THE IMPLEMENTATION OF A PROBABILISTIC RISK BASED INSPECTION APPROACH

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THE IMPLEMENTATION OF A PROBABILISTIC RISK BASED INSPECTION APPROACH

By

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Abstract

Equipment and units in the hydrocarbon and chemical process industry are subject to several deterioration mechanisms that could lead to a loss of containment. This work presents an enhancement of a risk based inspection methodology earlier presented by Kallen (2002). This risk based inspection methodology uses a stochastic gamma function to model the materials deterioration rate. Using the prior knowledge of the deterioration rate and a Bayesian updating method, a posterior material deterioration model is found for two cases: perfect and imperfect inspections. Then, this material deterioration model is used to estimate the optimal inspection, replacement and failure times.

Estimating inspection times depends on the material deterioration rate, age of the equipment, original material thickness, and the number of previous inspections that were carried on. The optimal inspection time aims to reduce the risk of failure due to deterioration mechanisms by maintaining the value of the equipment's damage factor as low as possible.

Acknowledgements

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In addition, the author would like to acknowledge the faculty members of Memorial University of Newfoundland, especially the faculty of Engineering and Applied Science.

Last but not least, a special word of appreciation goes to my husband, my beloved parents, and all my family members for the sacrifices and support they made during my study.

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CHAPTER 1
INTRODUCTION

The accepted inspection plans are those which can maintain a safe level of risk for the inspected equipment, and this is what is called risk based inspection (RBI). In risk based inspection (RBI), risk due to equipment failure is used as a criterion to prioritize the inspection process. The risk caused by failure is a function of both the probability of failure and its consequences. Items with high risk of failure will take a high priority on the list of items to be inspected and maintained. The methodology of planning inspection and maintenance activities based on risk minimizes the probability of system failure and its consequences, improves the existing inspection and maintenance policies, and reduces the cost of inspecting and maintaining by eliminating unnecessary inspection and maintenance activities.

Since the late 1980's several risk based inspection approaches and codes were developed (Ablitt and Speck, 2005). The literature review in chapter two outlines most of theses approaches and codes.

The model used in this work is a quantitative risk based inspection approach. This model is a combination of a quantitative risk based inspection approach earlier proposed by Kallen (2002) and justified and used by Khan et al (2005) and Khan et al (2006), and an approach developed by the American Petroleum Institute (API) and presented in its base resource document API 581. Appling this model maintains a safe level of risk for the inspected equipment by keeping the equipments damage factor at its lowest possible value.

1.1 Objective of Work

This work aims at improving and enhancing an earlier developed risk based inspection methodology by Kallen (2002) by combining it with another method developed by the American Petroleum Institute (API). The enhanced methodology can be used to design inspection plans which aim at reducing the risk of equipment failure caused by material deterioration.

1.2 Methodology

The risk based inspection methodology presented in this work uses a probabilistic model estimate the cumulative damage to the material of the component and update the estimated material deterioration model with available inspection data using Bayesian updating.

A stochastic gamma function is used to model material deterioration based on the work of Kallen (2002); Kallen and Noortwijk (2004); Kallen and Noortwijk (2005); Khan, Haddara, and Battacharya (2005); and Khan et al. (2006). The stochastic gamma distribution is a continuous time process. One of its advantages is that it gives a non-negative distribution that describes the deterioration process. Based on the established deterioration rate the optimal inspection, replacement, and failure times are estimated. Figure 1.1 depicts the overall framework of the used risk based inspection methodology in this work.

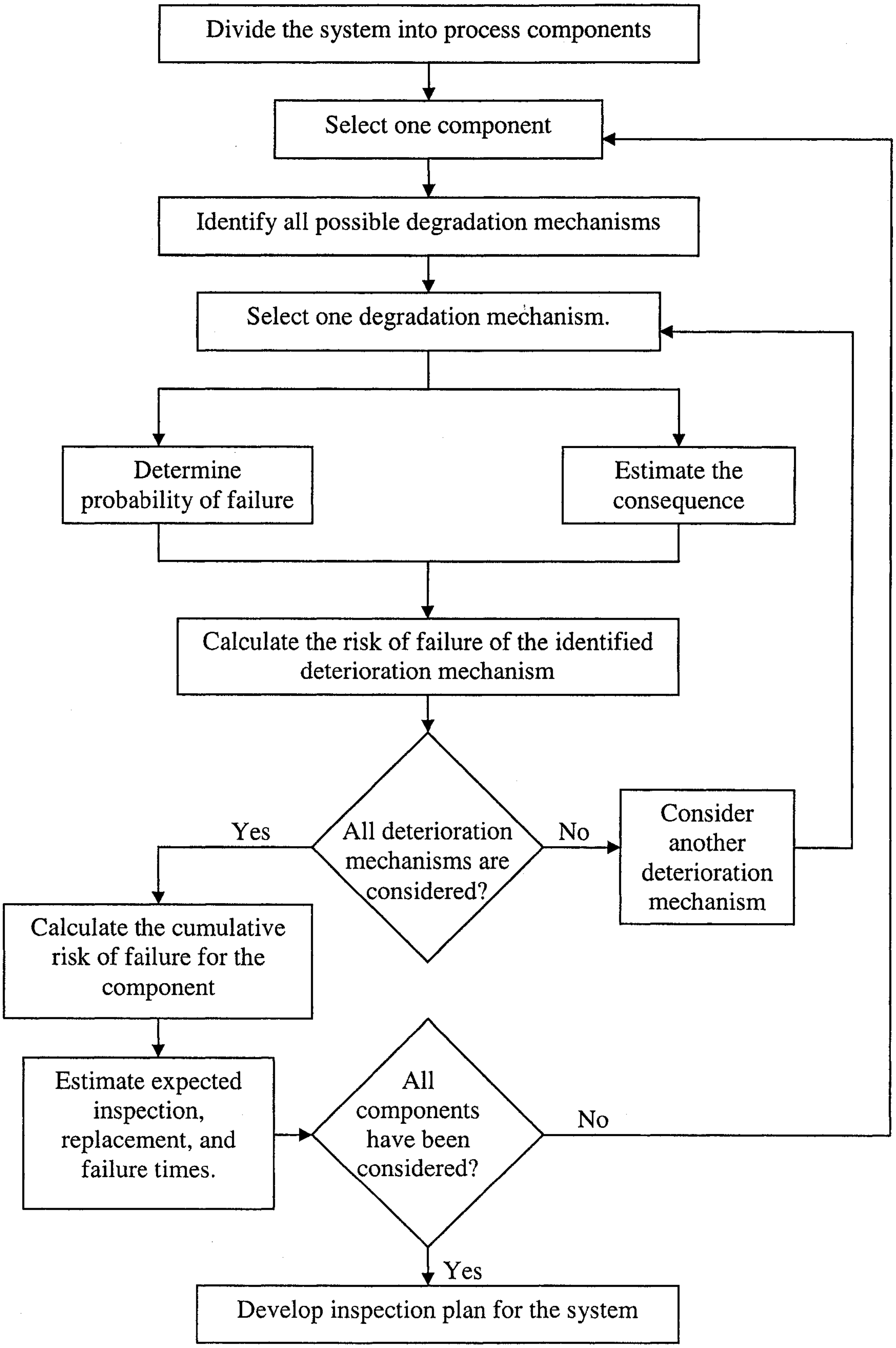


Figure 1.1: The overall framework of the RBI methodology

1.3 Organization of the Thesis

The organization of this thesis is described as follows:

The first chapter contains an introduction, states the objective of the work, and outlines the methodology used. The second chapter includes a literature review of the development of the various risk based methodologies, techniques, and software. The third chapter aims at giving background knowledge about the risk based inspection in general. It talks about the American Petroleum Institute (API) risk based inspection approach which can be applied at three different levels: qualitative, semi-quantitative, and quantitative risk based inspection. The fourth chapter illustrates the model used in this work to estimate the inspection, replacement, and failure times for process industry equipments. The fifth chapter contains two case studies which are used to illustrate the application of the risk based inspection model. The two cases studies are: a molecular sieve vessel, and a distillate hydrotreater reactor. Conclusions and recommendations are provided in the last chapter.

CHAPTER 2

LITERATURE REVIEW

Detecting potential system failures through an inspection is an important activity in industry. Inspection and maintenance programs aim to reduce the probability of the unexpected failure. The failure of equipment can result in accidents which would have major consequences. These may involve toxic and flammable material, operation interruptions, or environmental catastrophes. Several codes and standards were developed to help the engineers with the prioritization of component inspections since the late 1980's (Ablitt and Speck, 2005). This chapter reviews the available risk based approaches for inspection and maintenance planning.

Rasmussan, et al (1975) developed the basic seven tasks for the assessment of reactor safety. Event trees were used to analyze the damage likely to occur due to pipe breakage. Failure probability was investigated for 100 reactors per year. Failures investigated include the property damage, cancer fatalities, and early fatalities. Although risk concept was not employed for calculating failure probability of equipment in this work, it initiated the base for risk analysis to start playing a major role in equipment maintenance along with safety.

Moghissi (1984) described risk analysis as a complex and logical process that must be refined by the devotion of time, effort and resources. Political and legal constraints were termed as uncertainty of risk value. According to Moghissi (1984), the importance of the cost impact, and cost/benefit analysis are the basis for developing optimized programs for component replacement and inspection.

Rettedal (1990) discussed the integration of structural reliability analysis and quantitative risk assessment. The integration is achieved by adopting two Bayesian approaches: classical Bayesian approach that estimates the true objective risk, and fully Bayesian approach where the risk is a way of expressing uncertainties of the occurrence of an accidental event.

Vo et al (1990) developed a probabilistic risk assessment study for eight representative nuclear power plants. Failure probabilities were calculated based on historical data. The objectives of the study are to show the practicability of using risk based methods to develop plant specific inspection plans, to assess current in service inspection requirements for pressurized systems and to develop recommendations for improvements.

In 1991, the American Society of Mechanical Engineers (ASME) developed a risk based inspection guideline. ASME risk based inspection approach consisted of four steps: definition of the system, a qualitative risk assessment, a quantitative risk assessment, and development of inspection program (Wintel, Kenzie, Amphlett and Smalley 2001).

In May 1993 the American Petroleum Institute (API) initiated a risk based inspection (RBI) project. The aim of the American Petroleum Institute (API) was to build an RBI methodology that uses risk as a base for prioritizing and managing inspection programs. The developed RBI methodology was published in 2000 as API 581. Two years later a more generic recommended practice was published as API 580.

The RBI analysis can be carried out on three deferent levels; qualitative, semi-quantitative, and quantitative risk based inspection. The qualitative approach uses engineering experience and judgment as the bases for the risk analysis. Therefore, the accuracy of the results in the qualitative RBI approach depends totally on the analyst's experience and background. Risk ratings in the qualitative approach are determined by categorizing the two elements of risk: likelihood and consequence.

In the API qualitative RBI approach, risk ranking is achieved through a 5x5 matrix of likelihood and consequence. The likelihood five categories are ranked from 1 to 5 (1 is the lowest, 5 is the highest). The consequence categories are ranked using the letters A to E (A is the lowest, E is the highest), (API 581, 2000). Similarly to the qualitative API approach the American Society of Mechanical Engineers (ASME) codes rank the risk using a 5x5 but with three modifications:

1. The likelihood is ranked VL (very low), L (low), M (medium), H (high), and VH (very high) instead of numbers.
2. The consequence is ranked VL (very low), L (low), M (medium), H (high), and VH (very high).
3. The "Low Risk" region is extended to include "Very Low" consequence events, (Antaki, Monahon, and Cansler, 2005).

The semi-quantitative risk assessment approaches have aspects derived from both quantitative and qualitative approaches. It combines the speed of the qualitative approach and the accuracy of the quantitative approach. The data required for the semi-quantitative approaches are mostly like the ones required for quantitative approaches with less details. The results are usually given in consequence and probability categories that may have numerical values to permit the calculation of risk.

The API risk based inspection semi-quantitative approach presents the results in a 5×5 risk matrix showing likelihood categories vs. consequence categories (API 581, 2000). RIMAP's (Risk based Inspection and Maintenance procedure for European industry) guidelines includes a semi-quantitative approach that defines risk as the combination of probability of failure (POF) and consequence of failure (COF) for a given scenario (Lee, Chang, Choi, and Kim, 2006). RIMAP distinguishes between two types of scenarios: worst case scenario and expected scenario. COF is another semi-quantitative risk assessment approach. The COF methodology is based on API 580/581 codes, ASME code, RIMAP. The COF code assesses the risk ranking and design the appropriate inspection plan in oil refinery, petrochemical, and nuclear power plants (Lee et al., 2006).

