
- Engineered safeguards (Credit factor, CRF)
- Degree of exposure to damage (Damage potential factor, DPF)

Part C: Health consequence category

- Toxic quantity factor (TQF)
- Dispensability factor (DIF)
- Credit factor (CRF)
- Population factor (PPF)

From the Appendix choose the highest factor from part B and part C, this will be the consequence of damage.

There are two major potential hazards associated with refinery and petrochemical operations:

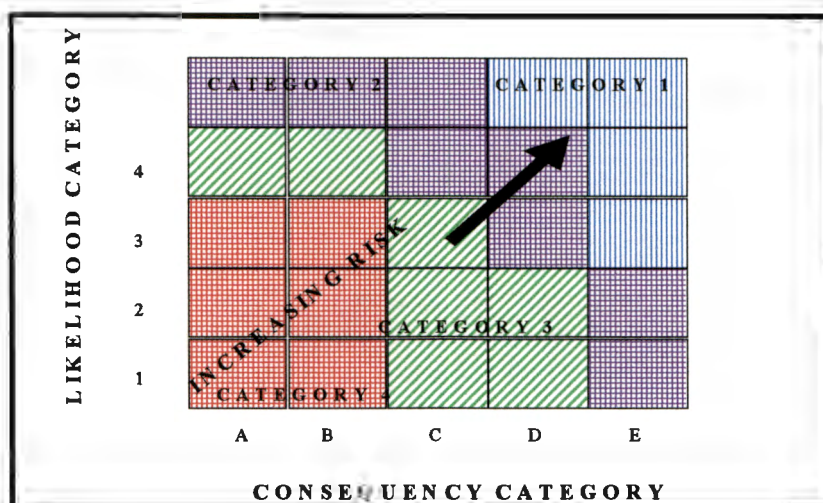
Fire and/or explosions or toxic risk

Thus if the predominant risk for a given chemical is known, it is necessary to determine only the factor for that risk and not for both. The consequence that generates the highest letter category is used to determine the qualitative risk rating.

Note that part B can be skipped if the chemical has no flammable characteristics, if it is obvious that no toxic hazards are present part C can be skipped.

The results from the likelihood and consequence analysis can now be plotted onto the risk matrix, in the following figure.

Figure 4.4 Risk Matrix



[API : 1995 : 8]

4.3 QUANTITATIVE RISK ASSESSMENT

The next step in the process is to do a quantitative risk assessment on the equipment, which pose the highest risk to determine the effect that each of the failure modes can have. Initially this will be done for equipment ranking in category 1 on the risk matrix. Other categories will follow. This will however not be addressed at this stage of the process, and will be done at a later stage.

A process to reduce the risk that was identified in the RISK evaluation is now implemented. We can reduce risk by reducing the probability of failure or by reducing the consequence of failure. Inspection influences risk primarily by reducing the probability of failure. There are many conditions (design errors, fabrication flaws, malfunction of control devices) that can lead to equipment failure, but in-service inspection is primarily concerned with the detection of progressive damage. The probability of failure due to such damage is a function of four factors:

- Damage mechanism and resulting type of damage (cracking, thinning, etc.)
- Rate of damage
- Probability of detecting damage and predicting future damage states with inspection techniques.
- Tolerance of equipment to the type of damage.
- Inspection frequency.

This inspection plan will systematically identify what, where, how and when to do specific inspections. The following basic data is needed to identify most damage mechanisms:

➤ **Fitness for service analysis**

- This concept is discussed in detail to show the impact the technique can have on the quantitative RBI decision making process that is followed with high risk equipment.
- See Chapter 5 and Appendix C for more detail

➤ **Design and construction data:**

- Equipment type and function
- Material of construction
- Heat treatment
- Thickness

➤ Process data, including changes

- Temperature
- Pressure
- Chemical service, including trace components
- Flow rate

➤ Equipment history

- Previous inspection data
- Failure analysis
- Maintenance activity
- Replacement information
- Modifications

➤ Identify experts who will give specific inputs

- Facilitator (Reliability Engineer)
- Production
- Mechanical
- SecMet (Corrosion Engineer)
- Sastech Design
- Inspection Services

It is advisable to work within the guidelines of the following codes at all times

- WG/004
- API Codes
 - 572 Inspection of pressure vessels
 - 510 Pressure Vessel Inspection Code, Maintenance Inspection, Rating, Repair and Alteration
 - 574 Inspection of Piping, Tubing Valves and Fittings

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- 570 Piping Inspection Code Inspection, Repair, Alteration and Rerating of In-service piping systems
- 653 Tank Inspection, Repair, Alteration and Reconstruction
- 651 Cathodic Protection of above - ground Petroleum Storage Tanks
- 573 Inspection of Fired Boilers and Heaters

In this process the following five steps can be isolated/identified

Step One

What damage types to look for and where to look for them.

In Appendix “D” the different damage types are given with descriptions, the damage mechanisms are also given for each damage type.

Step Two

Determine how to look for a specific damage type. The relative efficiency of the different inspection techniques to find certain damage types is given in Appendix “D”.

Step Three

Determine the inspection effectiveness. The following five factors must be evaluated:

- 1 Damage density and variability
- 2 Inspection sample validity
- 3 Sample size
- 4 Detection capability of the inspection methods
- 5 Validity of future predictions based on past observations

The RBI approach to assessing inspection effectiveness categorizes the ability of inspection types, or common combinations of inspection types, to detect and evaluate in-service damage.

The inspection effectiveness categories are:

- 1 Highly effective Inspection methods correctly identify the anticipated in-service damage in nearly every case (90%).

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2	Usually effective	The inspection methods will correctly identify the actual damage state most of the time (70%).
3	Fairly effective	The inspection methods will correctly identify the true damage state about half of the time (50%).
4	Poorly effective	The inspection methods will provide little information to correctly identify the true damage state (40%).
5	Ineffective	The inspection methods will provide no or almost no information that will correctly identify the true damage state (33%).

Since the rigorously quantitative approach is not usually possible with the data available, the RBI evaluation relies heavily on the professional judgement and expert opinion.

Quantifying the inspection effectiveness is however necessary. This is done by looking at the damage state categories as given in the next table.

Table 4.1 Damage state categories

Damage state category
Damage state 1 The damage in the equipment is not worse than what is expected, based on the damage rate models or experience (0-1X)
Damage state 2 The damage in the equipment is “somewhat” worse than anticipated. The level of damage is sometimes seen in similar equipment items. (1X - 2X).
Damage state 3 The damage in the equipment is “considerable worse than anticipated. This level of damage is rarely seen in similar equipment items, but has been observed on occasion industry wide. (2X - 3X).

[API : 1995 : 17]

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The effectiveness of inspections from the qualitative categories are quantified based on consideration of Bayesian updating technique as discussed in Chapter 3.

The following table gives a quantified assessment of the inspection effectiveness according to the Bayesian technique. The values can be calculated by using the Bayesian technique in conjunction with results from different inspection techniques. (Shown in API Base Resource Document on Risk Based Inspection).

Table 4.2 Bayes updated table for likely hood of determining true damage state

Likely hood that inspection results determines the true damage state					
Damage state category	Effectiveness category				
	“Highly effective”	“Usually effective”	“Fairly effective”	“Poorly effective”	“Ineffective”
First damage state: Measured rate	0.9	0.7	0.5	0.4	0.33
Second damage state: Higher rate	0.09	0.2	0.3	0.33	0.33
Third damage state: Higher rate	0.01	0.1	0.20	0.27	0.33

[API : 1995 : 19]

Step Four

Determine the probability of detection (POD) of defects.

From experiments that were done it was shown that the probability of detection increases as the flaw size increases. The POD data, where available, are also useful in helping assign the inspection methods to the appropriate inspection effectiveness category.

Step Five

Determine when (how often) to look for damage.

The frequency of inspection is determined by combining the five factors of RBI:

- Damage mechanisms and resulting type of damage (cracking, thinning, etc.)

- Rate of damage progression
- Tolerance of equipment to the type of damage
- Probability of detecting damage and the predicting future damage states with inspection techniques.
- Fitness-for-Service Analysis

A tool that can be used to effectively determine the effect of the abovementioned criteria is a fitness-for-service analysis (FFS), see Appendix “C” for an example of a FFS analysis that was done for a steam drum. An important point to note is the role pressure and temperature profile’s of the equipment for a specific period can play in the analysis of equipment.

From this procedure the frequency is selected as some fraction of the equipment’s remaining life. This inspection must be scheduled so that the “real” probability of failure can be estimated based on whether the damage is progressing at a higher or a lower rate than predicted.

To select the final inspection frequency the following steps must be followed, in the case of corrosion:

- 1 Calculate the ratio ar/t ,
where “a” is the age of the equipment up to date
“r” is the corrosion rate
“t” is the thickness of the equipment when going into the current service.
- 2 Determine the overdesign factor. This is a correction factor selected from the table in appendix D, that will be applied to the damage sub-factor. This correction is necessary because the sub-factors from the table are based on a vessel that has a corrosion allowance of 25% of the wall thickness.

Vessels with a greater corrosion allowance should have a lower damage factor, while those with less corrosion should have a higher damage sub-factor.

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Overdesign factor: = $t_{\text{actual}} / (t_{\text{actual}} - \text{corrosion allowance})$

- 3 Refer to the table and find the damage sub-factor for this vessel, at the ar/t ratio and one inspection and the specified inspection effectiveness.
- 4 Multiply the results of step three by results of step two.
For more detail on other mechanisms, see Appendix A on frequency analysis.

Following this procedure it can be seen that there are two different options:

- Increase activity level of frequency if insufficient reduction in risk occurs, or decrease activity level or frequency if no gain in risk reduction results from the higher level of inspections.

The following are general guidelines that may be used for program optimization:

- Damage factors can usually be kept close to one by inspection activities of a moderate extent. Values exceeding ten can usually be avoided.
- Damage factors significantly greater than ten may be calculated when an inspection program that has not previously been based on risk is first evaluated. Equipment items showing these higher values should receive first priority for inspection optimization. Within this set of equipment items, those with the **highest risk** should be evaluated first.
- Some equipment that has been inspected multiple times and has confirmed low damage rates may be over-inspected. Alternate plans to reduce inspection activity or frequency can be evaluated through the technical modules to determine the effect on risk. Within the set of equipment items, those with the **lowest risk** should be evaluated first.
- Equipment that is subject to a large uncertainty in the damage rate (as expressed in the Technical Module) will require frequent or thorough inspections to keep risk levels low, at least until sufficient history on performance has been established.
- Equipment that is approaching the end of its life due to corrosion or other deterioration requires increased inspection activity to be sure that the limits of deterioration (e.g.,

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corrosion allowance) are not exceeded. Increased inspection will not reduce the damage factor once the remaining life has been consumed.

- Inspection program options should be projected over a significant portion, at least half, of the equipment's intended remaining life. Damage factors may tend to increase later in the equipments life if insufficient inspections are performed.

In the next chapter an quick overview is given on a Fitness for Service analysis, and how it can be of assistance when doing a RBI study on a specific high risk piece of equipment.

FITNESS FOR SERVICE

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5.1 INTRODUCTION

In this chapter an overview is given on the basic principles of a fitness for service analysis of a pressurized piece of equipment. For the purpose of this study Fitness-for-Service Analysis can be seen as a scientific based tool to assist in the Risk Based Decision making process. The Fitness-for-Service techniques is used as an aid when high criticality equipment are assessed, or where little or no history is available. The technique is also used to determine the optimum inspection frequency when any fatigue mechanisms are active. This chapter will give general guidelines on what needs to be done within a Fitness for Service Analysis.

5.2 FITNESS FOR SERVICE ANALYSIS

First a background is given on fracture mechanics and fatigue and then the scientific detail is discussed.

5.2.1 FRACTURE MECHANICS AND FATIGUE

What is fracture mechanics and fatigue?

Determining the effect of a crack on a pressure vessel containing a crack or crack-like flaw requires the use of fracture mechanics.

Fracture mechanics draws upon the disciplines of applied mechanics and material science, to provide quantitative answers to specific problems concerning cracks in

structures. Making use of fracture mechanics, the maximum permissible applied internal pressure, acting on a vessel with an existing crack can be calculated for size and location of the crack. Fracture mechanics can also, be used as a tool to predict the rate at which a crack can approach the critical crack size under fatigue influences. The growth rate of a crack, is governed by the amplitude of the alternating stress. Next an abstract is given from a dissertation by [Schubert :1997] to show how fracture mechanics was developed as a specific field of study.

5.2.2 FRACTURE MECHANICS

“In order to determine the severity of a crack or crack-like flaw detected during inspection, it is necessary to make use of fracture mechanics. According to [Ewalds, et al. : 1984], fracture mechanics should attempt to provide quantitative answers to the following questions:

- 1 What is the residual strength as a function of crack size?
- 2 What crack size can be tolerated under service loading. What is the maximum permissible crack size?
- 3 During the period available for crack detection how often should the structure be inspected for cracks?

The objective of fracture mechanics is to provide quantitative answers to specific problems concerning cracks in structures. Strength failures of load bearing structures could be either of the yielding-dominant or fracture-dominant types. Defects are important for both types of failure, but those of primary importance to fracture, differ in an extreme way from those influencing yielding and the resistance to plastic flow. For fracture-dominant failures, i.e. fracture before general yielding of net section. the size scale of the defects which are of major significance is essentially macroscopic, because general plasticity is not involved, but only the local stress-strain fields associated with the defects. The residual strength of the structure, which is the failure strength as a function of crack size,

decrease with increasing crack size. After a time the residual strength becomes so low that the structure may fail in service.

According to [Broek, et al. : 1987], engineering fracture mechanics can deliver the methodology to compensate for the inadequacies of conventional design concepts. The conventional design criteria are based on tensile strength, yield strength and buckling strength. These criteria are adequate for many engineering structures, but they are insufficient when there is the likelihood of cracks.

The science of fracture mechanics describe quantitatively the trade-off among these three factors:

- ◆ stress
- ◆ material toughness
- ◆ flaw size

so that the designer can determine the relative importance of each of them during design rather than failure analysis.