A number of software packages were developed to implement the API semi-quantitative approach of risk based inspection. Tischuk Enterprises (UK) Company has developed an integrated software system for implementation and management of semi-quantitative RBI (Tischuk, 2002). Tischuk OCA addresses the results in a 3×3 risk matrix shows likelihood category vs. consequence category (Tischuk, 2002). Tischuk Risk Expert (T-Rex) another software developed by Tischuk Enterprises Company (Tischuk, 2003). The Health and Safety Executive of the United Kingdom sponsored

TWI (The Welding Institute) to develop a software system that implements the best practice of RBI .TWI's RISKWISE™ semi-quantitative RBI software system combines the recommendations of both HSE guidance document and API 581 (Ablitt and Speck, 2005). DNV developed the RBI software "ORBIT+IDS". ORBIT+IDS software system deals with quantitative and semi-quantitative RBI analysis. ORBIT Onshore software system developed also by DNV, it can model any fluid if physical property data are available and it has a database of 1500 chemicals and about 1700 materials. ORBIT Onshore software is available in English, French and Chinese (Topalis, Alajmi, Toe, and Rao, 2006).

Veswly, Belhadj, and Rezos (1994) used probabilistic risk assessment for maintenance prioritization applications. Two measures used to determine risk importance maintenance, minimal cutsets contribution and risk reduction. Using these measures, the importance of the maintenance based on the risk impact that would occur if maintenance were not carried out effectively can be determined, the basic events and their associated maintenances can be prioritized according to their risk level, and basic events having low risk and unimportant maintenances can be identified.

Nessim and Stephens (1995) presented a risk based methodology that estimates the optimal maintenance interval for an aging hydrocarbon pipeline network. The presented risk based maintenance methodology consists of two main steps: to rank different segments of the pipeline according to priority for maintenance, and to select an optimal set of maintenance action for the chosen segments.

Nicholls (1995) developed a risk assessment code for a nuclear power station. The languages used in the code were PASCAL, ORACLE, and FORTRAN. The developed code includes: component database, failure modes, fault tree, event tree, probabilistic risk assessment analysis and documented results for the nuclear power plant.

Vaurio (1995) presented a general procedure to optimize inspection and maintenance intervals of safety related systems and components. Optimizing inspection and maintenance intervals is done based on minimizing the cost under the condition that risk remains below a set criterion. Basic events modeled include component failures, common cause failures and human errors.

Balkey, Art and Bosnk (1998) developed a risk based ranking methodology that includes probabilistic risk assessment (PRA) method. The developed methodology integrates nondestructive examination data, failure data, structural reliability, and probabilistic risk assessment.

Hagemeijer and Kerkveld (1998) developed a risk based inspection methodology for pressurized systems. The methodology determines risk by evaluating the consequences and the probability of equipment failure. Probability of equipment failure is assessed by means of extrapolation for the future planned maintenance work to identify the corrective maintenance works. A qualitative consequence analysis is applied to filter subsequent analysis. The methodology aims optimize the inspection and maintenance based on minimizing the risk.

Harnly (1998) developed a risk ranked inspection recommendation procedure to prioritize repairs identified during equipment inspection. The equipments are prioritized based on severity index. Severity index is the combination of failure potential and its consequences.

Kumar (1998) provided a holistic risk based approach. The approach presented is referred to as risk based maintenance where cost consequences are assessed quantitatively. This risk based maintenance approach improves the existing maintenance policy through optimal decision procedures in different phases of the risk cycle of a system.

Apeland and Aven (2000) developed a risk based maintenance optimization (RBMO) approach. The optimal strategies can be determined by evaluating the relationship between the benefits associated with each maintenance alternative and its cost. The presented approach works in a probabilistic frame using a Bayesian approach.

Brown and Le May (2000) presented a risk based methodology for inspection and maintenance assessment. The proposed risk based methodology estimates probability of failure based on reliability concept. This risk based methodology used for hazardous release protection and prevention. Several cases were reviewed in which failures would be prevented if proper risk assessment procedures were applied.

Nessim, Stephens, and Zimmerman (2000) presented a quantitative risk based integrity model for maintenance planning for offshore pipelines. Benefits associated with different maintenance alternatives are quantified by calculating their impact on the likelihood of failure and risk level.

Vassiliadis and Pistikopoulas (2000) developed a risk based maintenance strategy that minimizes the environmental risk and increases the profitability in the process industry systems. Occurrence of unexpected events mechanism and the severity of its consequences are presented in the work.

Dey (2001) presented a risk based methodology for inspection and maintenance. Appling the methodology helps to identify the right pipeline for inspection and maintenance policy; reduces the cost of inspecting and maintaining petroleum pipelines; reduces the time spent on inspection; and suggests efficient design and operation philosophies, construction methodology and logical insurance plans.

Ponnambalam (2001) shown that the statistical and stochastic analyses can be used to integrate risk and reliability for system function design. A Bayesian model was used in this work estimate the risk. The advantages of utilizing available data and knowledge of experts in assigning probabilities in estimating risk to manage regulation of stream flow were demonstrated. The used procedure to analyze failure data consists of specifying an acceptable and unacceptable failure rates, and using a permitted number of failures as a control variable.

Anderson (2002) discusses the implantation and applying of risk based inspection programs. The origin of risk based inspection, establishing the bases for defining the risk, risk assessment process, key parameters of risk based inspection analysis, and risk based inspection implantation options were discussed. The author concluded that several methodologies are available to accomplish a successful implementation of risk based inspection programs, he stated that "sufficient risk based inspection studies are now complete on refineries and petrochemical that give good guidance on how these projects should be planned, initiated and implemented".

Backlund and Hannu (2002) studied maintenance decisions based on risk analysis results. A case study involving a hydro power plant is presented. Maintenance decisions for this case study were developed based on three independent risk analyses. A comparison between these three analyses revealed major differences in performance and results. Based on the study it was concluded that there is a need for a quantitative risk analysis.

Faber (2002) illustrated a theoretical framework for risk based inspection planning. The uncertainties of inspection measurement attributed to deterioration, physical uncertainties, statistical uncertainties, and model uncertainties were described. The physical uncertainties are associated with loading, environmental exposure, geometry and material properties. The statistical uncertainties arise from incomplete statistical information, e.g. due to smaller number of material tests. The model uncertainties are due to the mathematical approximation used to simplify the model.

Kallen (2002) developed a probabilistic risk based inspection methodology. This methodology uses gamma stochastic deterioration process to model the corrosion damage mechanism that used to develop safety optimal inspection plans. Cost functions associated with gamma process for modeling deterioration are developed.

Martinez Gonzalez et al (2002) presented a quantitative integrity and risk assessment approach. The presented approach is used for maintenance planning in natural gas transmission pipelines. The approach provides a helpful tool to make operating decisions that guarantees risk reduction in terms of business interruption, environmental and property damage, and public and employee safety.

Misewicz, Smith, Nessim, and Playdon (2002) developed a risk based integrity approach. The developed approach uses quantitative risk analysis to estimate the risk. This approach aims to select projects that fit within maintenance budget while providing risk reduction.

Montgomery and Serratella (2002) discussed a holistic risk based maintenance approach to asset integrity management. The approach is developed based on proven risk assessment and reliability analysis methodologies, in addition to the need to have appropriate management systems.

Jovanovic (2003) compared the current practices and trends in the area of risk based inspection (RBI) and risk based life management (RBLM) implemented in European and USA. Risk based life management (RBLM) is a concept that includes external damages, explosions and similar purely random causes.

Khan and Haddara (2003) presented a risk based maintenance methodology for designing an optimum inspection and maintenance programs. The methodology consists of three parts: risk estimation, risk evaluation and maintenance planning. This methodology was applied to a heating, ventilation and air-conditioning system.

Fujiyama et al (2004) developed a risk based maintenance (RBM) system for steam turbine plants coupled with inspection systems. The developed risk based maintenance system makes use of the field failure and inspection database accumulated over 30 years. Determining the optimum maintenance plan is depends on the simulated scenarios described through component breakdown trees, life cycle event trees and risk functions.

Kallen and Noortwijk (2004) developed a risk based inspection technique used in optimal inspection and replacement decisions for multiple failure modes. The deterioration model is presented along with the cost functions. The cost functions were extended to include multiple failure modes. The combined deterioration and cost function model is illustrated by an example considering an elbow in a pipeline that is susceptible to thinning due to corrosion.

Khan and Haddara (2004a) discussed a risk based maintenance (RBM) methodology. The proposed methodology developed based on integrating risk assessment strategies and reliability approaches. The risk based maintenance methodology is used to answer two questions: The maintenance program should be scheduled for which equipment? and when the maintenance should be scheduled?

Khan and Haddara (2004b) discussed a comprehensive and quantitative methodology for maintenance planning based on risk. This methodology is developed to obtain an optimum maintenance schedule that minimizes the probability of system failure and its consequences. A case study, which exemplifies the use of the methodology to an ethylene oxide production facility, is discussed.

Krishnasamy (2004) implemented a quantitative risk based maintenance approach to a hydrothermal power generation plant. This quantitative approach is comprised of three modules: risk assessment module, risk evaluation module, and maintenance planning module. Risk assessment module studies the occurrence of failures in equipment and the severity of their consequences. Failure data are collected from the historical failure data of the Newfoundland and Labrador hydrothermal power station over a period of twelve years, and then it was modeled using Weibull and Exponential distributions. Risk evaluation module determines an acceptable risk criterion and identifies the major systems and subsystems that have a risk higher than the acceptable risk. Maintenance planning module estimates the optimal maintenance interval that reduces risk level. It was concluded that, risk based maintenance prioritizes the systems for maintenance planning, improves the existing maintenance policies, minimizes the consequences (safety, economic and environmental) related to a system failure, and provides coast-effective means for maintenance.

Horikawa, Yoshikawa, Takasu (2004) presented a newly developed risk based maintenance system. This system is used to describe the structural integrity of buried pipeline based on the risk index. The benefits of the developed risk based maintenance system as a means of structural integrity assessment is discussed in this paper. The paper also discussed the features of the quantitative risk evaluation approach.

Brickstad (2005) studied five different Structural Reliability Models (SRMs) conducted in the frame of the European Project NURBIM (Nuclear Risk Based Inspection Methodology for passive components). Probabilities of failure for pipes of small, medium and large diameters were evaluated for 40 years. Two damage mechanisms were considered: fatigue and stress corrosion crack. Five different software were applied to fifteen parameters to calculate failure probabilities for 40 years.

Conley (2005) presented the application of risk based inspection (RBI) assessment technology. This risk based inspection approach was applied to ammonia storage to analyze the hazards presented by corrosion or other ongoing degrading mechanisms. The presented approach is a qualitative risk based inspection approach. Risk was presented in a risk matrix in this work. In the risk matrix the consequences were measured in terms of the area that would be affected by fire or explosion if flammables are released.

Kallen and Noortwijk (2005) presented a risk based inspection (RBI) technique that develops cost and safety optimal inspection plans. Bayesian decision model is used to determine these optimal inspection plans under uncertain deterioration. The presented risk based inspection technique uses the gamma stochastic process to model the corrosion damage mechanism and Bayes' theorem to update prior knowledge over the corrosion rate with imperfect wall thickness measurements. A periodic inspection and replacement policy which minimizes the expected average costs per year is found. An example using actual plant data of a pressurized steel vessel is presented.

Krishnasamy, Khan and Haddara (2005) developed maintenance strategy based on risk for a power generating plant. The risk based maintenance methodology consists of four parts, identification of scope, risk assessment, risk evaluation and maintenance planning. Applying this risk based maintenance methodology results in risk reduction, increases the reliability of equipment, and reduces the cost of maintenance.

Noori and Price (2005) implemented the semi-quantitative risk based inspection approach developed by the American Petroleum Institute (API) on furnace tubes. The calculated risk was addressed in a 5×5 risk matrix to target the tubes with the highest risk category to take the priority in planning the inspection program. Inspection intervals then developed based on the technical model subfactor (TMSF) according to the API code. Questions according to these inspection intervals were presented.

Straub and Faber (2005) presented a new risk based inspection approach. The presented approach is an integral approach that considers the entire systems in inspection planning, while most of the risk based inspection approach focus exclusively on individual components or have considered system effects in a very simplified manner only, because it is not possible to identify cost optimal solutions if the various types of functional and statistical dependencies in the systems are not explicitly addressed especially for large engineering systems. The paper discussed the various aspects of dependencies in the systems, decision problems encountered in inspection and maintenance planning of structural systems, and how these decision problems can be consistently represented by decision theoretical models.

Khan, Haddara, and Battacharya (2006) developed a risk based methodology for integrity and inspection modeling (RBIIM).The methodology presents quantitative risk based inspection approaches that use the gamma stochastic process to model the corrosion damage mechanism and Bayes' theorem to update prior knowledge over the corrosion rate. RBIIM finds a periodic inspection and replacement policy that minimizes the expected average costs per year.

Tien, Hwang, and Tsai (2007) developed a new risk based inspection model. The model consists of two parts: the first part is a risk based inspection system, and the second is a risk based piping inspection guideline model. The model is designed to analyze damage factors, damage models, and potential damage positions of piping in the petrochemical plants. The objective of developing the model is to provide inspection related personnel with the optimal planning tools for piping inspections; therefore, it enables effective predictions of potential piping risks and enhances the degree of safety in plant operations in the petrochemical industries.