It is evident that the fracture mechanics is an adequate tool to evaluate cracks and crack-like flaws in structures. The existence of these crack-like flaws cannot be precluded in any engineering structure. At the same time, increasing demands for energy and material conservation are dictating that structures should be designed with smaller safety margins. Consequently, accurate quantitative estimates of the flaw tolerance of structures, is increasingly becoming a direct concern for the prevention of fracture in load-bearing components of all kinds. The presence of a crack-like defect does not necessarily mean that a structural component is at, or even near the end of its useful service life. Presently there are a number of procedures available to assess the integrity of a structure containing a crack-like flaw. These models are:

- ◆ Linear-elastic fracture mechanics
- ◆ Elastic-plastic fracture mechanics

These procedures were developed, by making use of fracture mechanics” [Schubert : 1997]

For the purpose of this script the detail of the development of these methods will not be discussed. It is however stated that these methods are proven in practice as a scientific repeatable method to determine the expected life of a piece of equipment under cyclic loading.

Next a overview is given on, why can an integrity assessment be done by the methods as described.

5.2.3 INTEGRITY ASSESSMENT

A fundamental requirement of any engineering structure is, that it should not fail during its design life. Many of the vessels in operation today are nearing the end of their original design life and some may actually exceed these limits. In the last ten years, a number of fracture mechanics-based assessment procedures have been developed which enable structures to be assessed on a “fitness-for-service” basis (see previous paragraph). Using this concept, a structure is considered to be fit-for-service, provided that it could be operated safely in its design conditions throughout its design life.

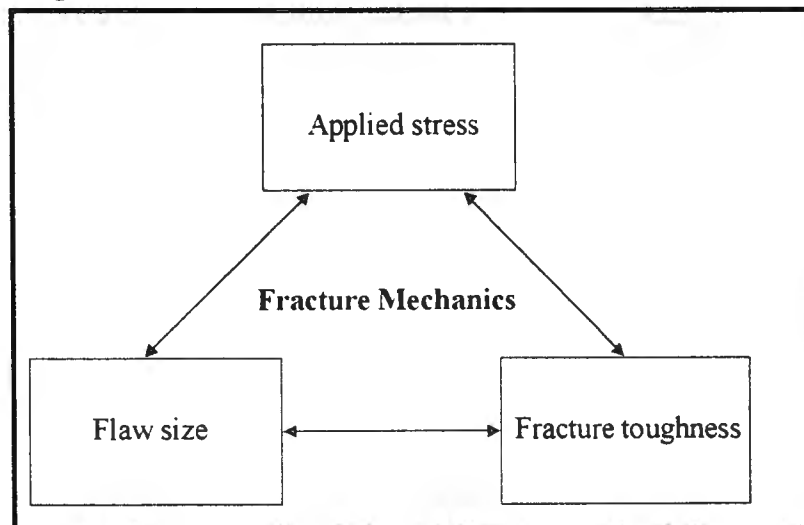
The adoption of fitness-for-service technology in the design and inspection of welded structures can result in a number of significant advantages. The major benefit undoubtedly is that the traditional weld discontinuity acceptance criteria which are included in design codes and standards could be supplemented by more rational fitness-for-service criteria. Although a fitness-for-service approach may allow weld discontinuity acceptance criteria to be relaxed, it should also lead to safer structures, because the attention will be on the more important aspects of overall quality, namely design and material selection. **The adoption of a fitness-for-service approach can also lead to significant economic benefits.** If flaw

acceptance criteria could be relaxed by means of improved design and material selection, then the incidence of repair welding can be reduced significantly. Bearing in mind that repair costs associated with the fabrication of a welded structure could frequently become a significant proportion of overall construction cost, then this aspect could be very important. Another example of the economic benefits of a fitness-for-service approach is, that it could frequently be demonstrated, that repairs on a structure in service, could be postponed until the next scheduled outage or a time when the cost of an outage is low or could be obviated completely without risking the integrity of the structure [Schubert : 1997].

5.3 FITNESS-FOR-SERVICE ANALYSIS BASIS

In contrast to arbitrary criteria, fitness-for-service analysis offer a rational basis for defining flaw acceptance limits. As discussed in the previous paragraphs fitness-for-service analysis uses fracture mechanics as basis of the analysis, with the following components as basis as shown in the figure.

Figure 5.1 Fracture Mechanics



[Anderson : 1995 : 2]

5.4 SUMMARY

Many traditional flaw acceptability limits are based on arbitrary criteria such as weld workmanship standards or NDE sensitivity. Fitness-for-service analysis however, provides a rational, quantitative basis for evaluating material imperfections. [Anderson : 1995 : 2]

There are a few codes and standards that can be followed in doing fitness-for-service analysis but it is recommended that a knowledgeable engineer must perform the analysis.

In the next chapter a summary is given on inspection frequency optimization techniques.

FREQUENCY ANALYSIS/OPTIMIZATION

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6.1 INTRODUCTION

In our process we are using the Reliability Centered Maintenance (RCM) approach to identify the equipment of facilities that may turn out to be critical with respect to safety, availability or to maintenance costs. It is for these critical pieces of equipment alone that a corrective or preventive maintenance policy is established.

But this approach has limitations:

- when there is little operating feedback and it concerns rare events affecting a piece of equipment judged critical on a priority ground. How is it possible, in this case, to decide whether or not it is critical, since there is conflict between the gravity of the potential failure and its frequency?
- when the aim is to propose an optimal maintenance frequency for a critical piece of equipment - changing the maintenance frequency hitherto applied may cause a significant drift in the observed reliability of the equipment, an aspect not generally taken into account in the RCM approach.

In these two situations, expert judgments can be combined with the available operating feedback (Bayesian approach) and the combination of risk of failure and

economic consequences taken into account (statistical decision theory) to achieve a true optimization of maintenance policy choices.

Keeping the above statements in mind we have adopted a semi-quantitative approach to determine the inspection / maintenance intervals at which specific actions must be taken.

In the next paragraph the API inspection frequency optimization model will be discussed in detail.

6.2 API FREQUENCY OPTIMIZATION

This process is semi-quantitative because there still is a certain amount of uncertainty in the exact value of specific parameters that is being used in the process.

The frequency analysis can basically be split into two different categories, namely:

- * **Category one** equipment where specific damage mechanisms are known and active, and where it can be quantified with a specific value and a amount of certainty.

- * **Category two** equipment is equipment which has probable failure mechanisms, but which cannot be quantified with the technology available at this stage. These pieces of equipment must therefore follow an intuitive process to determine the inspection frequency, backed by sound engineering judgment.

In both cases the frequency optimization can be backed by an economic consequence analysis if the information needed is obtainable.

The risk of a certain event happening will also determine the options, which are available. With the current knowledge as per API 581 the following degradation mechanisms can be analyzed by means of a spreadsheet model, to determine the

optimum inspection frequency for, statutory and non-statutory equipment. The following mechanisms can be addressed at this stage through the model:

1. Thinning Mechanisms (High and Low thinning rates)

- A - Aqueous HCC Corrosion
- B - High temperature Sulfidation
- C - Vapor / Liquid Impingement
- D - Under deposit attack
- E - High Corrosion Rates due to upset or Abnormal Conditions
- F - Erosion

2. High Temperature Hydrogen Attack

3. Stress Corrosion Cracking

- A - Wet H₂S Cracking
- B - Caustic Cracking
- C - Amine Cracking

As can be seen from the abovementioned mechanisms that can be used to determine the inspection frequency of equipment there are three main categories of degradation mechanisms, which can be quantified with respect to inspection frequency.

The detail of these analysis is given in Annexure A.

6.3 QUANTITATIVE FREQUENCY OPTIMIZATION

At this stage there are no quantitative frequency optimization techniques available except for actual accelerated testing of equipment. These tests are however also not repeatable enough to have a 99% certainty in the decision. There are too many factors that can change e.g. Material properties, cyclical loading, temperatures, product composition and many more. It can therefore be seen that the API method of accumulating the different probabilities of detection, the flaw size, the

inspections interval length and probability of a specific mechanism of being present and active to be the most reliable method of determining the optimum frequency of inspection. This is also a dynamic process and a plan-do-review is build into the process, as will be shown in the next paragraphs.

6.4 HOW TO ADDRESS FREQUENCY OPTIMIZATION

How do we approach these frequency analysis (optimization) studies?

By following the following steps; the first step is to gather field data.

6.4.1 FIELD DATA

- * The first step is to gather field data:
- * Check the general behaviour of the equipment
- * Check process conditions and upsets
- * Use a reliability data basis that is available for equipment worldwide
- * Check changes made to equipment
- * In-depth analysis of the history of equipment under consideration
- * It is important, if consideration is being given to lengthening the maintenance period, to evaluate the risk from possible aggravation of the degradation mechanisms.

The next step is to gather feedback from history and personal experience

6.4.2 FEEDBACK FROM HISTORY AND PERSONAL EXPERIENCE

Second step is analysis of feedback from experience, where inputs are needed from plant engineers, foremen and design experts. It can be seen that a multi-functional team must be considered to get the feedback.

- * Feedback from experience can yield objective factual data, from which it is possible by classical means to estimate failure rates in operation, or probabilities of operating on demand, when the equipment is initially sound, or when a known defect is left in service and monitored at a specific interval.

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- * It also yields consorted data, since it was found that some equipment functioned in a degraded condition without consequences for the safety or availability of the plant.
- * How long could the equipment have run under these conditions, and what would have been the risk and their consequences.

Answers to such questions as mentioned above presuppose a subjective approach combining the observed facts with estimates made by experts (discussed in the next paragraph).

This means of combining subjective data (prior probability density) and objective data (likelihood provided by feedback from experience) to obtain a posterior probability density that is richer applies Bayes' theorem:

$$\text{Posterior Probability} \propto \text{Prior Probability} \times \text{Likelihood} \dots\dots\dots 6.1$$

The last step is to get expert opinion by direct interaction and workshops.

6.4.3 QUESTIONS OF EXPERTS

Statistical analysis of field data makes it possible to determine the future risk of failure.

Expert opinions are needed for posterior evaluation of different probabilities, for example:

- * Probability of functioning in one or more degraded conditions.
 - The probability of failure due to as specific degradation mechanism in the specified mission time.
 - The probability that a failure under one of these conditions as identified would lead to a shutdown of a unit in application of operating procedures (Feedback from experience proved to be inadequate because no shutdowns have been observed).

Questioning experts produces lots of information, especially since they belong to different departments and their sensitivity to failure problems is not necessarily the same: operating departments, maintenance departments, management of tools or sub-contracts, economic departments, manufacturing, inspection QA, QC, etc. Given the quality and coherence of the replies received, it is generally not needed to weigh the analysis of the expert knowledge.

From this analysis it is also clear that this approach must also utilize the RCM process, to determine the functional boundaries of the equipment and to link the degradation mechanism to functional failures in the RCM process.

6.5 SUMMARY

From the information in this chapter it can be seen that a detailed knowledge of the equipment under consideration is needed to complete a frequency analysis exercise. This information must be accurate and quantifiable or else the results from the analysis can at best be a best guess and will be open to criticism.

To conclude this chapter it must be emphasized that a detail “*Fitness-for-Service*” assessment must be completed for all equipment under a high risk ranking.

This process is also done in a structured fashion with documentation and datasheets that are kept to facilitate the process and to aid the decision making process. The information is also kept for future reference to determine if the correct actions have been taken and to plan contingent actions.

In the next chapter the implementation of the RBI and RCM process is discussed and the learning points is highlighted to ensure a successful project implementation.

IMPLEMENTATION

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7.1 INTRODUCTION

In this chapter a breakdown is given of the actual implementation process and the learning points of the full project.

7.2 IMPLEMENTATION

The first step of implementation is to see the person responsible for maintenance strategies, according to the RACI, to inform them of what needs to be done, and how. This also involves the discussion of resources and the availability of the resources. Once the resources has been allocated to the project the time schedule is agreed upon and the person who will be doing the work is informed and it is being agreed that he/she is the right person to do a specific part of the work. This must be done per discipline (Mechanical, Electrical, Instruments and Production). If a person with the right skills or make-up is not selected, it can derail the process very easily.

The next step is the actual on-boarding of the people involved in the process. The first on-boarding is done in a two day session. (The on-boarding agenda can be seen in the Annexure “F”). In the on-boarding the basic principles, definitions and the way of work is conveyed to every person, and the session is structured in such a way to promote participation. A live example is also brought into the session to promote the learning experience. Time is also allocated in the program to let the

participants interact on group level to solve different problems. The whole process is a multi-disciplinary action with inter departmental awareness, as the central theme. Everybody receives the same training although everybody does not need all the tools that are available. This however promotes a mutual understanding for the processes that each group will follow. Another very important aspect of the on-boarding is to foster a common understanding of the RCM process (Reliability Centered Maintenance). The concept of risk and the importance of relative risk to the different strategies are also enforced. The third step of the process is to do a six week training program. In this phase all the people involved are taken through a hand system, until they are fully conversant in the process. The first step of the hand system is to collect all the relevant information that is needed to do the hand system. This includes code data books, PFD's, MFD's etc. which will be needed in the on-boarding process. The following step is to go through the RCM process with the hand system. This will not be discussed here as it can be tailored to any reverence on RCM. The next step in the hand system is to divide the plant into different systems according to the function of that specific system. This function in the process system function which will govern the function of that specific system or sub-system. The next step is to determine the relative risk of the specific systems to each other, this will then determine the amount of time that must be spend on the specific pieces of equipment.

Next expert meetings are held to determine what failure modes each piece of equipment in a given sub-system or system is subjected to, given certain conditions. Throughout the process the specific actions are noted by each member of the group to ensure traceability of decisions. Each divisions data is also stored in a database to ensure effective utilization of data. A generic library is also kept up to date to ensure the most effective utilization of time and information. (Don't re-invent the wheel).

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After all the actions have been completed an internal review is held by the group to ensure that the optimum decisions have been made and that nothing apparent is wrong. After this session an external review is held in which the responsible person is informed on the decisions that have been made. After this, if there are no revisions to be made, the documentation is approved and signed by the leader of the group.

In some instances one of results can also be the SOP (Standard Operating Procedures) pertaining to specific equipment and the decisions made around the equipment. After this the whole process repeats itself until all the systems are finished.

The next step is to load the information and schedules onto the MIS (Maintenance Information System) to generate the jobcards. The process and work is then measured according to certain agreed upon measures which will help to direct the business to the best practices.

The process then goes into the PDR (Plan-do-Review) phase where each decision is tested in the everyday workload. The PDR process is essentially a process that ensures that feedback is given on the relevant failure modes. This is done in a continuous basis and is in essence a continuous improvement process to ensure that the optimum maintenance strategy is followed for each piece of equipment. Care is also taken that a specific person takes responsibility for the maintenance of the system. This is to ensure that the process is followed everyday to ensure that the maximum benefit is received from the process.