Khan and Howard (2007) presented a simplified practical approach for the use of statistical tools for inspection planning and integrity assessment. The study is focused on corrosion related material degradation of piping on an offshore production facility. The application of the approach is demonstrated using 7 years past inspection data. The case studies presented herein illustrate the benefits to be gained by applying well-established statistical methods to the analysis of inspection data, amongst which are: quantification of inspection findings, the ability to specify the extent of inspection required for the defined level of confidence, and the use of limited inspection data to infer the condition of inspected areas under similar exposure conditions to those inspected. Further, this approach can be integrated with risk based inspection and integrity assessment methods thereby improving the value of these assessments.

The above literature review provides a clear understanding of the risk based inspection and maintenance in process and allied industries. It has been observed that most of the industry practiced approaches are qualitative; whereas API has recommended guidelines for semi quantitative and/or quantitative risk based inspection. What is lacking in the current literature is a simplified quantitative approach that is easy to use, rigorous, reliable, and follows the API recommended practice for RBI. After reviewing available models and methods for risk based inspection and maintenance planning, stochastic model proposed by Kallen (2002) and API approach (API 581, 2000) has been chosen for subsequent study. Kallen (2002) model has earlier used by Khan et al. (2006). In present study this model has been integrated with API risk based inspection planning method. The model was chosen to benefit from both the rigor of the API risk based inspection approach and the reliability of the stochastic model presented by Kallen (2002). Details of risk based inspection modeling, Kallen model, and integration of Kallen model with API approach and their application has been presented in subsequent chapters.

CHAPTER 3

RISK BASED INSPECTION

3.1 Definition of RBI

Risk based inspection (RBI) is a method that uses risk as a basis for prioritizing and managing inspection plans (API 580, 2002). A RBI program determines what incident could occur (consequence) if equipment fails, and how likely it could happen. The objectives of the RBI program are:

1. Using the concept of risk to target inspection and maintenance resources that can have the greatest effect in reducing risk.
2. To systematically reduce the occurrence and consequences of unplanned failures.
3. To reduce the cost of unproductive inspections.

Risk based inspection requires to undertake a risk analysis for the systems and equipments under consideration. The form of this analysis can vary considerably depending on the RBI approach. However, the risk analysis in all approaches should contain the following stages:

- Identification of potential deterioration mechanisms and modes of failure.
- Assessment of the probability of failure from each mechanism/mode.
- Assessment of the consequences resulting from equipment failure.
- Determination of the risks from equipment failure.
- Risk ranking and categorization.

Figure 3.1 illustrates a simplified block diagram of risk based inspection process.

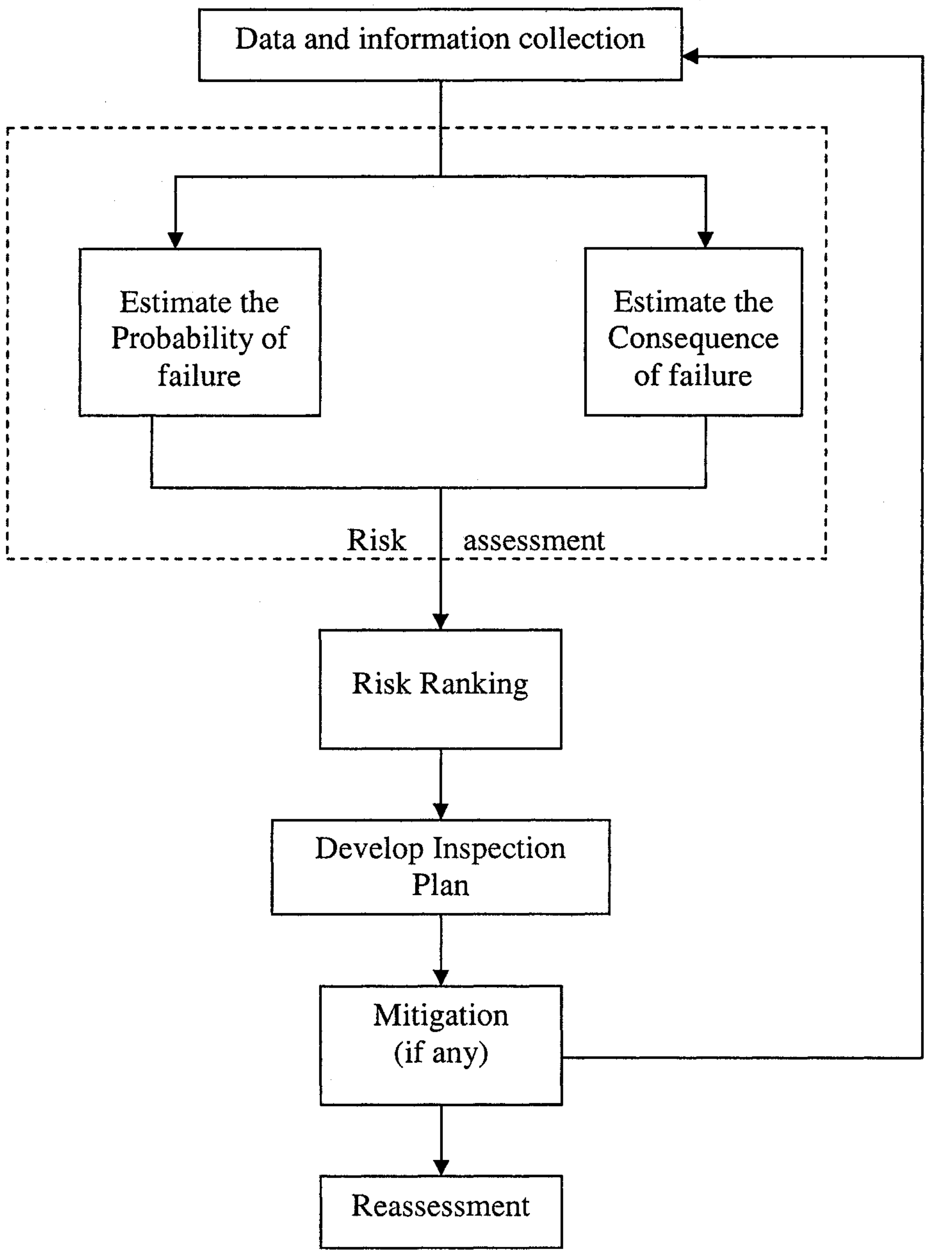


Figure 3.1 A simplified block diagram of RBI process (API 580, 2002).

3.2 The Concept of Risk

Risk is defined as the probability of an event occurring during a time period of interest with adverse consequence.

The probability of failure is defined as the frequency with which a specified failure event would be expected to occur in a given period of operation, normally one year.

The consequence of failure through the unintentional release of stored energy and hazardous material is the potential of harm. Risk analysis should concern of two basic consequence categories. The first consequence category is related to the potential harm to the Health and Safety of employees and/or the public, and to the environment from the release of flammable and/or toxic materials. The second consequence category is an economical one; it is concerned with consequence of failure on the business, such as the costs of lost production, and repair and replacement of equipment.

The risk of failure in mathematical terms is defined as:

$$\text{Risk} = \text{Probability} \times \text{Consequence} \qquad \ldots (3\text{-}1)$$

For a specific scenario (deterioration mechanism) the risk equation can be stated as:

$$Risk_s = POF_s \times COF_s \quad \ldots (3\text{-}2)$$

Where

$Risk_s$ is risk of a specific scenario,

POF_s is the probability of failure of a specific scenario/deterioration mechanism.

COF_s is the consequence of that scenario.

The total risk of an item is the sum of the risks for all possible scenarios/ all degradation mechanisms.

$$Risk_{\text{Item}} = \sum Risk_s \quad \ldots (3\text{-}3)$$

3.2.1 Probability of failure

The probability analysis calculates the probability of a specific adverse consequence resulting due to deterioration mechanisms.

The probability of failure analysis should adopt all deterioration mechanisms to which the studied equipment is susceptible. According to API 580 (2002), four major deterioration mechanisms are observed in the hydrocarbon process industry:

1. Thinning.

2. Stress corrosion cracking.
3. Metallurgical and environmental.
4. Mechanical.

In determining the probability of failure the effectiveness of the maintenance and inspection programs should be taken in consideration along with the deterioration susceptibility and rate.

Various methods can be applied to determine the probability of failure. These include qualitative, semi-quantitative and quantitative methods. The qualitative approach in determining the probability of failure relies on the judgment and experience of an expert.

The semi-quantitative methods that determine the probability of failure are:

- Failure rates for generic classes of equipment based on historical data.
- Failure rates for generic equipment classes modified by equipment specific factors.

The above semi-quantitative methods can be used quantitatively. In addition, the following methods are used in the quantitative approach in determining the probability of failure:

- Fault tree and/or probabilistic risk analysis,
- Structural reliability analysis - (e.g. probabilistic fatigue and fracture).

In this work the probability of failure is estimated quantitatively. A probabilistic material degradation is estimated through applying a mathematical function that models the deterioration rate of the material.

3.2.1 Consequence of failure

The consequence analysis in a RBI program estimates what might be expected to happen if a failure occurs in an assessed equipment item. It should focus on the subsequent events that can cause death, or harm to the employees and the general population, and economical losses.

In assessing the effects of the release of fluid resulting from failure of pressure systems and systems containing hazardous materials all the relevant factors should be included:

- Composition of the contained fluid.
- Physical and chemical properties of the material contained in the system.
- Potential leak area considering the mode of failure and pipe/vessel size.
- Release rate of mass/energy.
- Mitigation systems such as water curtains and secondary containments.
- Measures for detection of the leak and the means for its isolation.
- Total amount of fluid available for release.

- The final phase of the fluid when it release into the atmosphere.
- The dispersal characteristics of the fluid at the site.
- Possible subsequent events to release, such as fire and/or explosion.

The subsequent consequences resulting from the release depend on the type of fluid and the energy contained in the system. The events of flammable release, steam and hot gas release, toxic release, high pressure gas release and missile could endanger Health and Safety. The potential for one or a combination of these events should be determined.

The events of flammable materials release, hot gas release, and high pressure gas release generally leads to fire and/or explosion consequences. The results from fire and explosion consequences are given as effected area. Injuries and death from fires and direct blast effects of explosions can be estimated using probit analysis. Damage for common structures can be estimated depending on the overpressure generated in the explosion. For more details see Crowl and Louvar "Chemical process safety fundamentals with applications".

Missiles are the debris results from explosion occurring in a confined vessel or structure. Missiles can cause injury and death to people, and damage to structures. The maximum horizontal range that missiles could reach can be estimated from a figure developed by Clancey (1972).

Toxic release can cause serious accidents if the toxic material released quickly and in significant enough quantities. Toxic release and dispersion models estimate the effects of a release on the plant and community environment. These models study a wide variety of parameters:

- Wind speed.
- Atmospheric stability which is related to vertical mixing of the toxic material and the air.
- Ground conditions which affect the mechanical mixing of the toxic material in the air at the surface, and wind profile.
- Height of the release above ground level.
- The buoyancy and momentum of the initial material released.

3.3 Guidelines on Risk Based Inspection

3.3.1 Health and Safety Executive RBI

The Health and Safety Executive guideline issued by the Hazardous Installations Directorate (HID) describes a risk based approach to planned plant inspection (ASME, 1999).

Health and Safety Executive (HSE) issued the report 'Best practice for risk based inspection as a part of plant integrity management' in the year 2001. The report contains regulations and guidelines on both risk assessment and risk based inspection, the application of risk based inspection, plant data requirements, team competencies, the development of inspection plans and overall management of the RBI process. A case study of RBI practice, an audit tool to assist the evaluation of the RBI process, techniques to identify accident scenarios, types of deterioration mechanisms of pressurized systems and software packages supporting RPI of pressure systems and containments are given in the appendices. According to the welding institute publication, TWI (2005), the objective of issuing the Health and Safety Executive risk based inspection report is to provide guidelines for risk-based inspection planning of

- Pressure equipment and systems that are subject to the requirements for in-service examination under the Pressure Systems Safety Regulations 2000 (PSSR).
- Equipment and systems containing hazardous materials that are inspected as a means to comply with the Control of Major Accident Hazards Regulations (COMAH).

3.3.2 The American Society of Mechanical Engineers RBI

In 1991, the American Society of Mechanical Engineers (ASME) extended the risk assessment and developed a general guideline that gives a general overview of the principles involved in risk based inspection.

According to Wintel et al. (2001), the recommended process to rank or classify systems for inspection and to develop the strategy of inspection in ASME risk based inspection approach includes:

a. Definition of the system.

b. A Qualitative Risk Assessment.

c. A Quantitative Risk Analysis.

d. Development of Inspection Program.

The qualitative risk assessment enables the individual plant items within the system to be prioritized. This initial assessment involves:

a. Defining the failure modes and causes,
b. Identifying the consequences,
c. Estimating risk levels,
d. Ranking the subsystems.
e. Ranking the individual components based on risk level.

Then the quantitative risk analysis is applied to the individual components of the system. The quantitative risk analysis would capture information from the qualitative risk assessment and assign probabilities and consequences of failure for each component.

Development of the inspection program is the next stage, where the inspection strategies of technique and frequency are evaluated, performed and then the results are assessed to update the state of knowledge for the next inspection.

3.3.3 The American Petroleum Institute RBI

The America Petroleum Institute (API) risk based inspection program aims to define and measure the level of risk associated with an item; evaluate safety, environmental and business interruption risks; and reduce risk of failure by the effective use of inspection resources. The America Petroleum Institute (API) has established a number of documents on risk based inspection like API 580, API 581, API 510, API 570, and API 653. API 580 provides a general guideline for risk based inspection. API 581 is an industry specific document that can be applied to the petroleum and chemical process areas. API 510 provides a risk based inspection code for pressure vessel systems. API 570 is a piping inspection code. API 653 provides tank inspection, repair, and alteration and construction codes.

The level of risk is assessed by a quantitative analysis generally applied after an initial qualitative analysis has established those plant items for further analysis. The inspection program is then developed to reduce that risk.

3.4 RBI Approaches

The RBI program can be applied qualitatively, semi-quantitatively, or quantitatively. Choosing the appropriate RBI type or approach depends on multiple variables such as available resources and data, complexity of process and facilities, study frame time, and the objective of the study.

3.4.1 Qualitative RBI

The qualitative risk analysis is based basically on engineering judgment and experience made by the informed personnel and relevant experts in the RBI team. The likelihood and consequences of failure are expressed descriptively and in relative terms (e.g. very unlikely, possible, reasonably probable and probable for LOF, high, moderate, low for COF).

The qualitative approach is an ordered and prescribed process where judgments should reflect the consensus opinion of the team. It is assisted if a standard procedure is followed for each item. Risks within a qualitative approach are usually presented within in a risk matrix as combinations of the likelihood and consequences. The American Society of Mechanical Engineers (ASME) and the American Petroleum Institute (API) have developed two similar qualitative approaches that assigns risk ranking in a 5×5 risk matrix. Figure 3.2 shows risk estimating the API qualitative RBI approach.

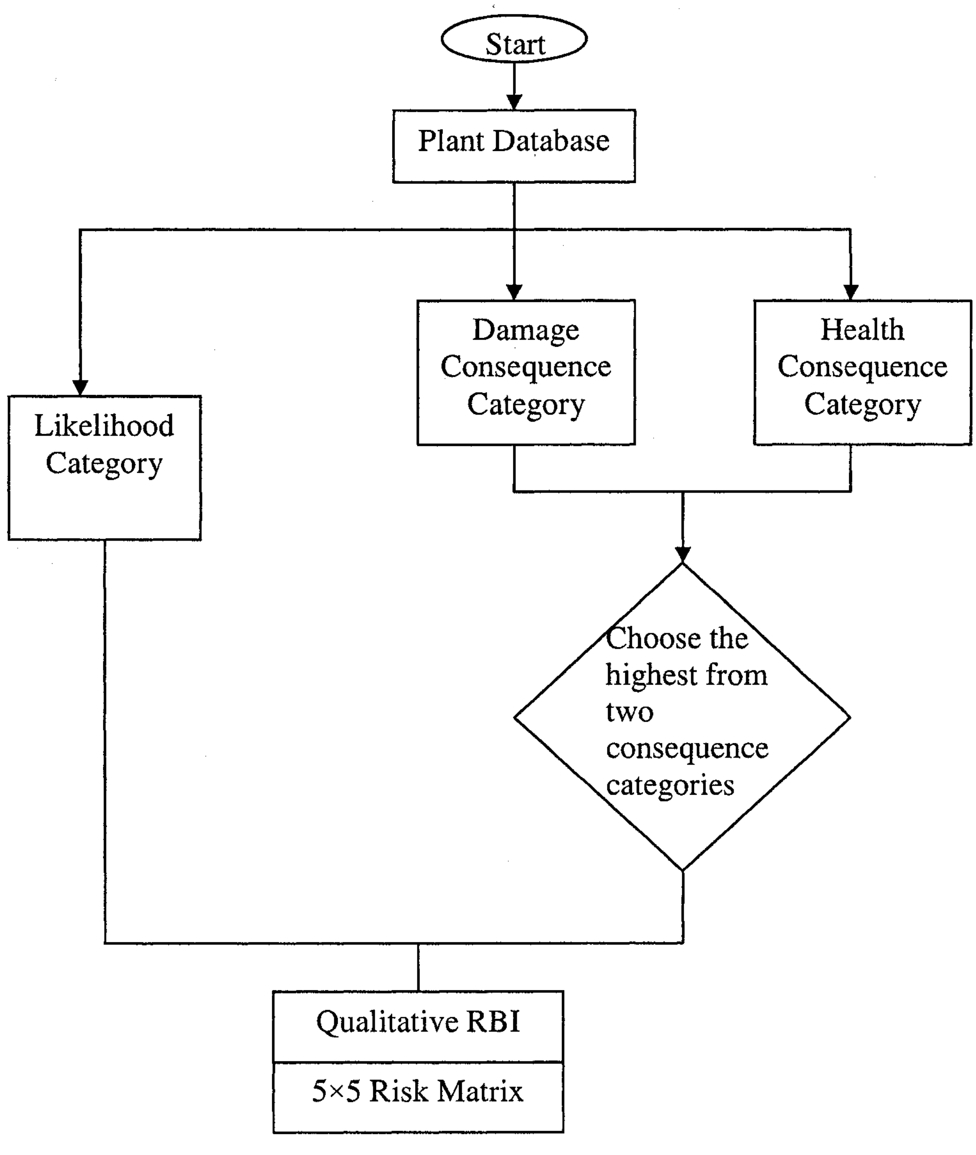


Figure 3.2 API Qualitative RBI Approach

The likelihood category in the qualitative API RBI approach is assigned by evaluating six factors, the sum of these six factors assigens the overall likelihood factor. The likelihood cateroy is estimated based on the over all likelihood factor. The six factors that establishes the likelihood category are:

1- The liklihood equipment factor (EF) which concerns about the number of components in the unit, it is strongly influenced by the number of equipment items in the studied unit.
2- The likelihood damage factor (DF), it is a measure of the risk related to known damage mechanisms.
3- The likelihood inspection factor (IF); it measures the effectiveness of the current inspection program to identify the anticipated damage mechanisms in the unit.
4- The likelihood condition factor (CCF) is related to the effectiveness of plant maintenance and housekeeping efforts.
5- The likelihood process factor (PF) accounts the potential abnormal operations or upset conditions to result in initiating events that could lead to a loss of containment.
6- The likelihood mechanical design factor (MDF) studies certain aspects of the design of the operating equipment.

According to the API 581(2000), the consequence analysis for the qualitative API RBI approach determines two major consequence factors: a damage cosequence factor and a health consequence factor. The damage cosequence factor studies the flammable consequence of failure. The health consequence factor studies the consequence of a contained material release on human health through studying the toxic consequences. The consequence category will consider the higest rating from either the damage or the health consequences.

The damage consequence category is estimated from the sum of six factors that determines the magnitude of fire and explosion hazard:

1- The chemical factor (CF) measures the chemical's inherent tendency to ignite.
2- The quantity factor (QF) estimates the largest amount of material which could be released from a unit in a single scenario.
3- The consequence state factor gives an indication of the fluid's tendency to vaporize and disperse when released to invironment.
4- The autoignition factor (AF) account the ignition probability of a fluid processed at a temperature above its autoignition temperature.
5- The pressure factor (PRF) represents the fluid's tendency to be released quickly.
6- The credit factor (CRF) determines the safety features engineered into the unit through the summation of several subfactors of engineered systems in place which can reduce the damage from an event.

The health consequnse category is derived from the combination of four factors which express the degree of a potential toxic hazard in th unit, these factors are:

1- The toxic quantity factor (TQF) measures both the quantity and the toxicity of a material.
2- The dispersibility factor (DIF) represents the ability of a material to disperse.
3- The credit factor (CRF) accounts the safety features engineered into the unit.
4- The population factor (PPF) estimates the number of people that can potentially be affected by a toxic release event.

The likelihood category rating and the highest rating from the two consequence categories are placed for each unit within a 5×5 risk matrix to give an indication of the risk level for each unit. The qualitative 5×5 risk matrix is shown in figure3.3.

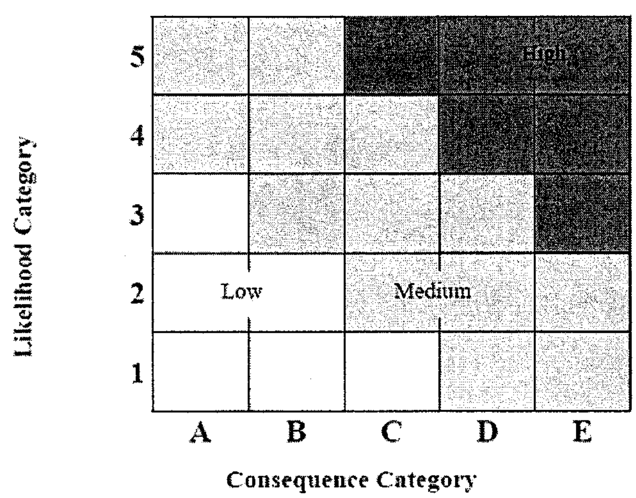


Figure 3.3 Qualitative Risk Matrix (API 580, 2002).

3.4.2 Semi-Quantitative RBI

The semi-quantitative risk based inspection approach has aspects derived from both the qualitative and quantitative approaches. It is designed to obtain the major benefits of both of the qualitative and quantitative approaches; it has the speed of the qualitative approach and the rigor of the quantitative approach (API 580, 2002).

The risk analysis for the API semi-quantitative risk based inspection approach is a straight forward assignment of the likelihood of failure and its consequences to their proper categories and placing them in the 5×5 risk matrix. Figure 3.4 shows the risk matrix for the API semi-quantitative approach. Two consequences are covered in the API semi-quantitative risk based inspection approach: flammable consequences and toxic consequences (API 581, 2000). Figure 3.5 shows the risk evaluation process of the semi-quantitative RBI approach based on API codes.

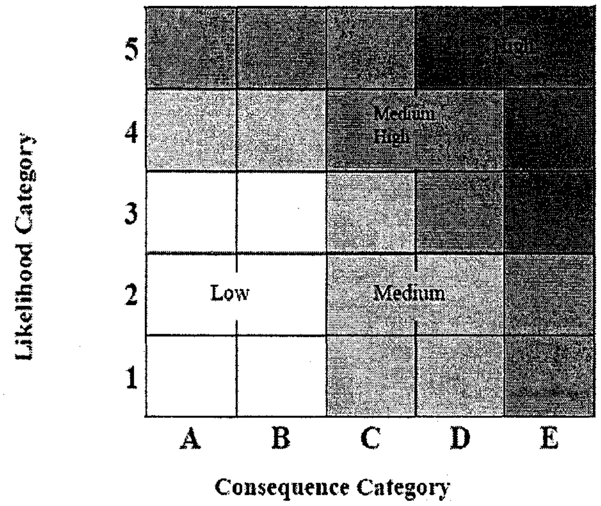


Figure 3.4 The API semi-quantitative approach Risk Matrix (API 581, 2000).

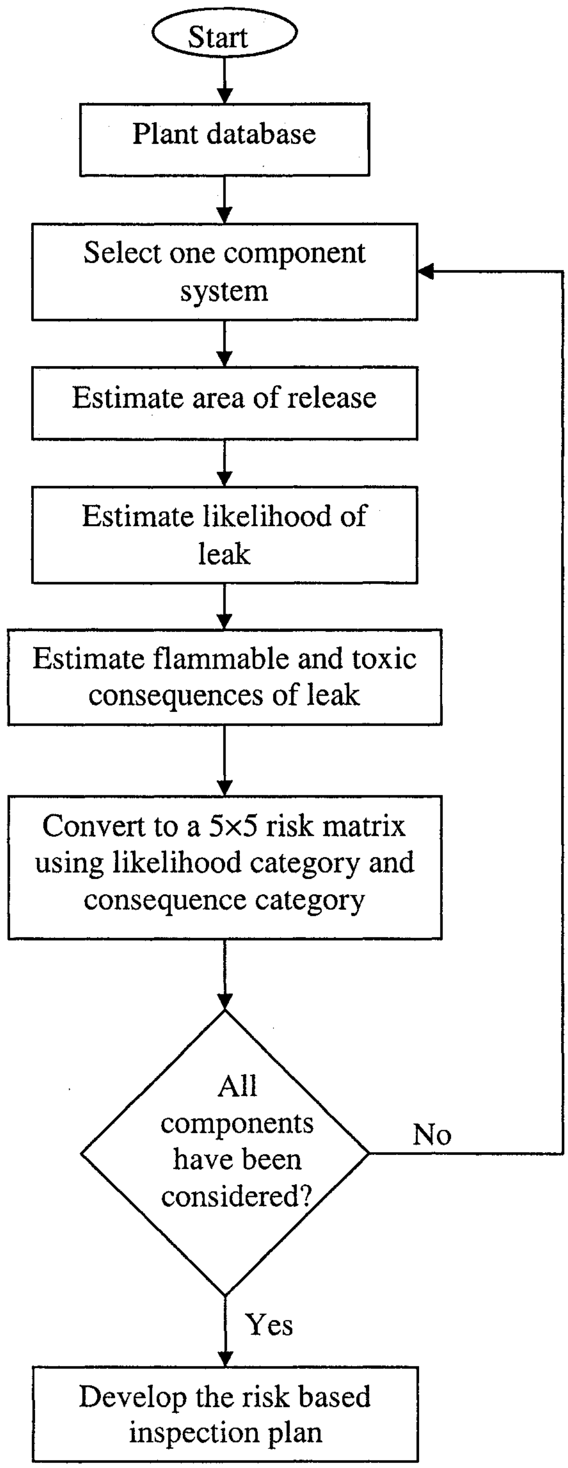


Figure 3.5 The semi-quantitative RBI approach based on API codes

3.4.3 Quantitative RBI

The quantitative RBI approach uses logic models depicting combination of events that could result in severe accidents and physical models representing the consequences of these events. The logic models that estimates the likelihood of failure generally consists of event trees and fault trees analysis.