Throughout the facilitation process a coaching and training role is performed by Reliability Group members to ensure a learning culture. We don't want to install a "monkey see monkey do" culture, we want to educate persons in the use of the

process, by making use of best practices and expert involvement. This will ensure that when the group disbands a core competence will remain, which will facilitate the decision making process in future, when new plants and equipment must be addressed by means of the same or updated methodology's.

In the next paragraph the learning points from the process will be discussed.

7.3 LEARNING POINTS

In the process as implemented a number of learning point were identified which could be of value, these are in no particular order:

The first point to be made is that the RCM process is still one of the best processes to determine maintenance strategies for any given piece of equipment.

This process combined with other tools such as RBI will give the maximum benefit to any maintenance strategy process. Next it should be noted that the maximum benefit will be realized when a multi-disciplinary/interdepartmental term is used to develop the strategies in conjunction with consultation from external and internal experts. One big advantage in our process was the commitment of the CEO and the expectations of this specific person. In sum specialized applications consultants can be used to do specific work that is out of scope for the Maintenance Strategy Team.

The next very important aspect of the implementation is the on-boarding process and the continuous training of the persons involved with maintenance strategies. This can also be seen as a coaching role which the Reliability Group members in our case had to fulfill.

An on-boarding file must be kept to keep track of each decisions that was made. Each and every decision that is made must be challenged by the codes and if necessary internal codes must be updated. Experience showed that internal codes

were very regulative and conservative, even more conservative than the OHSA itself.

In the process an exit visa is also given for each part of the process that is signed off by the CEO in person and this is also filed in the on-boarding and project files.

Another important aspect is the time lines that must be drawn up and progress must be measured on a weekly and sometimes on a daily basis.

The implementation process was staggered to ensure that the right resources are available for the workload. Another important aspect is to gather best practices from across the factory for mechanical, electrical and instrument equipment which will aid in the development of the maintenance strategies. These are then distributed to all the areas and are used until a next better practice is identified. These are also incorporated into a library which is centrally administrated. This library is then used to speed up the maintenance strategy development process, but care must be taken that there are differences between equipment under different conditions and there were also differences in operation of exactly the same units in the plant.

The libraries are build up for all types of equipment and are very easy to use in the case of instrument and electrical equipment.

7.4 SUMMARY

From the implementation of the process it was shown that teamwork and analysis of the implementation process is two key element in a successful project implementation. The most important aspect however is to get buy-in and thus involvement of the responsible manager in that area to give the right resources with the right make-up and skills. This is essential for a project of this size, where strategies are developed for more than a million pieces of equipment, with ten

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times that amount of failure modes. The last but the most important aspect of the whole implementation process is the actual implementation on the MIS. This process must be administered very carefully, and must be a PDR process in it's own right, to be a success.

In the next chapter a conclusion is drawn on the process and a few vital comments are made for a successful process. Future work is also discussed with links to the present work.

SUMMARY

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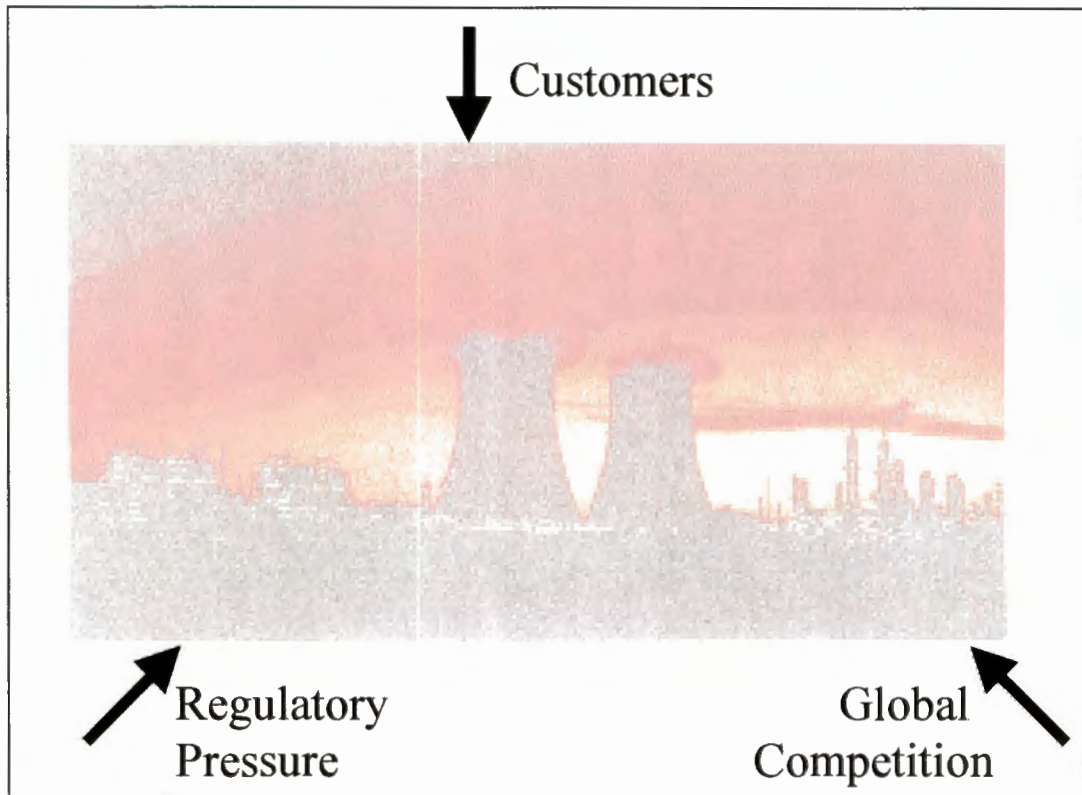
8.1 INTRODUCTION

In this chapter conclusion is drawn on the work presented in this script. A recommendation is also given on future work, and the implementation procedure.

8.2 CONCLUSION

In this script it is shown that there are various pressure from within an organization and from the external environment which will be playing a very important role in the direction any company, will be directing their future activities. The internal pressures will be because of the external environment. It can therefore be seen that an essential element in the survival of any organization will be the pro-active identification of all the key elements which are determining the direction in which they should be directing their effort and energy. They should also identify the key elements which will be determining the future developments in their line of business. These key elements, are depicted in the following figure.

Figure 8.1 External Influences



[Author : 1998]

The key elements that play a role in your business must be determined, and systems will play an important role in facilitating the role of identifying these elements.

When looking at the technologies currently available and the world trends it is obvious that the management of risk will be an integral part of any successful organization.

This is seen from the successes that were shown in the financial world over the past two, to three decades. It is also proof that the principals of one business sector can in most instances be transferred from one industry, to another. There will always be an opportunity to develop new procedures, based on sound principals adopted from another industry segment. In this picture it can also be seen that Life Cycle Cost (LCC) will always play a very important role in

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determining the amount of risk that can be taken. Very importantly, we must point out that the risk that is taken must be smaller after a risk based initiative has been implemented. The risk must be quantified and the risk must be fully understood and managed with the proper systems and tools. It must be understood that the return on investment of a given project is based on the amount of risk that the business unit is willing to take.

“In the picture as explained above it must be known that when it comes to quantifying costs and risks, people are inconsistent. “Concrete” costs, such as the purchase price of required materials, are easily established. At the other extreme, very few organizations quantify the impact (cost) of poor employee moral, public image and damage to the environment”. With this in mind it should always be strived to better public image, by quantifying the risk involved when specific decisions are taken.

It must also be understood that the tools utilized manage the assets. These tools include RCM, advanced inspection techniques and fitness for service analysis which could be done to aid in the development of specific strategies to manage the risk that is under consideration. Technology must also be utilized to it's full extend, for example the latest inspection techniques to do on-line inspections. This will help to manage the risk and to keep the operation productive. In future shutdowns should be limited to the absolute necessary. It should also be done in extreme cases, where a business case shows the benefit of intrusive inspection on the equipment under consideration.

Furthermore it was shown in the script that reliability principals can be used to determine the scope of an inspection on a specific piece of equipment. In particular it was shown that Bayes Theory is the most applicable technology at this stage. There is however more modern theory's.

It must be pointed out that a quantitative example of the RBI process can not be presented in this script due to the nature of the information.

8.3 RECOMMENDATION

From the work done in this script it became apparent that there are still a vast amount of technology's that will play a major part in the future of maintenance management procedures in the petrochemical industry. These specific aspects of maintenance management are listed below and are in no particular order of importance:

- Asset Management
- Human reliability
- Risk Based Inspection on Electrical and Instrument systems (Trips & Alarms)
- Expert systems
- Neural networks

As technology nature the aspects as listed will become more prominent in the maintenance management process.

Some of the technologies as listed will be more important than other, but others are more quantifiable than others.

Of immediate importance however is to manage the risk, risk based principals that are implemented are the following:

- Automated collection of plant health data
- Integrate the separate health assessment techniques
- Provide rapid response to enable pro-active maintenance
- Look at less labour intensive approaches
- Integrated workflow / asset management.

It was shown that on-line monitoring of critical process parameters will play a key role in the development of a pro-active approach to the review of the current strategies that are in place

8.4 CLOSURE

In this script a background was given on the concept of Risk Management, and how it can be used in the maintenance management of a Petrochemical facility. The procedure as shown is highlights from the API procedure. It is in no way exhaustive, and external consultation and information must still be used to implement a RBI process at a facility. It must be noted that there are various RBI processes, which were developed, by consultants, but the API process was chosen as the best practice for this specific industry segment after careful consultation and evaluation of the different techniques.

It must also be noted that this field of study is presently a very controversial topic and there is still a vast amount of skepticism. New developments and insights are daily added to the already complex study field.

This procedure as described has however been approved by the Sasol Synthetic Fuels management and will be used in the next number of years to ensure an optimum mix of maintenance strategies.

In conclusion this script gives a conclusive answer on how to manage equipment under pressure in a scientific fashion to ensure the maximum productivity of the equipment.

It is also shown what procedures can be followed to eliminate unnecessary or excessive maintenance. In other words – focus on the critical few. The method as described will ensure increased plant availability and thus an increase on investment.

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The approach as described focusses totally on risk. The planned maintenance and service's workload is reduced, this also means fewer people doing maintenance to maintain a certain level of plant output. The last and not the least are the optimized maintenance frequencies which is a result of the procedure as described.

From the above it can be seen that the combined RCM and RBI approach will provide a competitive benefit for each company if properly applied on a company wide basis.

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APPENDIX A

**FREQUENCY
ANALYSIS**

RBI frequency analysis is done by following the model as described in this Appendix. The module is divided into three categories and is an abstract of API 581.

This module uses various analytical tools to “*update*” the likelihood of damage based on inspections, and to calculate the relative severity of damage.

The calculation of the various damage subfactors was done by API/DNV and the details of this will not be discussed, it can however be mentioned that the principle used in the calculation of the factors is based on Baye’s theory.

Next each category will be discussed under the following headings:

- 1 Screening questions
- 2 Basic data required for Analysis
- 3 Damage state
- 4 Inspection effectiveness Category
- 5 Subfactor determination

CATEGORY 1: THINNING MECHANISMS (High and Low Thinning Rate)

Screening Question

Is the thinning rate <u>known</u> to be less than 0.0254 mm/y based on:	Yes - exit
* the non-corrosive nature of the internal environment, including trace, components, has been established by at least five years service experience in this equipment or similar equipment.	No - proceed to technical module
* the process does not include the possibility for inadvertent contamination by corrosives	
* no thinning mechanisms other than corrosion are operative.	

and

Is the equipment designed with a corrosion allowance?	No - exit; Yes - proceed to technical module
---	---

Basic Data Required for Analysis

Basic Data	Comments
Thickness (mm)	The thickness is the new construction minimum thickness, or the actual measured minimum thickness upon being placed in current service.
Time (years)	The number of years that the equipment has been exposed to the current process conditions that result in the corrosion rate used below. A suggested default value is the equipment age in years, unless process conditions or corrosion rates are known to have changed substantially.
Corrosion Allowance (mm)	The corrosion allowance is the design or calculated corrosion allowance upon being placed in current service.
Corrosion Rate (mm/year)	The current estimate of the rate of thinning.
Operating Pressure (kPa)	The highest expected operating pressure (may be the relief valve set pressure unless pressures that high are unlikely).
Design Pressure (kPa)	The pressure used to determine the minimum allowable wall thickness.
Inspection Type & Category	The category of inspection that has been performed on the equipment. See the supplements to this module describing thinning mechanisms for guidelines to inspection categories.
Number of Inspections	The number of inspections in each category that have been performed. The discussion under "Technical Module Subfactor Determination" is used for the determination of equivalent inspection numbers.

Damage States:

This technical database considers three possible damage states that are expected to represent most cases of damage:

Possible Damage States for Thinning Mechanisms

Damage State Category	Thinning Rate (λ)
<p><u>Damage State 1</u> The damage in the equipment is “no” worse than what is expected based on damage rate models or experience.</p>	<p>The rate of thinning is less than or equal to the rate predicted by past inspection records, or historical data if no inspections have been performed. ($\leq 1\lambda$)</p>
<p><u>Damage State 2</u> The damage in the equipment is “somewhat” worse than anticipated. This level of damage is sometimes seen in similar equipment items.</p>	<p>The rate of thinning is as much as twice the predicted rate. ($\leq 2\lambda$)</p>
<p><u>Damage State 3</u> The damage in the equipment is “considerably” worse than anticipated. This level of damage is rarely seen in similar equipment items, but has been observed on occasion industry wide.</p>	<p>The rate of thinning is as much as four times the predicted rate. ($\leq 4\lambda$)</p>

Inspection Effectiveness Category

Inspections are ranked according to their expected effectiveness at finding thinning and correctly predicting the rate of thinning. The actual effectiveness of a given inspection technique depends on the characteristics of the thinning mechanism, and other factors. More detailed guidelines for ranking the effectiveness of inspections are presented in the “mechanism specific” supplements (category A-E). The following table described the five effectiveness categories:

Table 1: Qualitative Inspection Effectiveness Categories

Qualitative Inspection Effectiveness Categories
<p>Highly Effective Correctly identify the anticipated in-service damage in nearly every case.</p>
<p>Usually Effective The inspection methods will correctly identify the actual damage state most of the time.</p>
<p>Fairly Effective The inspection methods will correctly identify the true damage state about half of the time.</p>
<p>Poorly Effective The inspection methods will provide little information to correctly identify the true damage state.</p>
<p>Ineffective The inspection method will provide no or almost no information that will correctly identify the true damage state.</p>

Table 2 below provides examples of inspection activities that are both intrusive (requires entry into the equipment) and non-intrusive (can be performed externally). Note that the effectiveness category assigned to the inspection activity differs depending on the degree to which the thinning is uniform or localized. For the purposes of this technical module, “localized” thinning is defined as any mechanism for which the maximum thinned area is less than 25% of the total equipment surface.