The likelihood of failure analysis in the API RBI approach is carried out using generic failure frequency as the starting point. This generic failure frequency is then modified by two terms the equipment modification factor and the management systems evaluation factor. According to API 581 (2000) the adjusted failure frequency is given by:

$$Frequency_{adjusted} = Frequency_{generic} \times F_E \times F_M \qquad \ldots (3\text{-}4)$$

Where:

$Frequency_{generic}$ is the generic failure frequency.

F_E is the equipment modification factor.

F_M is the management systems evaluation factor.

The generic failure frequencies are estimated using records from plants, literature sources, past reports, and commercial data base. Generic failure frequencies are assumed to follow a log-normal distribution. A detailed generic data base, and developed values of the generic failure for each type of equipment and each diameter of piping is presented in the API 581 (2000).

The equipment modification factor examines the specific conditions of each equipment item that have a major influence on the likelihood of failure of that equipment item. According to API 581 (2000), these specific conditions are categorized in four subfactors:

- The technical module subfactor that used to assess the effect of specific failure mechanisms on the likelihood of failure. Two categories are evaluated in the technical module subfactor: deterioration rate and effectiveness of the inspection program.
- The universal subfactor which covers the conditions that equally affect all equipment items in the plant. The universal subfactor is composed of the following three elements: plant condition, cold weather operation, and seismic activity.
- The mechanical subfactor that addresses conditions mainly related to the design of the equipment item and its fabrication. The mechanical subfactor includes five elements: equipment complexity, construction code, life cycle of equipment, safety factor, and vibration monitoring element.

- Process influences subfactor which can affect equipment integrity. Process influences subfactor includes three elements: continuity of the process, stability of the process, and relief valves.

The management systems evaluation factor measures the influence of the facility's safety management system on the likelihhod of failure of equipment items and the plant integrity.

The quantitative API RBI approach covers four different consequences:

a. Flammable consequences.
b. Toxic consequences.
c. Environmental consequences.
d. Business interruption consequences.

The results from both flammable and toxic consequences are given as effected area. Where, the environmental and business interruption consequences are calculated as economic loss. Figure 3.4 presents the consequence of failure estimation process based on API approach. The consequence of failure is estimated almost in the same way for the semi-quantitative and the quantitative approaches, with less detail while applying the semi-quantitative approach.

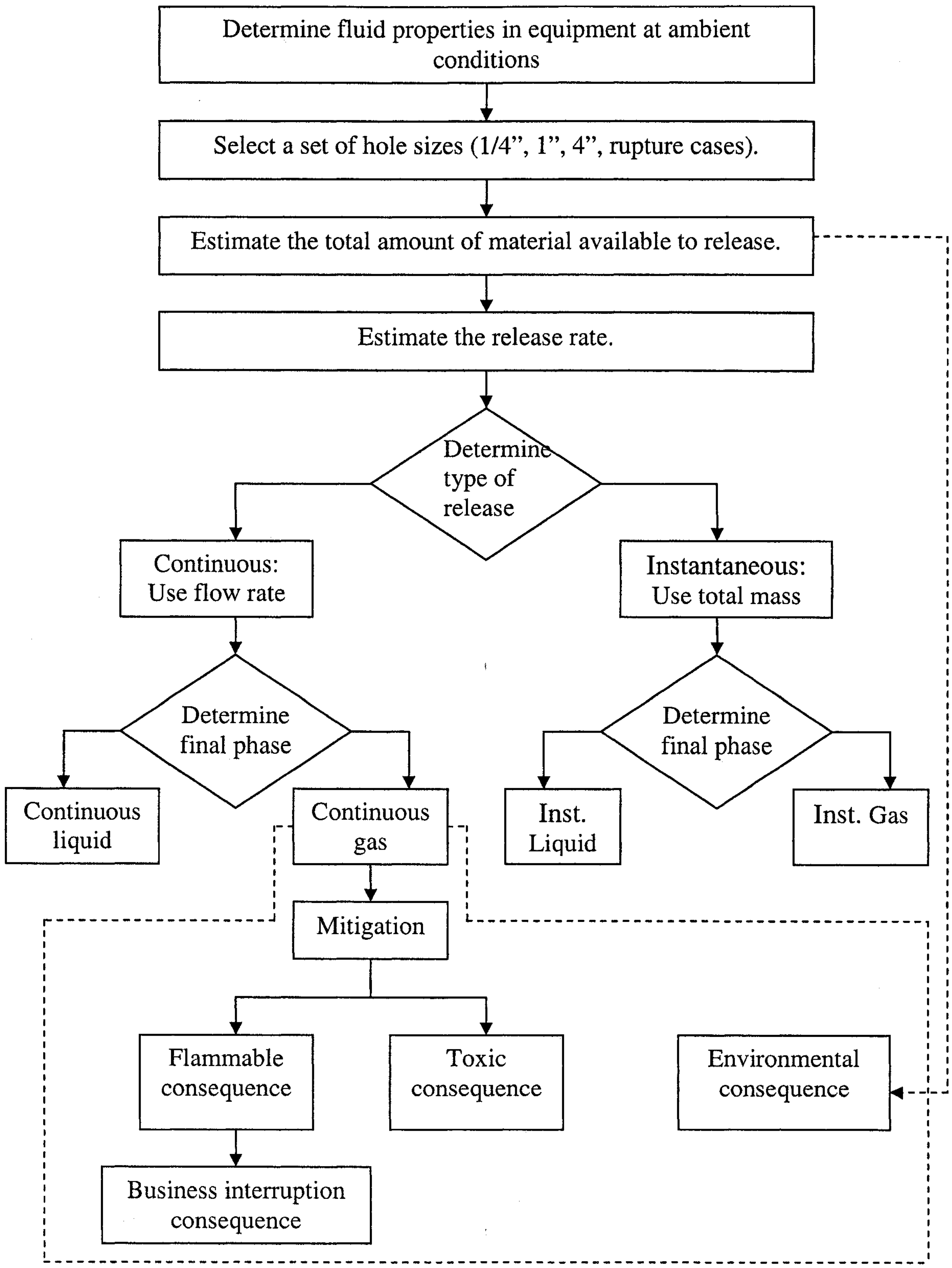


Figure 3.4: COF estimation process based on the semi-quantitative/ quantitative API RBI approaches (API 581, 2000).

3.5 Advantages of Applying RBI

According to Patel (2005), applying the risk based inspection methodology based on the American Petroleum Institute guidelines has the following advantages:

- Improving the health and safety management.
- Avoid unnecessary inspection: Inspection intervals are based on the risks associated with the equipment and therefore inspection personnel can spend most of their time on the high risk areas and less time in the low risk areas.
- Saves cost: Equipment with no history of problems and no anticipated problems is inspected on longer intervals rather than just inspecting every few years as is the case with a time-based inspection program.
- Information from inspections on one piece of equipment can be utilized in determining the inspection intervals and scopes for similar equipment.
- The RBI program is totally dynamic: risks are updated after inspections or even the inspection of similar equipment, changes to process conditions or even if new information becomes available. Any of the above may result in a change in inspection frequencies or changes to the inspection scopes.

- The methods used to determine the inspection intervals and inspection scopes are documented and repeatable.
- Increases plant availability and optimum repair and replacement scheduling.
- Extends plant and equipment life.

CHAPTER 4

THE RBI MODEL

4.1 Model Concept

The risk based inspection model presented in this work is a probabilistic model that combines a risk based inspection approach developed by the American Petroleum Institute API and published in its base resource document API 581 (2000), and a risk based inspection model developed by Kallen (2002). The American Petroleum Institute risk based inspection approach is developed to estimate the optimal inspection time using the prior knowledge of the average material corrosion (degradation) rate. The approach is based on the assumption that the material corrosion rate will remain constant with time which is unlikely to occur. Several factors are likely to affect the rate of material degradation e.g. the aging of the equipment, new degradation mechanisms may start affecting the system. To compensate for this effect, the API risk based inspection approach designs the inspection programs in time intervals that vary from four to six years with different inspection levels depending on the inspected system and type of equipment The API risk based inspection approach differentiates between different inspections levels where different inspection techniques are applied: highly effective, usually effective, fairly effective, and poorly effective inspections. By combining the American Petroleum Institute risk based inspection approach with the risk based inspection model developed by Kallen, the prior knowledge of the average corrosion rate can be effectively updated and converted to a density function that shows the change in the corrosion rate with time using a stochastic gamma model and Bayesian updating.

The main advantage of combining the API risk based inspection approach with the risk based inspection model developed by Kallen is that the new model gives more reliable inspection intervals. The resulting inspection intervals are not too short like the inspection intervals obtained from applying the risk based inspection approach developed by the American Petroleum Institute, so unnecessary inspections are avoided. Nor they are too long so the risk of failure due to deterioration mechanisms will exceed the acceptable risk level. Another advantage of combining the American Petroleum Institute risk based inspection approach with the risk based inspection model developed by Kallen is the ability to predict optimal inspection time as well as failure times.

The new risk based inspection model uses state functions to model the cumulative damage to the material of the component and update this model with available inspection data using Bayesian updating. The model aims at developing an optimum inspection strategy for the equipment. Figure 4.1 depicts the overall framework suggested for the application of this model. The framework includes five stages: identification of equipment to be analyzed, detecting degradation mechanisms for each component, calculation of risk of failure of each component, finding the optimal inspection interval for each component, development of a comprehensive policy for plant inspection.

Risk as previously stated has two components likelihood and consequence. The likelihood of failure is estimated using a stochastic gamma model. The gamma stochastic process is used to model the existing degradation mechanisms and to update the degradation model to extrapolate the expected degradation in the future based on previous inspection data. The consequence analysis is estimated using the damage rate to find the optimal expected replacement and failure times. The expected inspection time calculated keeps the damage factor as low as possible in a range that keeps the process within acceptable risk. Figure 4.2 represents the risk analysis methodology.