For localized thinning, selection of locations for examination must be based on a thorough understanding of the damage mechanism in the specific process. See the mechanism specific supplements to this module.

Table 2: Guidelines for Assigning Inspection Effectiveness

Inspection Effectiveness Category		Example: Intrusive Inspection	Example: Non-intrusive Inspection
Uniform Thinning	Localized Thinning		
Highly Effective	Highly Effective	50 to 100% examination of the surface, complete internal visual inspection with removal of internal packing, trays, etc. Visual inspection is accompanied by thickness measurements	50 to 100% coverage: Automated ultrasonic scanning Profile radiography
Highly Effective	Usually Effective	5 to 50% examination of the surface, partial internal visual inspection, internal not removed, internal inspection may be from spot locations (manways, nozzles, etc. Visual inspection is accompanied by thickness measurements)	5 to 50% coverage: Automated or manual ultrasonic scanning Profile radiography
Usually Effective	Fairly Effective	Less than 5% examination, spot external ultrasonic thickness measurements, little or no internal visual examination	Less than 5% coverage: Automated or manual ultrasonic scanning, profile radiography, external spot thickness with number and locations of reading statistically validated.
Fairly Effective	Poorly Effective	Internal visual examination, not coupled to external thickness measurements or measurements not taken.	Less than 5% examination, spot external ultrasonic thickness measurements, little or no internal visual examination.
Poorly Effective	Ineffective		Few thickness measurements taken externally, well organized inspection planning system.
Ineffective	Ineffective	No inspection	Few thickness, measurements taken externally, poorly organized inspection planned system.

SUBFACTOR DETERMINATION

Table 3: Technical Module Subfactor Determination

Step	Instructions								
<p>Step 1 Calculate ratio ar/t</p>	<p>Calculate (age * corrosion rate) / thickness. This result is equivalent to the fraction of wall loss due to corrosion. Note: "Age" refers to the time period over which the user wants to apply the corrosion rate. This may be the equipment age, or may be the time in current service. Thickness would be the actual original thickness (if known) or the thickness of the equipment at the time the equipment went into service.</p>								
<p>Step 2 Determine Inspection Equivalents</p>	<p>The number of inspections to be used when looking up the Technical Module Subfactor is to be the number of the highest level of inspection that has been performed. Credit for other inspections can be taken by equating them to an equivalent higher inspection level. The following relations are to be used:</p> <ul style="list-style-type: none"> • One "Highly Effective" inspection equals two "Usually Effective" inspections • One "Highly Effective" inspection equals four "Fairly Effective" inspections • One "Usually Effective" inspection equals two "Fairly Effective" inspections 								
<p>Step 3 Look up the Technical Module Subfactor</p>	<p>Use the Technical Module Subfactor Tables (Table 4 & 5). Look up the factor for each corrosion type (general corrosion, localized corrosion, or pitting corrosion) in the tables below, based on ar/t, the number of inspections, and the inspection effectiveness category.</p>								
<p>Step 4 Correct Technical Module Subfactor for Overdesign</p>	<p>Calculate the Overdesign Factor as the larger of:</p> <ul style="list-style-type: none"> • thickness / (thickness-corrosion allowance) or • MAWP* / operating pressure <p>* MAWP = Maximum Allowable Working Pressure</p> <p>Multiply the Technical Module Subfactor from the above tables by the correction factor below to obtain the corrected Technical Module Subfactor.</p> <table style="width: 100%; border: none;"> <tr> <td style="text-align: center;">Overdesign Factor</td> <td style="text-align: center;">Correction Factor</td> </tr> <tr> <td style="text-align: center;">< 1.1</td> <td style="text-align: center;">2.0</td> </tr> <tr> <td style="text-align: center;">1.1 to 1.5</td> <td style="text-align: center;">1.0</td> </tr> <tr> <td style="text-align: center;">> 1.5</td> <td style="text-align: center;">0.5</td> </tr> </table>	Overdesign Factor	Correction Factor	< 1.1	2.0	1.1 to 1.5	1.0	> 1.5	0.5
Overdesign Factor	Correction Factor								
< 1.1	2.0								
1.1 to 1.5	1.0								
> 1.5	0.5								
<p>Step 5 Correct Technical Module Subfactor for High Confidence Corrosion Rates</p>	<p>If the corrosion rate used in this module is based on extensive field data, and is believed to be highly accurate, multiply the Correct Technical Module Subfactor from Step 4 by an additional factor of 0.25.</p>								

Next five specific thinning mechanisms is described.

(A) AQUEOUS HCl CORROSION

Basic Data Required for Analysis

Basic Data	Comments
% HCl or % Cl	If % Cl is known only, the pH must be determined.
PH	In general, corrosion of carbon steel is greatly accelerated at pH<4
Temperature	Corrosion by HCl is highly dependent on temperature.
Material of Construction	Carbon steel is readily attacked by solutions of HCl. More resistant alloys include Ni/Cu and Ni/Cr/Mo.

Description of Damage

Aqueous solutions of HCl are highly corrosive to common carbon, low alloy, and stainless steels. In some services, such as refinery crude distillation units, small amounts of HCl may be formed by hydrolysis of inorganic chlorides. In such cases, is it often more economical to neutralize the acid (e.g. by ammonia or neutralizing amine addition) to control corrosion than to select alloys that are resistant to attack. In such cases, corrosion tends to occur locally and sporadically if the neutralizer is insufficient for the amount of acid. Additionally, corrosion may occur beneath deposits of chloride salts.

Inspection Effectiveness

Due to the localized nature of aqueous HCl corrosion, spot inspection methods may not detect the worst areas of corrosion where it occurs in process plants. Use the “Localized Thinning” column of Table 2 as a guideline to estimating the effectiveness of inspection programs.

(B) HIGH TEMPERATURE SULFIDATION

Basic Data Required for Analysis

Basic Data	Comments
% Sulfur, type of Sulfur Compounds	The types of sulfur compounds (organic, inorganic) as well as the total percent sulfur influence the corrosion rate.
Temperature	High temperature sulfidation corrosion generally occurs at temperatures above 260°C.
Material of Construction	Low alloy steel containing chromium are used to increase resistance.

Description of Damage

High Temperature Sulfidation involves the chemical reaction between iron and sulfur at high temperatures. Since this type of corrosion is not dependent on electrochemistry with corresponding areas of anode and cathode, the attack tends to occur fairly uniformly over the surface. A few exceptions to this uniformity of corrosion can occur in areas of high velocity, or in refineries processing crude's with a high napthenic acid number (TAN #). It should also be noted that corrosion rates tend to be 5 to 10 times higher in the vapor than in the liquid. The following tables suggest some corrosion rates (in mm/y) that can be used.

NOTE: corrosion rates tent to be higher in streams containing H₂S and H₂.

RISK BASED MANAGEMENT - FREQUENCY ANALYSIS

Table 4 THINNING MECHANISMS MODULES - SUBFACTOR TABLE																									
ar/t	0	1 Inspection				2 Inspections				3 Inspections				4 Inspections				5 Inspections				6 Inspections			
		Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness			
	Ineffective	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly
0.02	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.04	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.06	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.08	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.12	6	5	3	2	1	4	2	1	1	3	1	1	1	2	1	1	1	2	1	1	1	1	1	1	1
0.14	20	17	10	6	1	13	6	1	1	10	3	1	1	7	2	1	1	5	1	1	1	4	1	1	1
0.16	30	70	50	20	3	50	20	4	1	40	10	1	1	30	5	1	1	20	2	1	1	14	1	1	1
0.18	50	200	130	70	7	170	70	10	1	130	35	3	1	100	15	1	1	70	7	1	1	50	3	1	1
0.2	100	300	210	110	15	290	120	20	1	260	60	5	1	180	20	2	1	120	10	1	1	100	6	1	1
0.25	150	450	290	150	20	350	170	30	2	240	80	6	1	200	30	2	1	150	15	2	1	120	7	1	1
0.3	250	550	400	200	30	400	200	40	4	320	110	9	2	240	50	4	2	180	25	3	2	150	10	2	2
0.35	350	650	550	300	80	600	300	80	10	540	150	20	5	440	90	10	4	350	70	6	4	280	40	5	4
0.4	500	800	700	400	130	700	400	120	30	600	200	50	10	500	140	20	8	400	110	10	8	350	90	9	8
0.45	750	900	810	500	200	800	500	160	40	700	270	60	20	600	200	30	15	500	160	20	15	400	130	20	15
0.5	1000	1100	970	600	270	1000	600	200	60	900	360	80	40	800	270	50	40	700	210	40	40	600	180	40	40
0.55	1500	1200	1130	700	350	1100	750	300	100	1000	500	130	90	900	350	100	90	800	260	90	90	700	240	90	90
0.6	2000	1400	1250	850	500	1300	900	400	230	1200	620	250	210	1000	450	220	210	900	360	210	210	800	300	210	210
0.65	2500	1700	1400	1000	700	1600	1105	670	530	1300	880	550	500	1200	700	530	500	1100	640	500	500	1000	600	500	500

Instructions:

1. Calculate ar/t (equipment age (years) x corrosion rate (in/yr) / thickness (in)).
Find the row with this value or the next higher, value or interpolation may be used between rows.

2. Look up damage subfactor under appropriate column for number of inspections and inspection effectiveness level.

3. Multiply damage subfactor by correction factors below. (Do not apply correction factors to damage subfactors of 1)

Correction F actors:

Overdesign Factor.*	
T(act)/T (min	Factor
< 1.1	2
1.1 - 1.5	1
>1.5	0.5
* T (act) / T (act) - C.A.)	
or: P (design) / P (operating)	

Rate estimate quality:	
Corrosion rate based on extensive field data, multiple high quality inspections, etc.	Factor: 0.25

RISK BASED MANAGEMENT - FREQUENCY ANALYSIS

Table 5 THINNING MECHANISMS TECHNICAL MODULES - SUBFACTOR TABLE FOR HIGHLY VARIABLE RATES																									
ar/t	Ineffective	1 Inspection				2 Inspections				3 Inspections				4 Inspections				5 Inspections				6 Inspections			
		Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness				Inspection Effectiveness			
		Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly	Poorly	Fairly	Usually	Highly
0.002	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.004	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
0.006	43	33	23	10	1	25	11	2	1	18	5	1	1	13	2	1	1	10	1	1	1	7	1	1	1
0.008	€ 41	491	338	149	14	368	161	25	1	270	71	4	1	196	30	1	1	140	13	1	1	99	5	1	1
0.01	€ 41	491	338	149	14	368	161	25	1	270	71	4	1	196	30	1	1	140	13	1	1	99	5	1	1
0.012	€ 41	491	338	149	14	368	161	25	1	270	71	4	1	196	30	1	1	140	13	1	1	99	5	1	1
0.014	€ 41	491	338	149	14	368	161	25	1	270	71	4	1	196	30	1	1	140	13	1	1	99	5	1	1
0.016	€ 41	491	338	149	14	368	161	25	1	270	71	4	1	196	30	1	1	140	13	1	1	99	5	1	1
0.018	€ 41	491	338	149	14	368	161	25	1	270	71	4	1	196	31	1	1	140	13	1	1	99	5	1	1
0.02	€ 41	491	338	149	14	368	161	25	1	271	71	4	1	196	31	1	1	140	13	1	1	99	5	1	1
0.022	€ 42	491	338	149	14	368	161	25	1	271	71	4	1	196	31	1	1	140	13	1	1	99	5	1	1
0.024	€ 42	491	338	150	14	368	161	25	1	271	71	4	1	196	31	1	1	140	13	1	1	99	5	1	1
0.026	€ 42	491	338	150	14	368	161	25	1	271	71	4	1	196	31	1	1	140	13	1	1	99	5	1	1
0.028	€ 42	491	338	150	14	368	161	25	1	271	72	4	1	196	31	1	1	140	13	1	1	99	5	1	1
0.03	€ 42	491	338	150	14	368	161	25	1	271	72	4	1	196	31	1	1	140	13	1	1	99	5	1	1
0.032	€ 42	491	338	150	14	368	161	25	1	271	72	4	1	196	31	1	1	141	13	1	1	100	6	1	1
0.034	€ 42	492	338	150	14	368	161	25	1	271	72	4	1	197	31	1	1	141	13	1	1	100	6	1	1
0.036	€ 42	492	339	150	14	369	161	25	1	271	72	4	1	197	31	1	1	141	13	1	1	100	6	1	1
0.038	€ 42	492	339	150	14	369	162	25	1	272	72	4	1	197	31	1	1	141	13	1	1	100	6	1	1

Instructions:

1. Calculate ar/t (equipment age (years) x corrosion rate (in/yr) / thickness (in)).
Find the row with this value or the next higher, value or interpolation may be used between rows.

2. Look up damage subfactor under appropriate column for number of inspections and inspection effectiveness level.

3. Multiply damage subfactor by correction factors below. (Do not apply correction factors to damage subfactors of 1)

Correction Factors:

Overdesign Factor: [*]	
T(act)/T (min)	Factor
< 1.1	2
1.1 - 1.5	1
>1.5	0.5
[*] T(act) / T(act) - C.A.)	
or: P (design) / P (operating)	

Table 6: High Temperature Sulfidation Corrosion Rates (Crude Oil, 0.6% S)

Temperature	Carbon Steel	5% Chrome Steel	7% Chrome Steel	9% Chrome Steel	12% Chrome Steel	18/8 Stainless Steel
260.000	2.540	0.889	0.635	0.381	0.203	0.051
287.778	5.334	1.600	1.143	0.889	0.254	0.064
315.556	10.922	3.302	2.032	1.524	0.457	0.076
343.333	19.812	5.842	3.302	2.032	0.635	0.152
371.111	30.480	8.636	5.588	3.302	1.016	0.254
398.889	40.640	11.938	7.366	4.826	1.397	0.356

- **NOTE:** 7% Chrome steels are rarely used.

Table 7: High Temperature Sulfidation Corrosion Rates (Naphtha Desulfurizers, 0.6 H₂S)

Temperature	Carbon Steel	5% Chrome Steel	9% Chrome Steel	12% Chrome Steel	18/8 Stainless Steel
260.000	0.254	0.089	0.064	0.038	0.020
287.778	0.533	0.160	0.114	0.089	0.025
315.556	1.092	0.330	0.203	0.152	0.046
343.333	1.981	0.584	0.330	0.203	0.064
371.111	3.048	0.864	0.559	0.330	0.102
398.889	4.064	1.194	0.737	0.483	0.140

Table 8: High Temperature Sulfidation Corrosion Rates (Gas Oil Desulfurizers, 0.6% H₂ S)

Temperature	Carbon Steel	5% Chrome Steel	9% Chrome Steel	12% Chrome Steel	18/8 Stainless Steel
260.000	0.178	0.127	0.102	0.025	0.005
287.778	0.254	0.254	0.254	0.051	0.008
315.556	0.457	0.381	0.330	0.076	0.013
343.333	0.762	0.635	0.508	0.102	0.018
371.111	1.092	0.889	0.762	0.152	0.025
398.889	1.524	1.168	1.118	0.229	0.038

Inspection Effectiveness

Due to the uniform nature of high temperature sulfidation corrosion in most cases where it occurs in process plants, spot inspection methods may be effective to detect the worst areas of corrosion. Use the “Uniform Thinning” column of Table 2 as a guideline to estimating the effectiveness of inspection programs. **NOTE:** A few exceptions to this

uniformity of corrosion can occur in areas of high velocity, or in refineries processing crude's with a high naphthenic acid number (TAN #).

(C) VAPOR / LIQUID IMPINGEMENT

Basic Data Required for Analysis

Basic Data	Comments
pH	If the pH of the entrained liquid droplets is <4, the rate of corrosion can be expected to be much higher. If the entrained liquid is non-corrosive, attack by this mechanism would not be expected to occur.
Velocity	The velocity at which vapor liquid impingement will occur differs for different environments, but generally will occur at velocities >6.096 m/s.

Description of Damage

Vapor/liquid impingement corrosion occurs when entrained droplets in a vapor stream remove corrosion products that would ordinarily serve to reduce overall corrosion rates. The attack tends to occur at areas where the droplets impact the metal surface at a sharp angle, such as changes of flow direction (elbows, tees, heat exchanger inlets), or areas of high turbulence (control valves, orifice plates). The attack is often highly localized to these areas, with little or no corrosion occurring at other locations.

Inspection Effectiveness

Due to the localized nature of vapor/liquid impingement corrosion in most cases where it occurs in process plants, spot inspection methods may not detect the worst areas of corrosion. However, since the locations of attack can be predicted, a well planned inspection program can focus on those areas most subject to attack. Use the "Localized Thinning" column of Table 2 as a guideline to estimating the effectiveness of inspection programs.

(D) UNDERDEPOSIT ATTACK

Basic Data Required for Analysis

Basic Data	Comments
% Cl -	Chlorides tend to increase corrosion beneath deposits.
Temperature	Corrosion by underdeposit attack is increased by temperature, similar to other corrosion mechanisms. At temperatures above the aqueous dew point of the systems, under deposit attack does not occur.
Material of Construction	Most alloys can be subject to corrosion under deposits in certain environments.

Description of Damage

Deposits forming on metals can result in corrosion beneath the deposit due to different electrochemical potential between the area beneath the deposit and the surrounding area. Additionally, corrosive chemicals can concentrate beneath the deposit, resulting in accelerated attack. Since deposits can form in random areas on the metal surface, this type of corrosion can occur in highly localized spots with little or no corrosion elsewhere.

Inspection Effectiveness

Due to the localized nature of under deposit corrosion in most cases where it occurs in process plants, spot inspection methods may not detect the worst areas of corrosion. Use the "Localized Thinning" column of Table 2 as a guideline to estimating the effectiveness of inspection programs.

(E) HIGH CORROSION RATES DUE TO UPSET OR ABNORMAL CONDITIONS

Basic Data

The basic data that will determine if an equipment item is subject to unusual high corrosion will vary from process to process, and may not be predictable for all cases where it can occur, except through experience with similar equipment. For the technical module analysis, all that is required in the general case is an assessment of whether or not the equipment being evaluated is subject to the unusual high corrosion rates. See the special instructions for analysis below.

Basic Data Required for Analysis

<i>Basic Data</i>	<i>Comments</i>
Is the equipment subject to high corrosion rates due to process upsets or abnormal conditions?	Yes or no, based on experience with similar operations or sensitivity analysis on key process parameters with respect to corrosion rates.
What is the measured or expected normal corrosion rate?	Use the measured or expected rate. NOTE: Since highly variable rates will normally require inspection at short frequencies, thickness measurements may show no short term wall loss. In this case, use the expected normal corrosion rate.

Special Instructions for Analysis

High corrosion rates due to upset conditions can be addressed in a similar manner to any other corrosion mechanism, using the subfactor Table 5.

Determine Technical Module Subfactor

Step	Instructions								
Step 1 Calculate ratio ar/t	Calculate (age * corrosion rate) / thickness. This result is equivalent to the fraction of wall loss due to corrosion. NOTE: "Age" refers to the time period over which the user wants to apply the corrosion rate. This may be the equipment age, or may be another time period.								
Step 2 Determine inspection equivalents	The number of inspections to be used when looking up the Technical Module Subfactor is to be the number of the highest level of inspection that has been performed. Credit for other inspections can be taken by equating them to an equivalent higher inspection level. The following relations are to be used: <ul style="list-style-type: none"> • One "Highly Effective" inspection equals two "Usually Effective" inspections. • One "Highly Effective" inspection equals four "Fairly Effective" inspections. • One "Usually Effective" inspection equals two "Fairly Effective" inspections. 								
Step 3 Look up the Technical Module Subfactor	Use the Technical Module Subfactor Table for Highly Variable Rates (Table 5). Look up the factor in the table below, based on ar/t, the number of inspections, and the inspection effectiveness category.								
Step 4 Correct Technical Module Subfactor for Overdesign	Calculate the Overdesign Factor as the larger of: <ul style="list-style-type: none"> • thickness / (thickness-corrosion allowance) or • MAWP * / operating pressure * MAWP = Maximum Allowable Working Pressure Multiply the Technical Module Subfactor from the above tables by the correction factor below to obtain the corrected Technical Module Subfactor. <table border="0" style="width: 100%; margin-top: 10px;"> <tr> <td style="width: 50%;">Overdesign Factor</td> <td style="width: 50%;">Correction Factor</td> </tr> <tr> <td>< 1.1</td> <td>2.0</td> </tr> <tr> <td>1.1 to 1.5</td> <td>1.0</td> </tr> <tr> <td>> 1.</td> <td>0.5</td> </tr> </table>	Overdesign Factor	Correction Factor	< 1.1	2.0	1.1 to 1.5	1.0	> 1.	0.5
Overdesign Factor	Correction Factor								
< 1.1	2.0								
1.1 to 1.5	1.0								
> 1.	0.5								

CATEGORY 2: HIGH TEMPERATURE HYDROGEN ATTACK

Screening Question:

<p>Does the operating temperature exceed the “Nelson curve temperature (API 941:4” Edition, 1990) for the hydrogen partial pressure?</p> <p>(For C-½ Mo steels: - Does the operating temperature exceed the carbon steel “Nelson” curve by more than 37.7°C for the hydrogen partial pressure, and is the hydrogen partial pressure greater than 10.3MPa?)</p>	<p>Yes - proceed to Technical Module No - exit</p>
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(Alternate screening question):

<p>Is the hydrogen partial pressure greater than 6.896MPA and does the operating temperature of the equipment exceed the following temperatures:</p> <table data-bbox="151 924 687 1260"> <thead> <tr> <th>Material</th> <th>Temperature</th> </tr> </thead> <tbody> <tr> <td>Carbon Steel</td> <td>232.22°C</td> </tr> <tr> <td>Carbon - ½ Mo</td> <td>287.77°C</td> </tr> <tr> <td>1 Cr - ½ Mo</td> <td>343.33°C</td> </tr> <tr> <td>1.25 Cr - ½ Mo</td> <td>343.33°C</td> </tr> <tr> <td>2 Cr - ½ Mo</td> <td>398.88°C</td> </tr> <tr> <td>2.25 Cr - 1 Mo</td> <td>454.44°C</td> </tr> <tr> <td>3 Cr - ½ Mo</td> <td>510.00°C</td> </tr> <tr> <td>6 Cr - ½ Mo</td> <td>593.33°C</td> </tr> </tbody> </table>	Material	Temperature	Carbon Steel	232.22°C	Carbon - ½ Mo	287.77°C	1 Cr - ½ Mo	343.33°C	1.25 Cr - ½ Mo	343.33°C	2 Cr - ½ Mo	398.88°C	2.25 Cr - 1 Mo	454.44°C	3 Cr - ½ Mo	510.00°C	6 Cr - ½ Mo	593.33°C	<p>Yes - proceed to Technical Module No - exit</p>
Material	Temperature																		
Carbon Steel	232.22°C																		
Carbon - ½ Mo	287.77°C																		
1 Cr - ½ Mo	343.33°C																		
1.25 Cr - ½ Mo	343.33°C																		
2 Cr - ½ Mo	398.88°C																		
2.25 Cr - 1 Mo	454.44°C																		
3 Cr - ½ Mo	510.00°C																		
6 Cr - ½ Mo	593.33°C																		

Basic Data Required for Analysis

Basic Data	Comments
Nelson Curve Temperature (°C)	The temperature corresponding to operational temperature, pressure, H ₂ partial pressure, and material of construction. From API Publication 941.4 th Edition, April 1990.
Operating temperature (°C)	The normal expected operating temperature.
Operating pressure (Kpa)	The normal expected operating pressure.
Mole or volume % H ₂ in process	To calculate the hydrogen partial pressure.
Material of construction	Must be one of the materials in API 941.
Equipment Age (years)	The age is the number of years that the equipment has been exposed to the current process conditions.
Inspection Type & Category	The category of inspection that has been performed on the equipment. See the “Inspection Effectiveness Category” section for guidelines to inspection categories.

RISK BASED MANAGEMENT - FREQUENCY ANALYSIS

Basic Data	Comments
Number of Inspections	The number of inspections in each category that have been performed. The discussion under “Technical Module Subfactor Determination” is used for the determination of equivalent inspection numbers.

Description of Damage

Hydrogen attack is a result of the reaction between atomic hydrogen and carbon in the steel at elevated temperatures and pressures to form methane. The likelihood of hydrogen attack is primarily a function of temperature, hydrogen partial pressure, and the presence of unstable carbides in the material. The rate of attack is dependent on the internal methane pressure, creep rate of the material, and the amount of grain boundary damage. At high temperature and stress, hydrogen attack may also interact with creep to accelerate damage.

The progress of hydrogen attack through the wall thickness depends on the hydrogen partial pressure. At low hydrogen partial pressure, hydrogen attack will tend to concentrate at the exposed surface and progress slowly through the wall thickness. In high stress areas, such as weld heat-affected zones, cracking can progress through the wall. This is caused by the alignment of microcracks into macrocracking, which in some cases can result in brittle fracture.

At high hydrogen partial pressure, the time for hydrogen attack to progress from the exposed surface to midwall is relatively short. The effect will be a general reduction in the material properties due to embrittlement. This will result in an increased creep rate, and eventually failure by rapid ductile tearing of the remaining, unaffected material due to overload.

RISK BASED MANAGEMENT - FREQUENCY ANALYSIS

Detection of hydrogen attack by inspection is difficult in the undisturbed base material and in critical areas, such as weld and heat-affected zones. Localized hydrogen attack caused by unstable carbides in the base material represents another problem. A full inspection program would therefore include a global assessment for detection and location of cracklike features, and follow-up using NDE methods for quantification and confirmation of attack.

Possible Damage States for High Temperature Hydrogen Attack

Damage State Category	Damage Rate
<p>Damage State 1 The damage in the equipment is no worse than what is expected based on damage rate models or experience.</p>	Complete loss of metal strength (at any depth) requires twenty times the incubation time at that depth.
<p>Damage State 2 The damage in the equipment is “somewhat” worse than anticipated. This level of damage is sometimes seen in similar equipment items.</p>	Complete loss of metal strength (at any depth) requires ten times the incubation time at that depth.
<p>Damage State 3 The damage in the equipment is “considerably” worse than anticipated. This level of damage is rarely seen in similar equipment items, but has been observed on occasion industry wide.</p>	Complete loss of metal strength (at any depth) occurs at the incubation time at that depth.

Inspection Effectiveness Category

Due to the nature of high temperature hydrogen attack, detection is difficult by many inspection methods. The following guides are for inspection effectiveness of commonly used inspection techniques:

Inspection Effectiveness Category	Typical Inspection Practices
“Usually Effective”	Extensive AUBT (Advanced Ultrasonic Backscatter Technique) or spot AUBT based on stress analysis.
“Fairly Effective”	Spot AUBT.
“Poorly Effective”	Ultrasonic backscatter plus attenuation.

RISK BASED MANAGEMENT - FREQUENCY ANALYSIS

Technical Module Subfactor Determination

The following table describes the steps required to determine the High Temperature Hydrogen Attack Technical Module Subfactor:

Step	Instructions
Step 1 Calculate ($a\sqrt{\Delta T}$)	Calculate the age (in years) times the square root of the amount by which the operating temperature exceeds the "Nelson" curve temperature.
Step 2 Determine inspection equivalents	<p>The number of inspections to be used when looking up the Technical Module Subfactor is to be the number of the highest level of inspection that has been performed. Credit for other inspections can be taken by equating them to an equivalent higher inspection level. The following relations are to be used:</p> <ul style="list-style-type: none"> • One "Usually Effective" inspection equals two "Fairly Effective" inspections. • One "Usually Effective" inspection equals four "Poorly Effective" inspections. • One "Fairly Effective" inspection equals two "Poorly Effective" inspections.
Step 3 Look up the Technical Module Subfactor	Use the Technical module Subfactor Tables. Look up the damage from the table below, based on a $\sqrt{\Delta T}$, the number of inspections, and the inspection effectiveness category.