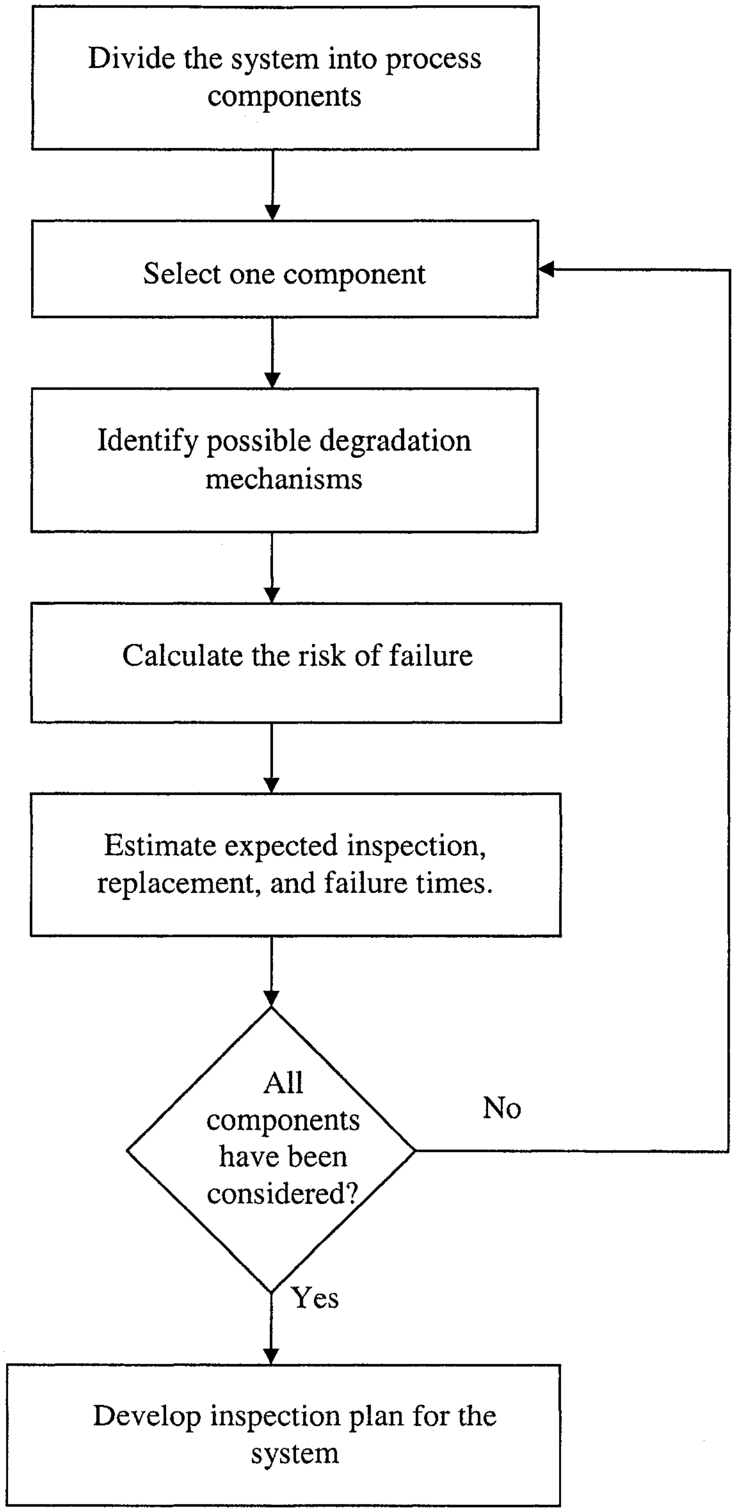


Figure 4.1 Framework for the RBI model methodology

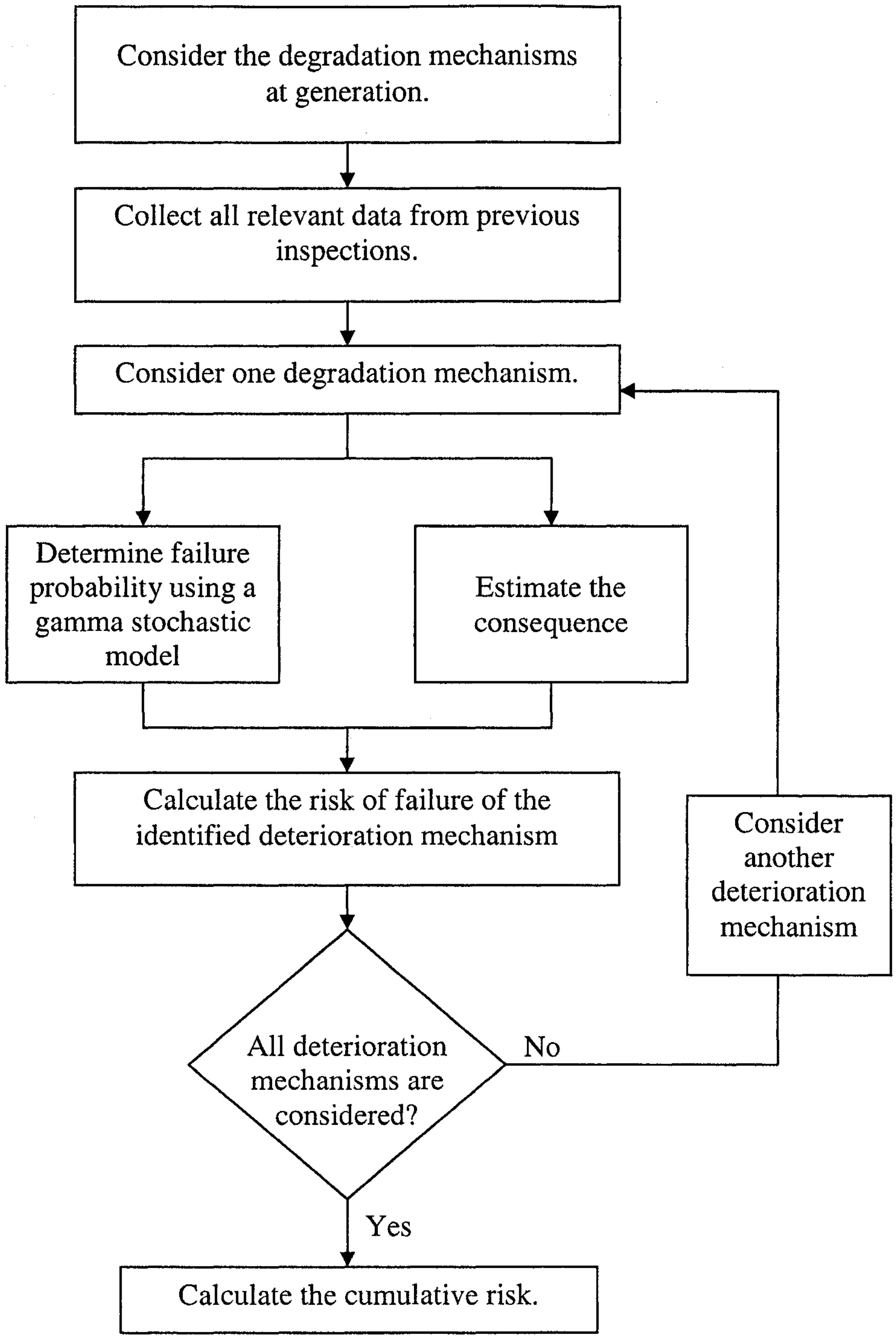


Figure 4.2 Risk analysis methodology

4.2 Deterioration Mechanisms and Failure Probability

Deterioration mechanisms are defined as deterioration types that could lead to a loss of contaminant. Identifying the appropriate deterioration for all equipment included in a risk based inspection study is essential to the effectiveness and quality of the RBI evaluation. The probability of failure due to a deterioration mechanism is a function of the rate of deterioration, the probability of detecting all deterioration mechanisms through inspection, the deterioration type, and the tolerance of equipment to the type of deterioration. According to API 580 (2002), four major deterioration mechanisms are observed in the hydrocarbon and chemical process industry:

a. Thinning.

b. Stress corrosion cracking.

c. Metallurgical and environmental.

d. Mechanical.

4.2.1 Thinning Deterioration

Thinning is the most common damage mechanism that causes leak in process component system. Thinning can be defined as the loss of material due corrosion. The effects of thinning can be determined from measuring the original thickness of the material and its current thickness, corrosion allowance and corrosion rate. Thinning includes a number of damage mechanisms that can cause loss of material from internal or external surfaces. Thinning can be caused by either a general corrosion or localized corrosion. General thinning is usually observed in carbon steel or copper, while localized thinning and pitting usually occurs in stainless steels and higher alloy materials.

1. General thinning. According to API 580 (2002) includes the following degradation mechanisms:
    - Amine Corrosion: generally caused by desorbed acid gases or amine deterioration products.
    - Atmospheric Corrosion: General uniform corrosion occurs under atmospheric conditions where carbon steel is converted to iron dioxide.
    - Corrosion Under Insulation: A specific case of atmospheric corrosion.
    - High Temperature Sulfidic Corrosion: General uniform corrosion occurs in all locations with temperature above 450°F with the present of 2% sulfur or more.
    - Oxidation: General uniform corrosion where metal is converted to a metal oxide above specific temperatures.

- Soil Corrosion: highly observed in tank bottoms and underground piping.

2. Localized thinning. According to API 580 (2002) includes the following degradation mechanisms:
   - Ammonia Bisulfide Corrosion: Localized corrosion in carbon steel and admiralty brass. Formed by catalytic cracking, coking, hydrocracking, amine treating and sour water effluent and gas separation systems.
   - Carbon dioxide Corrosion: happens often in refinery steam condensate systems, hydrogen plants, and vapor recovery section of the catalytic cracking unit.
   - Galvanic Corrosion: Localized corrosion occurs when two metals are joined and exposed to an electrolyte.
   - Hydrochloric Acid Corrosion: Localized corrosion in carbon and low alloy steel.
   - Hydrofluoric Acid Corrosion: Localized corrosion that occurs often in Hydrofluoric acid alkylation units.
   - Naphthenic Acid Corrosion: Localized corrosion attacks steel alloys when the organic acids are condensed in the range of 350°F to 750°F.
   - Phenol Corrosion: Localized carrion usually happens in heavy oil and dewaxing plants.

- Phosphoric Acid corrosion: Localized corrosion generally occurs in water treatment plants.

The state function ($g_{thinning}$) can be applied on thinning that cause material loss on the internal or external surfaces of the component. The state function is based on the material resistance minus the applied stress. Kallen (2002) defined the state function as

$$g_{thinning} = \text{material resistance} - \text{applied stress} \qquad \ldots (4\text{-}1)$$

$$= S\left(1 - \frac{C \times \Delta t}{d}\right) - \left(\frac{P \times D}{2 \times d}\right) \qquad \ldots (4\text{-}2)$$

Where

S is residual stress in MPa,

C is corrosion rate in mm/yr,

P is operating pressure in bar,

D is the diameter of the component in mm,

d is the material thickness in mm,

and Δt is a time increment.

Kallen (2002) defined the residual stress S as

$$S = \min\{1.1(YS+TS)/2, TS\} \qquad \ldots (4\text{-}3)$$

Where

YS is the material yield strength in MPa.

TS is the material tensile strength in MPa.

The material tensile and yield strengths are determined by the material grade. One of the most common systems for the classification of material grade is developed by the American Society of Mechanical Engineers (ASME) and (ASTM) the American Society for Testing and Materials (Wintel, Kenzie, Amphlett, and Smalley, 2001). Knowing the material grade is a key to find all material properties, including the tensile and the yield strengths.

The state function ($g_{thinning}$) is a measure of the ability of the material to resist failure due to thinning. It can be used to determine the time at which a component is expected to fail. As long as $g_{thinning} > 0$ the unit is considered to function safely. At the limit state when $g_{thinning} = 0$ the unit fails.

4.2.2 Stress Corrosion Cracking Deterioration

Stress corrosion cracking (SCC) is the cracking of normally ductile metals induced from the combined influence of tensile stress and a corrosive environment especially at elevated temperature. Stress corrosion cracking is a dangerous type of failure as it can occur without an externally applied load or at loads significantly below yield stress. Thus, catastrophic failure can occur without significant deformation or obvious deterioration of the component. Pitting is commonly associated with stress corrosion cracking phenomena (API 581, 2000).

Stress corrosion cracking comprises different cracking mechanisms such as amine cracking, ammonia cracking, caustic cracking, chloride cracking (CISCC), hydrogen induced cracking (HIC), sulfide stress cracking (SSC), hydrogen blistering, hydrogen cyanide cracking, and polythionic acid cracking (API 581, 2000).

Amine cracking is cracking of a metal under the combined actions of corrosion and tensile stress in environments containing aqueous alkanolamine solution at elevated temperatures. Carbon steels and low alloy steels are susceptible to amine cracking. Amine cracking usually occurs in amine treating units, where amine is used in gas treatment to remove dissolved CO_2 and H_2S acid gases (API 581, 2000).

Ammonia cracking is generally present in ammonia production and handling units. Ammonia cracking causes damage to carbon steel and copper zinc alloys (API 580, 2002).

Caustic cracking is cracking of a metal under the combined actions of corrosion and tensile stress caused by caustic (sodium or potassium hydroxide) at elevated temperatures. It is primarily initiated in carbon steel equipment, primarily due to fabrication or residual stress (API 581, 2000).

Chloride stress corrosion is one of the most important forms of stress corrosion that concerns the nuclear industry. Chloride stress corrosion occurs in austenitic stainless steel under tensile stress in the presence of oxygen, chloride ions, and high temperature. It is thought to start with chromium carbide deposits along grain boundaries that leave the metal open to corrosion. This form of corrosion is controlled by maintaining low chloride ion and oxygen content in the environment and use of low carbon steels (API 580, 2002).

Hydrogen-induced cracking (HIC) can occur in carbon and low alloy steel materials exposed to aqueous environments containing hydrogen sulfide (H_2S). Deterioration of the material properties is caused when nascent hydrogen atoms (H^o) diffuses into the material and reacts with other nascent hydrogen atoms to form molecular hydrogen gas in inclusion of the steel (API 581, 2000).

Sulfide stress cracking (SSC) occurs in carbon and low alloy steel materials exposed to aqueous environments containing hydrogen sulfide. SSC usually occurs more readily in high hardness steels in hard weld deposits or heat effected zones of lower strength steels. Deterioration takes the form of cracking in improperly stress relived equipments (API 581, 2000).

Hydrogen blistering is a type of hydrogen-induced failure produced when hydrogen atoms enter low-strength steels that have macroscopic defects. It occurs usually in sour environments and it does not cause a brittle failure but it can produce rupture or leakages (API 580, 2002).

Water solutions of hydrogen cyanide cause stress-cracking of carbon steels under stress even at room temperature and in dilute solution, and water solutions of hydrogen cyanide containing sulfuric acid as a stabilizer severely corrode steel above 40 degrees C (API 580, 2002).

Polythionic acid cracking (PTA) is the cracking of austenitic stainless steels in the sensitized condition in the presence of polythionic acid in wet ambient conditions. Polythionic acid cracking causes damage in the petroleum refining industry, particularly in catalytic cracking, desulfurizer, hydrocracker, and catalytic reforming processes (API 580, 2002).

Susceptibility of equipment to stress corrosion cracking depends on five main factors:

1. Material of construction.
2. Stress corrosion cracking mechanisms.
3. Operating temperature and pressure.
4. Concentration of key process corrosives such as pH.
5. Fabrication variables such as post weld heat treatment.

Paris and Erdogan (1963) developed a crack rate law for use in linear elastic homogeneous materials. Paris law is only applicable in the propagation phase; it assumes the crack advances when any stress is applied (Grant, 2001). Based on Paris low the stress corrosion cracking state function uses a resistance minus stress model. Kallen (2002) defined the stress corrosion cracking state function as

$$g_{scc} = \text{material resistance} - \text{applied stress} \qquad \ldots(4\text{-}4)$$

$$= K_{IC} - Y\left(\frac{PD}{2d} + S\right)\sqrt{\pi A} \qquad \ldots(4\text{-}5)$$

Where

K_{IC} is the material fracture toughness in MPa $\sqrt{\text{mm}}$,

Y is a dimensionless geometric factor,

P is operating pressure in bar,

D is the diameter of the component in mm,

d is the material thickness in mm,

S is residual stress in MPa,

and A is the crack depth in mm.

The material fracture toughness for stainless steel equals to 300 Ksi (in) $^{1/2}$, and for carbon and low alloy steel can be calculated using the following equation (Kallen, 2002):

$$K_{IC} = Minimum\{33.2 + 2.806\exp\{0.02(T + 100)\}, 200\} ksi\sqrt{in} \qquad \ldots(4\text{-}6)$$

where T is the operating temperature.

According to Kallen (2002), the crack depth A can be obtained using the following equation:

$$A = l \div R_{l/a} \quad \ldots (4\text{-}7)$$

Where

l is the crack length in mm

$R_{l/a}$ is the crank length to depth ratio.

According to Kallen (2002), the crack length is determined by:

$$l = C \times \Delta t^n \quad \ldots (4\text{-}8)$$

Where

C is the crack growth rate.

Δt is the time since the service start of the component.

4.2.3 Metallurgical and Environmental Deterioration

Metallurgical and environmental failure is the mechanical and/or physical property deterioration of the metal due to exposure to the process environment.

According to API 580 (2002), carburization, decarburization, high temperature hydrogen attack, grain growth, graphitization, sigma phase embrittlement, 885°F embrittlement, temper embrittlement, liquid metal embrittlement, , and metal dusting are examples of metallurgical and environmental failure.

Carburization is the carbon diffusion into the surface of steel due to interactions with the environment at elevated temperatures. The increased carbon content leads to an increase in the hardenability of ferritic steels and some stainless steels (API 580, 2002).

Decarburization is the decrease of the carbon content from the surface of a ferrous alloy as a result of heating in a medium that reacts with carbon. The decreasing carbon content causes a degradation of these properties, as the hardness as well as the strength decrease. However, the elongation of the metal when subjected to a tensile stress increases (API 580, 2002).

HTHA damage can take two forms, internal decarburization and fissuring from the accumulation of methane gas at the carbide matrix interface and surface decarburization from the reaction of the atomic hydrogen with carbides at or near the surface (API 581, 2000).

High temperature hydrogen attack (HTHA) occurs in carbon and low alloy steels in the presence of high temperature and hydrogen. HTHA occurs as a result of atomic hydrogen diffusing through the steel and reacting with carbides in the microstructure. Two reactions associated with HTHA. The first reaction is the dissociation of hydrogen molecule to form atomic hydrogen. This reaction occurs more readily at high temperatures and high hydrogen partial pressure. The second reaction occurs between atomic hydrogen and the metal carbides.

$$H_2 \rightleftharpoons 2H$$

$$4H + MC \rightleftharpoons CH_4 + M$$

Grain growth occurs when steels are heated above a certain temperature, beginning about 1100°F for carbon steel and most pronounced at 1350°F. Austenitic stainless steels and high nickel chromium alloys are subjected to grain growth when it is heated to above 1650°F. Grain growth is usually observed in furnace tubes and equipments susceptible to run-away reactions (API 580, 2002).

Graphitization occurs when the normal pearlite grains in steels decompose into soft weak ferrite grains and graphite nodules usually due to long term exposure in the 825°F to 1400°F range. It occurs in fluid catalytic cracking (FCC) units (API 580, 2002).

Sigma phase is a non-magnetic intermetallic phase produces loss of ductility, toughness and is generally strain intolerant at temperatures under. Sigma phase embrittlement occurs in ferritic and austenitic stainless steels with more than 17%

chromium during exposure at 1000°F – 1500°F for extended time periods (API 580, 2002).

885°F embrittlement causes a loss of ambient temperature ductility. 885°F embrittlement occurs after aging of ferritic stainless steels exposed to temperature range of 650°F to 1000°F (API 580, 2002).

Temper embrittlement occurs in low alloy steels during exposure to temperature range of 700°F – 1050°F for a long time period. Temper embrittlement produces a loss in toughness that can lead to a brittle fracture (API 580, 2002)..

Liquid metal embrittlement is a corrosive degradation forms catastrophic brittle failure of normally ductile metals such as stainless steel copper based alloy in the presence of certain liquid metals such as mercury, zinc, lead, cadmium (API 580, 2002)..

Metal dusting is a highly localized carburization of steels in environments containing mixtures of hydrogen, methane, carbon monoxide, CO_2, and light hydrocarbons in the temperature range of 900°F – 1500°F (API 580, 2002).

4.2.4 Mechanical Deterioration

According to API 580 (2002), the most common mechanical deterioration mechanisms are corrosion-fatigue, mechanical and thermal fatigue; brittle fracture; cavitation; stress/creep rupture; and tensile overload.

Corrosion-fatigue is a form of fatigue results from the combined action of an alternating or cycling stresses and a corrosive environment where pitting corrosion promotes the mechanical fatigue process. The fatigue process causes rupture of the protective passive film, upon which corrosion is accelerated (API 580, 2002).

Mechanical fatigue causes failure of a component by cracking after the continued application of cyclic stress which exceeds the material's endurance limit. If mechanical fatigue develops until catastrophic failure it usually involves nucleation of permanent structural damage, nucleation of microcracks, growth and coalescence of microcracks to form a dominant crack, propagation of the dominant crack, and at the end unstable fracture (API 580, 2002).

Thermal fatigue is a process cyclic change in stress in a material due to cyclic change in temperature. Coke drums, bypass valves and piping with heavy weld reinforcement on reactors in cyclic temperature service are subject to thermal fatigue (API 580, 2002).

Brittle fracture is a rapid run of cracks through a stressed material. It causes loss of ductility wherein the steel is referred to as having low notch toughness or poor impact strength (API 580, 2002).

Cavitations occur when a fluid's operational pressure drops below its vapor pressure causing gas pockets and bubbles to form and collapse. This can occur in what can be a rather explosive and dramatic fashion (API 580, 2002).

Stress rupture is failure of a metal at elevated temperatures under applied stress below its normal yield strength (API 580, 2002).

Creep is a high temperature mechanism wherein continuous plastic deformation of a metal takes place while under stress below the normal yield strength. The rate of creep damage is a function of the material properties and the exposure time, exposure temperature and the applied load (stress). When evaluating components that operate under high stresses or temperatures, creep is usually a concern to engineers and metallurgists. Creep is not necessarily a failure mode, but is instead a damage mechanism (API 580, 2002).

Tensile overloading occurs when loads exceeds the maximum allowable or permitted by design are applied to the equipment (API 580, 2002).

4.3 Gamma Deterioration Process

Although the degradation of the material mechanisms are determined to be deterministic, there is a level of uncertainty associated with some of their variables. Therefore, these variables have to be considered random and the material degradation process is expected to be a stochastic process (Kallen, 2002).

According to Kallen (2002), the stochastic process $\{X(t): t \geq 0\}$ is a continuous time process that consists of a collection of random variables, where t is interpreted as time and X (t) is the state of the process at time t.

Here X (t) is defined as the amount of material deterioration at time t. A non-negative distribution is needed to describe the deterioration process; the probability of a negative increment would be interpreted as a sudden increase in the construction material quality. Therefore, a gamma distribution is used to describe the material deterioration process (Kallen, 2002).

Kallen (2002) defined the gamma density with shape parameter $\alpha > 0$ and scale parameter $\beta > 0$ as:

$$Ga(x/\alpha,\beta)=\frac{\beta^{\alpha}}{\Gamma(\alpha)}\left(\frac{1}{x}\right)^{-\alpha+1}\exp\{-\beta x\} \qquad \text{for } x\geq 0 \qquad \ldots (4\text{-}9)$$

The continuous time gamma process {X (t): t ≥ 0} with shape function at > 0, t≥ 0 and scale parameter > 0 has the following properties:

1. $X(0) = 0$ with probability 1,

2. $X(\tau) - X(t) \sim \mathrm{Ga}(a(\tau - t), b)$ for all $\tau > t \geq 0$,

3. $X(t)$ has independent increment.

According to Kallen (2002), the probability density function of $X(t)$ is given by:

$$f_{X(t)}(x) = \mathrm{Ga}\,(x/at,\, b) \qquad \ldots (4\text{-}10)$$

The mean and variance of $X(t)$ are given by:

$$E(X(t)) = \frac{a}{b}t \qquad \ldots (4\text{-}11)$$

$$Var(X(t)) = \frac{a}{b^2}t \qquad \ldots (4\text{-}12)$$

For the cumulative deterioration function $X(t)$ at time t, E ($X(t)$) = μ t and Var($X(t)$) = σ^2 t . Therefore, Kallen (2002) defined μ and σ^2 as:

$$\frac{a}{b} = \mu \text{ and } \frac{a}{b^2} = \sigma^2 \qquad \ldots (4\text{-}13)$$

According to Kallen (2002), the probability density function for the cumulative deterioration function $X(t)$ is given by

$$f_{X(t)}(x) = \mathrm{Ga}\left(x \middle| \frac{\mu^2 t}{\sigma^2}, \frac{\mu}{\sigma^2}\right). \qquad \ldots (4\text{-}14)$$

In order to keep the method practical and easy to use for the plant engineer the standard deviation σ relative to the mean μ should be fixed through the use of a coefficient of variation *v*. Kallen (2002) defined the coefficient of variation *v* as:

$$v = \sigma / \mu \qquad \ldots (4\text{-}15)$$

Using this relationship, Kallen (2002) rewrite the gamma density function for corrosion as:

$$f_{X(t)}(x) = \mathrm{Ga}\left(x \middle| \frac{t}{v^2}, \frac{1}{\mu v^2}\right)$$

$$= \frac{\left(\frac{1}{\mu v^2}\right)^{\frac{t}{v^2}}}{\Gamma\left(\frac{t}{v^2}\right)} (x)^{\frac{t}{v^2}-1} \exp\left\{-\frac{x}{\mu v^2}\right\} \qquad \ldots (4\text{-}16)$$

4.4 Prior and Posterior Deterioration Distributions

The prior knowledge of the average degradation rate (μ) can be effectively updated using the results of previous inspections. Kallen (2002), Kallen and Noortwijk (2003), and Khan *et al.*(2005) used Bayes's theorem to do this updating. The updating modeling involves selecting an appropriate prior, and Bayesian updating of the prior using new inspection data which can be applied for the two cases: perfect or imperfect inspection data.

Kallen (2002) defined the prior density $\pi(\mu \setminus x)$ as:

$$\pi(\mu \setminus x) = \frac{l(x \setminus \mu)\pi(\mu)}{\int_{\mu=0}^{\infty} l(x \setminus \mu)\pi(\mu)d\mu} \qquad \ldots (4\text{-}17)$$

where μ is the mean corrosion rate and $l(x \setminus \mu)$ is the likelihood of a measurement x given μ.

Kallen (2002) defined the posterior density in the case of multiple perfect inspections as:

$$\pi(\mu \setminus x_1, \ldots, x_n) = I_g\left(\mu \left| \frac{\sum_{i=1}^{n} t_i - t_{i-1}}{v^2} + \alpha, \frac{\sum_{i=1}^{n} x_i - x_{i-1}}{v^2} + \beta \right.\right) \qquad \ldots (4\text{-}18)$$

Where α is the shape parameter of the gamma function, β is the scale parameter of the gamma function, and v is the coefficient of variation

According to Kallen (2002), the posterior of multiple imperfect inspections is given by:

$$p(\mu_i \setminus y) = \frac{p(\mu_i)\frac{1}{N}\sum_{j=1}^{N}\prod_k Ga\left(d_k - \min\{\delta_k^j, d_k\} \middle| \frac{\Delta t_k}{v^2}, \frac{1}{\mu v^2}\right)}{\sum_{i=1}^{n} p(\mu_i)\frac{1}{N}\sum_{j=1}^{N}\prod_k Ga\left(d_k - \min\{\delta_k^j, d_k\} \middle| \frac{\Delta t_k}{v^2}, \frac{1}{\mu v^2}\right)} \quad \ldots (4\text{-}19)$$

Where

$$\delta_k = \varepsilon_k - \varepsilon_{k-1} \qquad \ldots (4\text{-}20)$$

$$d_k = y_k - y_{k-1} \qquad \ldots (4\text{-}21)$$

And

$$\Delta t_k = t_k - t_{k-1}. \qquad \ldots (4\text{-}22)$$

4.5 Replacement and Failure Probabilities

According to Kallen and Noortwijk (2004), the cumulative deterioration gamma distribution at time t is given by:

$$F_{X(t)}(x) = \Pr\{X(t) \le x\}$$

$$= \int_{\theta=0}^{x} \frac{\beta^{\alpha(t)}}{\Gamma(\alpha(t))} \theta^{\alpha(t)-1} \exp(-\beta\theta) d\theta$$

$$= \frac{\gamma(\alpha(t), \beta x)}{\Gamma(\alpha(t))}, \quad \text{for } x \geq 0. \qquad \ldots(4\text{-}23)$$

According to Kallen and Noortwijk (2004), the term $P(a,x) = \frac{\gamma(a,x)}{\Gamma(a)}$ for $a > 0$ and $x \geq 0$ is the incomplete gamma function.