RISK BASED MANAGEMENT - FREQUENCY ANALYSIS

TECHNICAL MODULE # 2 - HIGH TEMPERATURE HYDROGEN ATTACK

Table 9		HIGH TEMPERATURE HYDROGEN ATTACK TECHNICAL MODULE - SUBFACTORS TABLE																										
Number of Inspections																												
Inspection Effectiveness																												
	0				1				2				3				4				5				6			
	Ineffective	Poorly	Fairly	Usually	Poorly	Fairly	Usually	Poorly	Fairly	Usually	Poorly	Fairly	Usually	Poorly	Fairly	Usually	Poorly	Fairly	Usually	Poorly	Fairly	Usually						
100	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1							
120	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1							
140	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1							
160	2	2	2	1	2	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1							
180	4	3	2	2	3	2	1	2	1	1	2	1	1	2	1	1	2	1	1	1	1							
200	7	5	4	2	4	2	1	3	2	1	3	1	1	2	1	1	2	1	1	2	1							
220	13	10	7	4	7	4	2	6	2	1	4	2	1	3	1	1	3	1	1	3	1							
240	28	21	14	7	15	7	3	11	4	2	8	2	1	6	2	1	5	2	1	5	2							
260	62	45	30	14	33	14	4	24	7	2	17	4	2	12	2	2	9	2	2	9	2							
280	133	97	63	29	70	29	7	50	13	3	35	6	2	25	4	2	18	2	2	18	2							
300	253	184	119	54	132	53	12	94	24	4	66	11	2	47	6	2	33	3	2	33	3							
350	326	237	154	70	171	69	15	122	31	5	86	14	3	61	7	2	43	4	2	43	4							
400	333	243	159	74	176	72	18	126	33	7	90	16	4	64	8	3	46	5	3	46	5							
450	351	259	171	86	190	81	25	138	39	10	101	20	6	74	11	5	54	7	4	54	7							
500	403	306	208	118	230	106	43	174	55	20	131	30	12	99	18	9	76	12	7	76	12							
550	542	429	306	204	338	170	90	267	96	46	211	56	26	167	35	16	134	23	12	134	23							
600	828	682	506	380	560	302	187	458	181	98	375	110	54	307	68	32	252	44	21	252	44							
650	971	810	608	470	672	371	238	556	225	126	459	139	70	379	88	42	314	58	28	314	58							
700	976	815	614	476	677	377	244	561	232	133	465	146	77	385	95	49	320	65	35	320	65							

Instructions: 1. Determine the difference between the operating temperature of the equipment and the Nelson curve temperature at the appropriate hydrogen partial pressure.

NOTE: For Carbon - 1/2 Moly steels, use the carbon steel Nelson curve, and subtract 100 degrees F from the difference determined above.

2. Multiply the age of the vessel by the square root of the temperature difference determined above.

3. Identify the number of inspections and the level of inspections, and find the damage factor in the appropriate column.

CATEGORY 3: STRESS CORROSION CRACKING

Scope

This module only applies to equipment areas that are susceptible to stress corrosion cracking. Wet H₂S cracking, amine cracking, caustic cracking, are within the scope of the module. Supplements are added to this module to deal with specific damage mechanisms that result in corrosion cracking. Expert advice is recommended to determine susceptibility of equipment to corrosion cracking.

Screening Questions

For carbon steel, is the equipment exposed to hydrogen sulfide at temperatures less than 148°C.	Yes - proceed to technical module.
For carbon steel, is the equipment exposed to sodium hydroxide at temperatures greater than 48°C.	Yes - proceed to technical module.
For carbon steel, is the equipment exposed to gas treating amines (MEA, DEA, DIPA, MDEA).	Yes - proceed to technical module.

Definitions:

- MEA - Mono Ethyl Amine
- DEA - Di Ethyl Amine
- DIPA - Di Iso Propyl Amine
- MDEA - Methyl Di Ethyl Amine

Basic Data Required for Analysis

Basic Data	Comments
Susceptibility to cracking (Low, Medium, High)	See the supplements to this Technical Module for guidelines to ranking the susceptibility to corrosion cracking.
Material of construction	Most corrosion cracking mechanisms affect non-post weld heat-treated carbon and low alloy steels, and some stainless steels.
Post Weld Heat Treatment (Y/N)	Post Weld Heat Treatment is effective in reducing or eliminating many types of corrosion cracking in carbon and low alloy steels. In addition, the reduction of residual stress greatly reduces the susceptibility to failure due to cracks, based on current fracture mechanics models.
Crack size found by inspections (Length, in inches)	In the absence of a crack growth model, cracks are assumed to be capable of growing to the size already observed.
Inspection Type & Category	The category of inspection that has been performed on the equipment. See the "Inspection Effectiveness Category" section of this module for guidelines to inspection categories.
Number of Inspections	The number of inspections in each category that have been performed. The discussion under "Technical Module Subfactor Determination" is used for the determination of equivalent inspection numbers.

Possible Damage States for Corrosion Cracking

Damage State Category	Crack Growth Rate
<p><u>Damage State 1</u> The damage in the equipment is no worse than what is expected based on damage rate models or experience.</p>	<p>The equipment is subject to cracks of a size equal to what was previously observed (or assumed to exist if not inspected).</p>
<p><u>Damage State 2</u> The damage in the equipment is “somewhat” worse than anticipated. This level of damage is sometimes seen in similar equipment items.</p>	<p>The equipment is subject to cracks of a size twice what was previously observed (or assumed to exist if not inspected)</p>
<p><u>Damage State 3</u> The damage in the equipment is “considerably” worse than anticipated. This level of damage is rarely seen in similar equipment items, but has been observed on occasion industry wide.</p>	<p>The equipment is subject to cracks of a size four times what was previously observed (or assumed to exist if not inspected).</p>

Inspection Effectiveness Category

Corrosion cracking is difficult to detect visually without magnetic particle or dye penetrant testing to increase the visibility of cracks. Spot inspection methods may not detect the worst areas of cracking in equipment. The following guides are for inspection effectiveness of commonly used inspection techniques:

Inspection Effectiveness Rating Guidelines

Inspection Effectiveness Category	Typical Inspection Practices
“Highly Effective”	Magnetic Particle Testing (or Dye Penetrant for stainless steels) over 50% to 100% of the welds and HAZ.
“Usually Effective”	Magnetic Particle Testing (or Dye Penetrant for stainless steels) over 20% to 50% of the welds HAZ. AE testing with UT follow up of indications.
“Fairly Effective”	Magnetic Particle Testing (or Dye Penetrant for stainless steels) over less than 20% of the welds.
“Poorly Effective”	Magnetic Particle Testing (or Dye Penetrant for stainless steels) over less than 5% of the welds.

RISK BASED MANAGEMENT - FREQUENCY ANALYSIS

Damage Factor Determination

The following table describes the steps required to determine the Corrosion Cracking Technical Module Subfactor:

Technical Module Subfactor Determination

Step	Instructions
Step 1 Technical Module Subfactor Table	Look up the Technical Module Subfactor from the table based on whether or not the vessel is Post Weld Heat Treated, the number and type of inspections performed, and the previous inspection results (or cracking susceptibility if no inspections have been performed).
Step 2 Determine inspection equivalents	The number of inspections to be used when looking up the Technical Module Subfactor is to be the number of the highest level of inspection that has been performed. Credit for other inspections can be taken by equating them to an equivalent higher inspection level. The following relations are to be used: <ul style="list-style-type: none">• One “Highly Effective” inspection equals two “Usually Effective” inspections.• One “Highly Effective” inspection equals four “Fairly Effective” inspections.• One “Usually Effective” inspection equals two “Fairly Effective” inspections.

RISK BASED MANAGEMENT - FREQUENCY ANALYSIS

Corrosion Cracking Technical Module - Subfactors Table											
NO INSPECTIONS											
	Years Without an Inspection	PWHT	NO PWHT		Years Without an Inspection	PWHT	NO PWHT		Years Without an Inspection	PHWT	NO PWHT
Low	5 years	1	1	Low	5 years	1	24	Low	5 years	1	281
Susceptibility	10 years	1	18	Susceptibility	10 years	1	228	Susceptibility	10 years	1	1164
to Cracking	15 years	1	74	to Cracking	15 years	1	609	to Cracking	15 years	1	1963
(1/2" Crack)	20 years	1	183	(1/2" Crack)	20 years	1	1032	(1/2" Crack)	20 years	1	2508

Next three specific corrosion cracking mechanisms to described to determine the estimated cracking susceptibility.

(A) WET H₂S CRACKING

Basic Data Required for Analysis

Basic Data	Comments
% S	Refineries processing sour crude's may be more susceptible to Wet H ₂ S Cracking.
Operating Temperature (°C)	Wet H ₂ S Cracking is unlikely to occur at temperatures above 148.88°C.
Cracking Susceptibility	See the following table:

Wet H₂S Cracking Susceptibility by Refinery Location

Refinery Unit Classifications for Wet H ₂ S Cracking		
Class A (High susceptibility)	Class B (Medium susceptibility)	Class C (Low susceptibility)
FCCU Compression and vapor recovery	Crude vapor recovery	Crude tower overheat
Coker vapor recovery	Catalytic reformers (Vapor Recovery)	All others
Hydrotreaters, downstream from reactors	Sats gas	
Sour amine units		
Sour water strippers		
Unsaturated gas plants		
Catalytic crackers (main fractionator overhead)		

Description of Damage

Wet H₂S cracking occurs in refinery process equipment when hydrogen sulfide is present under conditions where water may also be present. The basic mechanism is in doubt, although it is generally recognized that "hydrogen embrittlement" is important. The cracking is especially severe in steels with a hardness exceeding 22 Rc.

(B) CAUSTIC CRACKING

Basic Data	Comments																		
NaOH Concentration (%)	Caustic Cracking can occur at all concentrations of NaOH. Note that bulk concentrations of NaOH may not represent the concentration at all locations in the equipment.																		
Maximum Metal Temperature (°C)	Caustic cracking does not occur at temperatures below 48.8°C. Note that heat tracing and steam out (if prior to washing out residual caustic) should be considered when determining maximum metal temperature																		
Cracking Susceptibility	<p>Non-PWHT carbon steel:</p> <table border="0"> <thead> <tr> <th></th> <th>NaOH Conc.</th> <th>Max. Metal Temp.</th> </tr> </thead> <tbody> <tr> <td>“High” Susceptibility</td> <td>15-35%</td> <td>> 87.7°C</td> </tr> <tr> <td>“Medium” Susceptibility</td> <td>5-15%</td> <td>> 76.66°C</td> </tr> <tr> <td></td> <td>15-35%</td> <td>54.44-87.7°C</td> </tr> <tr> <td></td> <td>> 35%</td> <td>> 48.8°C</td> </tr> <tr> <td>“Low” Susceptibility</td> <td>< 5%</td> <td>< 76.66°C</td> </tr> </tbody> </table> <ul style="list-style-type: none"> In addition, locations where caustic can concentrate due to boiling are also ranked as “Highly” susceptible. Examples include distillation columns with caustic added for neutralization (especially if the aqueous phase goes overhead from the column), and leaking flanges in boiler feed water service that can cause cracking of the flange bolts due to concentration of caustic. 		NaOH Conc.	Max. Metal Temp.	“High” Susceptibility	15-35%	> 87.7°C	“Medium” Susceptibility	5-15%	> 76.66°C		15-35%	54.44-87.7°C		> 35%	> 48.8°C	“Low” Susceptibility	< 5%	< 76.66°C
	NaOH Conc.	Max. Metal Temp.																	
“High” Susceptibility	15-35%	> 87.7°C																	
“Medium” Susceptibility	5-15%	> 76.66°C																	
	15-35%	54.44-87.7°C																	
	> 35%	> 48.8°C																	
“Low” Susceptibility	< 5%	< 76.66°C																	

Description of Damage

Caustic cracking refers specifically to stress corrosion cracking on non-PWHT carbon steel caused by sodium hydroxide at elevated temperatures. The cracking is usually purely intergranular, producing a noticeably “crystalline” appearance to the fracture surface.

The above guidelines for cracking susceptibility are based on bulk concentrations of NaOH. Caustic cracking sometimes occurs when low concentrations of NaOH are concentrated by boiling of the water. Notable case histories include caustic cracking of distillation columns when caustic is added to the column for pH control, and cracking of boiler feed water valve bolts when gasket leaks expose the bolts to flashing boiler feed water. There are also many case histories of caustic cracking of “ambient temperature” caustic equipment that was heat traced or steamed out.

(C) AMINE CRACKING

Basic Data Required for Analysis

Basic Data	Comments																				
Type of Amine: MEA, DEA, MDEA, DIPA or Sulfinol	Amine cracking can occur in the lean solutions of various alkanolamines associated with amine treating units.																				
Max. Metal Temperature (°C)	Amine cracking is more severe at elevated temperatures. Note that heat tracing and steam out (if prior to washing out residual amine) should be considered when determining maximum metal temperature.																				
Cracking Susceptibility	<p>Non-PWHT carbon steel:</p> <table border="1"> <thead> <tr> <th></th> <th>Amine</th> <th>Max. Metal Temp.</th> </tr> </thead> <tbody> <tr> <td>"High" Susceptibility</td> <td>MEA, DIPA</td> <td>>82°C</td> </tr> <tr> <td rowspan="2">"Medium" Susceptibility</td> <td>MEA, DIPA</td> <td>37-82°C</td> </tr> <tr> <td>DEA</td> <td>> 82°C</td> </tr> <tr> <td rowspan="4">"Low" Susceptibility</td> <td>MEA, DIPA</td> <td>< 37°C</td> </tr> <tr> <td>DEA</td> <td>60-82°C</td> </tr> <tr> <td>MDEA</td> <td>> 82°C</td> </tr> <tr> <td>Sulfinol</td> <td>> 87.7°C</td> </tr> </tbody> </table>		Amine	Max. Metal Temp.	"High" Susceptibility	MEA, DIPA	>82°C	"Medium" Susceptibility	MEA, DIPA	37-82°C	DEA	> 82°C	"Low" Susceptibility	MEA, DIPA	< 37°C	DEA	60-82°C	MDEA	> 82°C	Sulfinol	> 87.7°C
	Amine	Max. Metal Temp.																			
"High" Susceptibility	MEA, DIPA	>82°C																			
"Medium" Susceptibility	MEA, DIPA	37-82°C																			
	DEA	> 82°C																			
"Low" Susceptibility	MEA, DIPA	< 37°C																			
	DEA	60-82°C																			
	MDEA	> 82°C																			
	Sulfinol	> 87.7°C																			

Description of Damage

Amine cracking refers to intergranular stress corrosion cracking of non-PWHT carbon steel observed in amine treating units which use aqueous alkanolamine solutions for removal of acid gases such as H₂S and CO₂ from various gas or liquid streams. This type of cracking occurs in the lean alkanolamine solution which is alkaline and contains very low levels of acid gas. Amine cracking does not occur in fresh amine solutions, i.e., those that have not been exposed to acid gases. Studies have concluded that the cracking occurs in a narrow range of electrochemical potential, which is very dependent upon the solution composition.

Carbonate is a critical solution contaminant and other contaminants, such as chlorides, cyanides, etc., have been shown to affect cracking susceptibility.

Cracking susceptibility is generally higher at elevated temperatures. Cracking has occurred in lower temperature equipment that was heat traced or steamed out prior to water

washing to remove residual amine solution. Results of an NACE survey indicate that amine cracking is most prevalent in MEA and DIPA units, and to a somewhat lesser extent in DEA units. Cracking is much less prevalent in MDEA and Sulfinol units. Amine concentration is a factor in cracking susceptibility in MEA solutions, where cracking susceptibility has been shown to be higher in the 15 to 35% concentration range. There is not sufficient understanding of this relationship in other amine solutions, but it is noteworthy that cracking susceptibility is lower in MDEA and Sulfinol units which typically utilize higher concentration amine solutions. Postweld head treatment (PWHT) has been proven to be effective in preventing this type of cracking.

NOTE: Other forms of cracking have been reported in amine units. Most of these occurred in equipment and piping exposed to rich alkanolamine solutions and have typically been forms of hydrogen damage such as sulfide stress cracking (SSC), hydrogen-induced cracking (HIC), and stress-oriented hydrogen-induced cracking (SOHIC).

APPENDIX B

**QUALITATIVE
RISK RANKING**

PART A DETERMINATION OF LIKELIHOOD CATEGORY		POINT	
EQUIPMENT FACTOR (EF)			
<p>The size of the study will affect the probability of failure of a component in the study. The qualitative risk analysis is intended for use at three different levels:</p> <p>1 Unit - A will operating unit at a site is evaluated. This would typically be done to compare and prioritize operating units based on risk of operation.</p> <p>2 Section of an operating unit - an operating unit can be broken into logical (functional) sections to identify the high risk section of the unit.</p> <p>3 A system or unit operation - this is the greatest level of detail that the qualitative method is intended to address.</p>			
<p>To define the Equipment Factor, use the following table:</p> <p>If a full operating unit is being evaluated, (typically greater than 150 major equipment items) EF = 15</p> <p>If a major section of an operating unit is being evaluated, (typically 20 - 150 major equipment items) EF = 5</p> <p>If a system or unit operation is being evaluated (typically 5 - 20 major equipment items) EF = 0</p> <p>Select the appropriate value for EF from above.</p> <p>This is the overall Equipment factor</p>		1	0
DAMAGE FACTOR (DF)			
<p>The damage factor is a measure of the risk associated with known damage mechanisms that are active or potentially active in the operating being evaluated.</p> <p>The mechanisms are prioritized based on their potential to create a serious event.</p>			
<p>If there are known, active damage mechanisms that can cause corrosion cracking in carbon or low alloy steels, DF1 = 5</p>		2	5
<p>If there is a potential for catastrophic brittle failure, including carbon steel materials due to low temperature operation or upset conditions, temper embrittlement, or materials not adequately qualified by impact testing. DF2 = 4</p>		3	0
<p>If there are places in the unit where mechanically thermally-induced fatigue failure has occurred and the fatiguemechanism might still be active, DF3 = 4</p>		4	0

RISK BASED MANAGEMENT - QUALITATIVE RISK RANKING

If there is known high temperature Hydrogen attack occurring, DF4 = 3	5	0
If there is known corrosion cracking of austenitic stainless steel occurring as a result of the process, DF5 = 3	6	0
If localized corrosion is occurring, DF6 = 3	7	0
If general corrosion is occurring, DF7 = 2	8	2
If creep damage is known to be occurring in high temperature processes, including furnaces and heaters, DF8 = 1	9	0
If materials degradation is known to be occurring, with such mechanisms as sigma phase formation, carburization, spheroidization, etc., DF9 = 1	10	0
If other active damage mechanisms have been identified, DF10 = 1	11	0
If the potential damage mechanisms in the operating unit have not been evaluated and are not being periodically reviewed by a qualified materials engineer, DF11 = 10	12	0
The overall Damage Factor will be the sum of lines 2 through 12, up to a maximum of 20	13	7
INSPECTION FACTOR (IF)		
The Inspection Factor is a measure of the effectiveness of the inspection program to identify the active or anticipated damage mechanisms in the unit		
Step 1 Vessel Inspection - Gage the effectiveness of the vessel inspection program to find the identified failure mechanisms above.		
If the inspection program is extensive and a variety of inspection methods and monitoring are being used, IF1= -5		
If there is a formal inspection program in place and some inspections are being done, but primarily visual and UT thickness readings, IF1 = -2		
If there is no formal inspection program in place, IF1 = 0		
Select appropriate IF1 from above.....	14	-5
Step 2 Piping Inspection - Gage the effectiveness of the piping inspection program to find the identified failure mechanisms above.		
If the inspection program is extensive, and a variety of inspection methods are being used, IF2 = -5		
If there is a formal inspection program in place and some inspections are being done, but primarily visual and UT thickness readings, IF2 = -2		
If there is no formal inspection program in place, IF2 = 0		

RISK BASED MANAGEMENT - QUALITATIVE RISK RANKING

Step 3 In a review of the effectiveness of the plant maintenance program, including fabrication, PM programs, and QA/QC, they would be judged:		
Significantly better than industry standards, CCF3 = 0		
About industry standard, CCF3 = 2		
Significantly below industry standards, CCF3 = 5		
Select the appropriate value for CCF3	20	0
The overall Condition Factor is the sum of 18 through 20	21	2
PROCESS FACTOR (PF)		
Process Factor is a measure of the potential for abnormal operations or upset conditions to result in relating events that could lead to a loss of containment.		
Step 1 The number of planned or unplanned process interruptions in an average year. (This is intended for normal continuous process operations). PFI is taken from the following table.		
Number of Interruptions	PFI	
0 to 1	0	
2 to 4	1	
5 to 8	3	
9 to 12	4	
more than 12	5	
Determine appropriate PFI from above		22 0
Step 2 Assess the potential for exceeding key process variables in the operation being evaluated ; (PF2)		
If the process is extremely stable, and no combination of upset conditions is known to exist that could cause a runaway reaction or other unsafe conditions, PF2 is 0		
Only very unusually circumstances could cause upset conditions to escalate into an unsafe situation, PF2 is 1		
If upset conditions are known to exist that can result in accelerated equipment damage or other unsafe conditions, PF2 is 3		
If the possibility of loss of control is inherent in the process, PF2 is 5		
Select the appropriate value for PF2 from the table above		23 1

RISK BASED MANAGEMENT - QUALITATIVE RISK RANKING

Step 1 Determine the Likelihood Factor. The Likelihood Factor is the sum of the previously determined factors.														
Add lines 1, 13, 17, 21, 25 and 28. This is the Likelihood Factor	29	6												
Step 2 The Likelihood Category is determined from the Likelihood Factor (line 29 above) using the following table:														
<table border="1" style="width:100%; border-collapse: collapse;"> <thead> <tr> <th align="left">Likelihood Factor</th> <th align="left">Likelihood Category</th> </tr> </thead> <tbody> <tr><td>0-15</td><td>1</td></tr> <tr><td>16-25</td><td>2</td></tr> <tr><td>26-35</td><td>3</td></tr> <tr><td>36-50</td><td>4</td></tr> <tr><td>51-75</td><td>5</td></tr> </tbody> </table>	Likelihood Factor	Likelihood Category	0-15	1	16-25	2	26-35	3	36-50	4	51-75	5		
Likelihood Factor	Likelihood Category													
0-15	1													
16-25	2													
26-35	3													
36-50	4													
51-75	5													
Enter the Likelihood Category	30	1												
<input type="checkbox"/>														
PART B : DETERMINATION OF DAMAGE CONSEQUENCY CATEGORY														
This section is to be used for flammable materials, if only toxic chemicals are present, go directly to Part C.														
CHEMICAL FACTOR (CF)														
The Chemical Factor is a measure of a chemical's inherent tendency to ignite. The answers to this section should be based on the performed if the unit has a number of different process streams.														
Step 1 Determine a "Flash Factor"														
NFPA Class III B (Flash point > 93°C) CF1 = 1														
NFPA Class II & III A (Flash point in 37 - 93°C range) CF1 = 2														
NFPA Class I B & C (Flash point < 100 °C, B. Pt > 100°C) CF1 = 3														
NFPA Class I A, or flammable gases with density < 1 CF1 = 4														
Flammable gases with vapor density > 1 CF1 = 5														
Enter the appropriate value from the table above, this is CF1	31	4												
Step 2 Determine a "Reactivity Factor"														
Substance is completely stable CF2 = 1														
Mild reaction if heated CF2 = 2														
Moderately reactive CF2 = 3														
Explosion possible if vapor confined CF2 = 4														
Explosion possible even if not confined CF2 = 5														
Select the appropriate value from the table above, this is CF2	32	4												

RISK BASED MANAGEMENT - QUALITATIVE RISK RANKING

Step 3 Determine "Chemical Factor"							
Reactivity Factor (line 32)							
	1	2	3	4	5		
	1	1	5	10	15	20	
Flash Factor (Line 31)	2	2	5	10	15	20	
	3	4	5	10	15	20	
	4	7	8	10	15	20	
	5	10	11	12	15	20	
Select the Chemical Factor from the chart above							
.....						33	15
QUANTITY FACTOR (QF)							
The Quantity Factor represents the largest amount of material which could be released from a unit in a single scenario.							
The Quantity Factor is taken directly from the chart below. For amount of material released, used the largest amount of flammable inventory that can be lost in a single leak event.							
Material Released	Quantify Factor						
< 4.5 ton	0.2						
4.5-45 ton	1.0						
45 - 453 ton	5						
453 - 4535 ton	20						
> 4535 ton	100						
Enter the appropriate value from the table above, this is QF							
.....						34	5
STATE FACTOR							
The State Factor is dependent on the temperature of the material relative to its boiling point (that is, how much will it flash upon release).							
Select a State Factor based on the process temperature (Tp) and the boiling temperature (Tb) for operating pressures, for each chemical.							
Tp / Tb	State Factor						
< 0.8	0.5						
0.8-0.9	0.75						
0.9-1.0	1.0						
1.0-1.1	1.5						
1.1-1.2	2.0						
> 1.2	2.5						

RISK BASED MANAGEMENT - QUALITATIVE RISK RANKING

If the isolation capability of the equipment in this area can be controlled remotely AND the isolation and associated instrumentation is protected from fires and explosions, then enter 0.80,		
OR if the isolation and associated instrumentation is protected from fires only, enter 0.85,		
OR if there is no protection for the isolation capability from fires or explosions, enter 0.9		
Otherwise, enter 1.0		
.....	43	0.8
If there are blast walls around the most critical (typically highest pressure) equipment, enter 0.9, otherwise enter 1.0	44	1
If there is a dump, drain, or blowdown system that will deinventory 75% or more of the material in 5 minutes or less, with 90% reliability, enter 0.8, otherwise enter 1.0.	45	0.8
.....		
If there is fireproofing in place on both structures and cables, enter 0.9, if there is fireproofing on either structures or cables, enter 0.95, otherwise, enter 1.0	46	1
.....		
If there is a fire water supply that will last at least 4 hours, enter 0.95, otherwise enter 1.0	47	0.95
.....		
If there is a fixed foam system in place, enter 0.95, otherwise enter 1.0	48	1
.....		
If there are firewater monitors that can reach all areas of the affected unit, enter 0.95, otherwise, enter 1.0	49	0.95
Multiply lines 40 through 49. This is the Credit Factor	50	0.3962
.....		

DAMAGE POTENTIAL FACTOR (DPF)

Step 1 Estimate the value of equipment within a 30 meter radius of largest inventory in unit:		
Equipment Value DPF1		
< R400K 1		
R400K - R4MM 2		
R4MM - R40MM 4		
R40MM - R400M 8		
> R400MM 16		
Enter the appropriate value for DPF1	51	4
.....		
Step 2 Estimate the value of equipment within a 150 meter radius of largest inventory in unit:		
Equipment Value DPF2		
< R400K 1		

RISK BASED MANAGEMENT - QUALITATIVE RISK RANKING

R400K - R4MM	1.2		
R4MM - R40MM	1.5		
R40MM - R400MM	2		
> R400MM	4		
Enter the appropriate value for DP2			
.....		52	4
Step 3 Add lines 51 and 52. This is the overall Damage Potential Factor			
.....		53	8
DAMAGE CONSEQUENCE CATEGORY			
Step 1 Determine the Damage Consequence Factor.			
Multiply lines 33, 34, 35, 39, 50 and 53 together, this is the Damage Consequence Factor			
.....		54	1158.8
Step 2 The Damage Consequence Factor (line 54) is then converted into a Damage Consequence Category based on the table below:			
Consequence Factor	Consequence Category		
0 - 3	A		
3 - 50	B		
50 - 1000	C		
1K - 25K	D		
> 25K	E		
Enter the Damage Consequence Category			
.....		55	D
PART C HEALTH CONSEQUENCE CATEGORY			
If the process fluid of concern has only flammable consequences, skip Part C.			
TOXIC QUANTITY FACTOR (TQF)			
The Toxic Quantity Factor is measure of both the quantity of the chemical and its toxicity.			
Step 1 The Toxic Quantity Factor is taken directly from the chart below. For amount of chemical released, used the largest amount of toxic inventory that can be lost in a single leak event.			
Material Released	Quantity Factor		
< 0.4 ton	50		
0.4 - 4.5 ton	150		
4.5 - 45 ton	600		
> 453 ton	2500		
Enter the Factor from the chart above, this is TQF1			
.....		56	600
Step 2 Estimate the Toxicity Factor (TWF2) from the chart below			

RISK BASED MANAGEMENT - QUALITATIVE RISK RANKING

NFPA NH	Toxicity Factor (TQF2)		
0	0		
1	0.01		
2	0.1		
3	1.0		
4	10.0		
Enter the Toxicity Factor			
.....		57	0.01
Step 3 Multiply lines 56 and 57, this is the Toxic Quantity Factor		58	6

DISPERSIBILITY FACTOR (DIF)

The Dispersibility Factor is a measure of the ability of the material to disperse, given typical process conditions.

Step 1 Determine the Dispersibility Factor from the table below.

Boiling Point (°C)	Dispersibility Factor
< -1	1
-1 - 26	0.5
26 - 60	0.3
60 - 93	0.1
93 - 148	0.05
> 148	0.03

Enter the Dispersibility Factor	59	0.05
---------------------------------	----	------

CREDIT FACTOR (CRF)

The Credit Factor accounts for safety features that reduce the consequences of a toxic release by detection, isolation and mitigation.

Step 1 If there are detectors in place for the process fluid of interest that would detect 50% or more of incipient leaks, enter 0.8,

otherwise enter 1.0

Step 2 If major vessels containing this material can be isolated automatically, and isolation is initiated from a high reading from a toxic material detector, enter 0.80,

OR if the isolation is remote with a manual initiation, enter 0.90,

Or if the isolation is manually operated only, enter 0.95

60 1

RISK BASED MANAGEMENT - QUALITATIVE RISK RANKING

Choose the highest letter from line 55 or 66. This is the Overall Consequence Category	67	D
THE LIKELYHOOD IS:	1	
THE CONSEQUENCE IS:	D	
125.xls		
PROCESS PEOPLE; 151, 162, 170, 196, 233, 242, 274, 289, 301, 311, 402, 412,		
hjvr\hein\alg.125_1.DOC		

APPENDIX C

**FITNESS-FOR-
SERVICE**

With a fitness-for-service analysis a variety of different techniques can be used to evaluate the effect of specific defects that can have a potential catastrophic effect in the operation of the equipment.

The first step in determining what level of analysis is necessary is the criticality of the equipment in the specific process as described in Appendix B and Chapters 3,4 and 5.

With the real risk determined the level of analysis that is necessary is set.

The next step is the actual fitness-for-service, which will involve the calculation of the following parameters:

- Minimum wall thickness allowable to hold the pressure
- The stress concentration factors that are relating to the specific minimum wall thickness'es in specific high stress regions as per example the regions around nozzles and manholes can be pointed out.
- Leak before break scenarios is also determined to quantify the effect of cracks in the parent material.
- The effect of cracks in the shell and nozzle in the regions of the high stress concentrations is calculated by means of the techniques as described in Chapter 5 of the fitness-for-service analysis.
- By determining the critical crack lengths for specific scenarios it will help to focus the attention and resources to the correct areas. This will also facilitate a proactive approach in determining which cracks are critical and which can be left and can be monitored. The Fitness-for-Service analysis will also determine the specific inspection interval of which specific defects must be inspected to see if any deterioration has occurred since the last inspection. This will then overrule the RBI guidelines in favor of the more detail knowledge of the defect under considerations.

In the fitness-for-service examination the specific different geometries are also examined to determine the effect of the different crack lengths and depths at those geometry's on the crack propagation time.

Due to the nature of the sensitivity of this information a real example is not given and an example that is dreamed up is of no value.

From the above it can be seen that this technique is an extremely powerful technique to determine the total effect of any mechanical defect. This technique in calibration will ensure a reliable and exact decision base from which any decisions can be motivated. These decisions will also stand up in a court of law and will ensure a standardized decision making process which will enhance the end results and will ultimately empower the management of a firm to save money and resources in the short and long term by focussing on the right and real problems at hand.

APPENDIX D

**DAMAGE
MECHANISMS AND
INSPECTION
METHODS**

Below a list is given of all the damage mechanisms that are considered in the expert meeting to determine the criticality of a specific piece of equipment.

RISK BASED MANAGEMENT – DAMAGE MECHANISMS AND INSPECTION METHODS

METALLURGICAL INPUTS CHECKLIST

PLEASE REFER TO LATEST HAZOP STUDIES & DESIGN DRAWINGS / CALCULATIONS

ASSEMBLY NUMBER :			
EQUIPMENT NUMBER :			
DAMAGE TYPE	NOTES	DESCRIPTION	NOTES
Thinning (includes general localized and pitting)		Removal of material from one or more surfaces may be general or localized	
Surface connected cracking		Cracking that is connected to one or more metal surfaces	
Subsurface cracking		Cracking beneath the metal surface	
Microfissuring/microvoid formation		Microscopic fissures or voids beneath the metal surface	
Metallurgical changes		Changes to the metal microstructure	
Dimensional changes		Changes in the physical dimensions or orientation of an object	
Blistering		Hydrogen-induced blisters forming in plate inductions	
Material properties changes		Changes in the material properties of the metal	
CORROSION	NOTES	STRESS CORROSION CRACKING DUE TO:	NOTES
HCl Corrosion		Amine	Erosion - solids
Organic chlorides corrosion		Ammonia	Erosion – droplets
Inorganic chlorides corrosion		Caustic	Cavitation
Organic sulfur corrosion		Carbonate	Sliding Wear
H ₂ S Sulfidation		Chloride	Fatigue
CO ₂ corrosion		Polythionic acid	Thermal fatigue
Naphthenic acid corrosion		Liquid metal embrittlement	Corrosion fatigue
Sour water corrosion		Hydrofluoric acid	Creep and stress rupture
Sulfuric acid corrosion		Corrosion fatigue	Creep cracking
Hydrofluoric acid corrosion			Thermal ratcheting
Phenol/NMP corrosion			Overload (plastic collapse)
Phosphoric acid corrosion		METALLURGICAL AND ENVIRONMENTAL EFFECTS	NOTES
Caustic corrosion		Incipient melting	
Ammonia corrosion		Spheroidization and graphitization	
Chlorine/sodium hypochlorite corrosion		Hardening	HYDROGEN EFFECTS NOTES
Corrosion under insulation/fireproofing		Sigma and Chi phase embrittlement	Blistering
Cooling water corrosion		385 F Embrittlement	Hydrogen induced cracking, including step-wise cracking
Atmospheric corrosion		Temper embrittlement	Stress oriented hydrogen induced cracking (SOHIC)
Soil corrosion		Reheat cracking	Sulfide stress cracking
High temperature oxidation		Carbide precipitate embrittlement	Cyanide stress cracking (HCN)
Hot corrosion		Carburization	Hydriding
Fue gas corrosion		Decarburization	Hydrogen attack
Dealloying		Metal dusting	Hydrogen embrittlement
Galvanic corrosion		Welding	
Crevice/underdeposit corrosion		Strain aging	
Biological corrosion		Softening due to overaging	
Injection point corrosion		Brittleness due to high temperature aging	
Boiler water/condensate corrosion			
Fue gas dewpoint corrosion			
Chelant corrosion			

COMPILED BY : _____ SIGNATURE: _____ DATE : _____

With these specific damage mechanisms the inspection type and intensity can then be determined.

Table D-1 gives an overview of the inspection techniques that can be used and where they can be used in the most effective way.

Table D-1 : Effectiveness of Inspection Techniques for Various Damage Types

Inspection Technique	Thinning	Surface Connected Cracking	Subsurface Cracking	Microfissuring/ Microvoid Formation	Metallurgical Changes	Dimensional Changes	Blistering
Visual Examination	1-3	2-3		X	X	1-3	1-3
Ultrasonic Straight Beam	1-3	3-X	3-X	2-3	X	X	1-2
Ultrasonic Shear Wave	X	1-2	1-2	2-3	X	X	X
Fluorescent Magnetic Particle	X	1-2	3-X	X	X	X	X
Dye Penetrant	X	1-3	X	X	X	X	X
Acoustic Emission	X	1-3	1-3	3-X	X	X	3-X
Eddy Current	1-2	1-2	1-2	3-X	3-X	X	X
Flux Leakage	1-2	X	X	X	X	X	X
Radiography	1-3	3-X	3-X	X	X	X	X
Dimensional Measurements	1-3	X	X	X	X	1-2	X
Metallography	X	2-3	2-3	2-3	1-2	X	X

1 = Highly effective

2 = Moderately effective

3 = Possibly effective

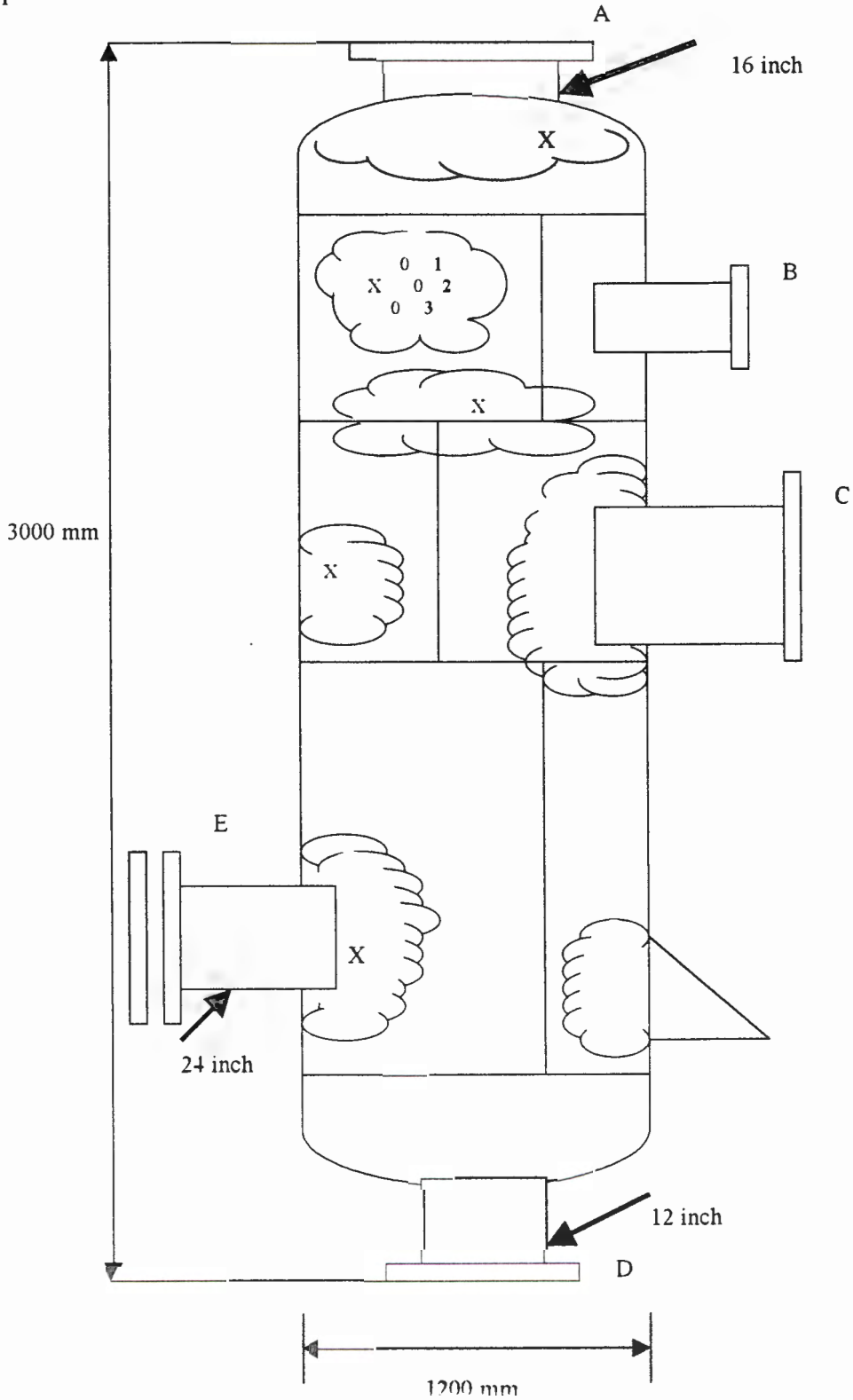
X = Not normally used

APPENDIX E

**EXAMPLE OF
DAMAGE
MECHANISMS
LOCATION AND
INSPECTION
TECHNIQUE**

RISK BASED MANAGEMENT - EXAMPLE OF DAMAGE MECHANISMS AND LOCATION AND INSPECTION TECHNIQUES

Next an example is given on how a specific inspection scope will be compiled. It must be stressed that this is an example. Due to the nature of the business exact data cannot be supplied.



From the drawing a typical scope of work can then be compiled by using the process as discussed in the script. A typical scope will commit of the following information:

- 1 Remove / aging and sandblast external (including nozzles, supports and man ways).
- 2 Open manhole.
- 3 Conduct preliminary visual inspection.
- 4 Clean internal as agreed in the areas as indicated on the figure. (Red areas)



5. ***Inspection scope activities***
 - a. External
 - Visual in areas where insulation was removed as per scope (Red areas)
 - Do wall thickness measurement as indicated *
 - MT 50% of nozzles and support as indicated (Red areas)
 - PT nozzles carbon steel to stainless steel joints (1 2 3)
And stainless steel flanges.
 - b. Internal
 - Visual
 - MT 50% of T-joints
 - PT nozzle boxes A,C,E, 1, 2, and 3.
6. Close manhole, flash blast, repaint and replace lagging.

This scope can vary depending on the criticality of the equipment, the history, design conditions and the specific service in which the vessel operates.

As noted a preliminary visual inspection is done without any cleaning of the equipment.

This is to give the inspector a feeling of what happened in the vessel. It will also show if something went wrong which much to be anticipated in the initial determination of the scope. This will also help to plan the work in advance.

RISK BASED MANAGEMENT - ON-BOARDING AGENDA

Next the onboarding agenda is shown which is used by the reliability group to onboard persons who will be using the process for the first time.

MAINTENANCE STRATEGY HAND SYSTEM TIME LINE

TOPIC	PRESENTER	DATE	DURATION	TIME	VENUE
ONBOARDING - Session	Team	8/10-9 /10	2 Days	08:00 - 16:00	Indaba
HAND SYSTEM - Ground Rules - Deliverables - PDR	Facilitators	10 /10	1 Day	08:00 - 16:00	O/Venue
OBTAIN INPUTS - Session - Risk History - Gather info - Process Overview	Riaan Kruger	13/10-15/10 13 /10	3 Days 1 Day	08:00	Khula C/R Own Venue
SBS - Session - Develop SBS - Pieter Ackermann - SBS MIMS Correction - André Mathee - SBS MPDS Conversion - Process info FMEA - Time Line	Hein Pienaar	16 /10-22/10 16 /10	4 Days	08:00	Khula C/R Own Venue
RCM - RCM Session - RISK Session - Complete FMEA - Start small system (choose 5 critical items per discipline) - Expert Meeting + Review - Review Session - H2 Address - Benefits	Johan Strauss Jaco / Riaan	23/10- 3/11 23 /10 24 /10	8 Days	08:00 08:00	Khula C/R Khula C/R Own Venue
MPDS - Practice on hand system	André Mathee	4/11-11/11 5/11-10/11	5 Days	08:00	Khula C/R

RISK BASED MANAGEMENT - *ON-BOARDING AGENDA*

This agenda is modified on a continuous basis to ensure that the information that is given is shared in the best possible way to suite the business units particular operating environment.