For a nonrandomized inspection plan, the time interval between two inspections is Δk years and inspections are carried out at times $j\Delta k$ ($j \geq 1$). The amount of deterioration at time $j\Delta k$ is represented by the simplified notation $X_j \equiv X(j\Delta k)$.

The probability of no replacement after an inspection at time (j-1) Δk and a failure at time $j\Delta k$ according to Kallen and Noortwijk (2004) is given by:

$$\Pr\{X_{j-1} \leq r, X_j > s\} = \Pr\{X_{j-1} \leq r, X_j - X_{j-1} > s - X_{j-1}\} \quad \ldots(4\text{-}24)$$

Where r and s represents the replacement and failure conditions respectively, and 0 < r <s.

Using the fact that the increments in the gamma process are independent, Kallen and Noortwijk (2004) defined the probability of no replacement after an inspection at time (j-1) Δk and a failure at time $j\Delta k$ as:

$$\Pr\left\{X_{j-1} \le r, X_j > s\right\} = \int_{\theta=0}^{r} \int_{\phi=s-\theta}^{\infty} f_{X_{j-1}}(\theta) F_{X_j - X_{j-1}}(\phi) d\phi d\theta$$

$$= F_{X_{j-1}}(r) - F_{X_j}(s) + \int_{\theta=r}^{s} f_{X_{j-1}} F_{X_j - X_{j-1}}(s-\theta) d\theta \quad \ldots (4\text{-}25)$$

Kallen and Noortwijk (2004) defined the probability of X(t) passing the replacement condition level during the inspection interval (j-1,j) as:

$$\Pr\left\{X_{j-1} \le r, X_j > r\right\} = F_{X_{j-1}}(r) - F_{X_j}(r) \qquad \ldots (4\text{-}26)$$

Using these results, all the possible probabilities can be easily determined.

4.6 Reducing Risk through Inspection

The risk of system failure due to material deterioration mechanisms is achieved through building a posterior material degradation rate for both cases perfect and imperfect inspection based on the prior knowledge of the damage rate in the material of construction. Now the inspection time is chosen so that the risk is maintained to have the minimum possible value.

The American petroleum institute API in its base resource document API 581 (2000) has built an approach of inspection planning that aims to have an inspection program keeps the risk of damage due to deterioration mechanisms as low as possible through maintaining a low value of the damage factor. The approach can be applied to pressurized vessel systems in both cases of thinning and stress corrosion cracking deterioration mechanisms. The approach differentiates between different inspection levels where different inspection techniques are applied: highly effective, usually effective, fairly effective, and poorly effective inspections. The highly effective inspection can correctly identify the anticipated in-service damage in nearly every case. It can identify the anticipated in-service damage mechanisms with ninety percent efficiency. The assessment of general corrosion in the highly effective inspection is done by complete internal visual examination coupled with ultrasonic thickness measurements.

According to API 581 (2000) usually effective inspections can correctly identify the actual damage state most of the time. It can identify the anticipated in-service damage mechanisms with 70% efficiency. The assessment of general corrosion during inspections is done by partial internal visual examination coupled with ultrasonic thickness measurements. Fairly effective inspections can correctly identify the true damage state about half of the time. The assessment of general corrosion in fairly effective inspections is done by external spot ultrasonic thickness measurements. Less effective inspection methods do not provide information that can correctly identify the true damage state. Damage identification efficiency in such cases are less than33%.

According to API 581 (2000) applying the risk reducing approach of inspection planning is carried out following four steps:

1. Calculate the ratio *ar/t.*

The ratio *ar/t* represents time in current service (a) times the corrosion rate (r) divided by the original material thickness (t). This ratio can be calculated easily; the original material thickness is a known value, and the corrosion rate with time is estimated using the stochastic gamma deterioration model. The gamma function models the material corrosion rate by developing a prior and a posterior density function for the material deterioration. The gamma model, and the prior and the posterior density functions are given in sections 4.3 and 4.4.

2. Calculate the over-design factor.

The over design factor is a correction factor that will be applied to the damage factor. According to API 581 (2000), the over-design factor is calculated using the following formula:

$$\text{Over-design factor} = \frac{t_{original}}{t_{original} - C.A.} \qquad \ldots (4\text{-}27)$$

Where

$t_{original}$ is the original material thickness.

C.A. is the corrosion allowance.

The over design factor can be also determined by calculating the ratio between the designed pressure and operating pressure.

3. Estimate the correction factor

The correction factor is estimated based on the value of the over-design factor. Table 4.1 illustrates the values of the correction factor. It is necessary to estimate the correction factor because the damage sub-factor estimated from the chart is based on materials with 25% corrosion allowance.

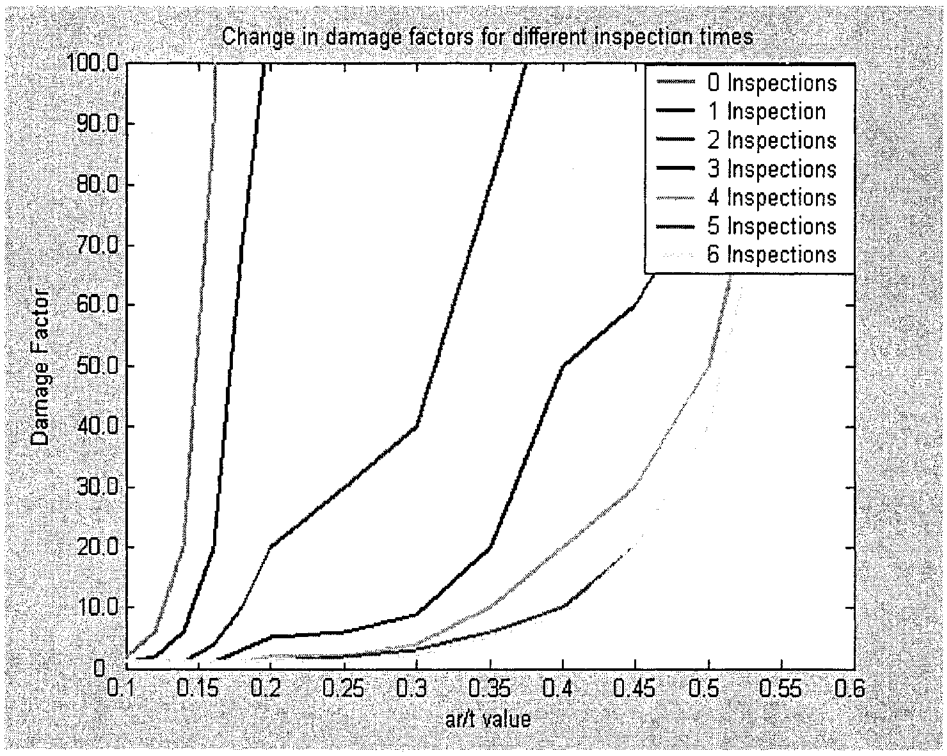
Table 4.1 Correction factor

Over-design Factor	Correction Factor
<1.1	2.0
1.1–1.5	1.0
>1.5	0.5

4. Determine the damage factor.

The damage factor can be determined from the damage factor chart that is given by the API 581 (2000). Figure 4.3 shows the change in the damage factor value when carrying a number of inspections for the case of having a usually effective inspection. After finding the damage sub-factor value using figure 4.3 it is multiplied with the correction factor. It should be noted that the correction factor should not be applied to damage sub-factors of one.

Figure 4.3: Damage factor for different inspection times.



5. Find the appropriate inspection time.

The appropriate inspection time is the time which keeps the damage factor as low as possible. According to API 581 (2000) damage factors should be usually kept close to one by inspection activities of a moderate extent. Damage factor values exceeding ten should be avoided.

The following example illustrates the methodology of estimating the damage sub-factor: A pressure vessel with an original wall thickness of 25 mm is subjected to a localized thinning with a corrosion rate of 0.143 mm/year. The corrosion allowance for this vessel is 6.5 mm. Determine the optimal inspection interval for this vessel knowing that it was in-service since 2000, and no previous inspections were carried on?

Solution:

1. Calculate the ratio *ar/t.*

a = equipment age = 7 years.

r = corrosion rate = 0.143 mm/year.

t = original thickness = 25 mm.

$$\frac{ar}{t} = \frac{7 \times 0.143}{25} = 0.04$$

2. Calculate the over-design factor.

$$\text{Over-design factor} = \frac{t_{original}}{t_{original} - C.A.}$$

$$= \frac{25}{25 - 6.5} = 1.35$$

3. Estimate the correction factor

Using table 3.1; for an over-design factor value between 1.1 and 4.5 the correction factor equals to one.

4. Determine the damage sub-factor.

Using figure 4.3; for 0 number of inspections and *ar/t* equals to 0.04, the damage sub-factor equals to 1.

CHAPTER 5

CASE STUDIES

The risk based inspection model described in chapter four is used to determine the optimal inspection, replacement, and failure times for two cases of study: molecular sieve vessel, and distillate hydrotreater reactor. The two cases of study are adopted from Geary (2002).

5.1 Case 1: Molecular Sieve Vessel

The molecular sieve vessel commissioned in 1982 under the design standard BS5500. The molecular sieve vessel has the following dimensions: 2374mm diameter, 16000 mm length. The maximum designed temperature equals to 350°C, and the minimum designed temperature equals to -62°C. The maximum operating temperature equals to 320°C, and the minimum operating temperature equals to 0°C. The maximum designed pressure is 121 barg, the minimum designed pressure is 0 barg, the maximum operating pressure is 115 barg, and the normal operating pressure is 110 barg. Three inspections were carried on the molecular sieve vessel in the years 1986, 1992, and 2000. Through theses inspections the following damage mechanisms were observed: pitting corrosion, hydrogen induced cracking and sulphide SCC (Geary, 2002). These types of damage mechanisms are listed in the stress corrosion cracking deterioration mechanism. The case study data for the molecular sieve vessel is shown in table 5.1.

Table 5.1: Molecular sieve vessel

Component type	Vessel
Material Type	Low temperature Carbon steel Grade BS 1501-225-490B-LT62
Service start	1982
Initial material thickness	20 mm*
Drum diameter	2374 mm
Tensile strength	448.16 MPa
Yield strength	206.84 MPa
Operating pressure	110 bar
Corrosion rate	0.1 mm/yr**
Corrosion Allowance	4.0 mm
Inspections carried on previously	1986 : 19.9 mm wall thickness** 1992 : 19.1 mm wall thickness** 2000 : 18.2 mm wall thickness**

* The value of the material thickness is changed to give a realistic value of the failure time.

** These values were assumed since it was not mentioned clearly in Geary (2002). It was estimated after carrying sensitivity analysis that studies the effect of changing the input data like wall thickness and corrosion rate on the optimal replacement and failure times. The sensitivity analysis is provided in Appendix B.

Finding the optimal inspection time according to the API approach concerns with maintaining the risk of failure for the inspected equipment item in a safe level risk, it does focus on keeping the equipment damage factor near to one and try to avoid damage factor values of ten or more. In order to do so, the steps illustrated in section 4.6 should be followed. The first step is to calculate the ratio *ar/t* where: *a* is the equipment age, *r* is the corrosion rate, and *t* is the original material thickness. Now the need of the gamma function rises up to estimate the material corrosion rate behavior with the increasing age of the equipment.

The stochastic gamma function described in section 4.3 is used to generate the prior and posterior deterioration mechanism functions which are used to find the ratio *ar/t*, where the assumed effective deterioration mechanism in this case study is stress corrosion cracking. The prior density function is given by equation (4-17), the posterior density for a multiple perfect inspections is given by equation (4-18), and the posterior density for a multiple imperfect inspections is given by equation (4-19).

For more details about the prior and posterior density functions please see chapter four. The MATLAB code used to estimate the prior and posterior density functions for this case study is given in Appendix A. The prior and posterior density functions for 2000 simulations with measurement error of 0.3 times of standard deviation are shown in figure 5.1.

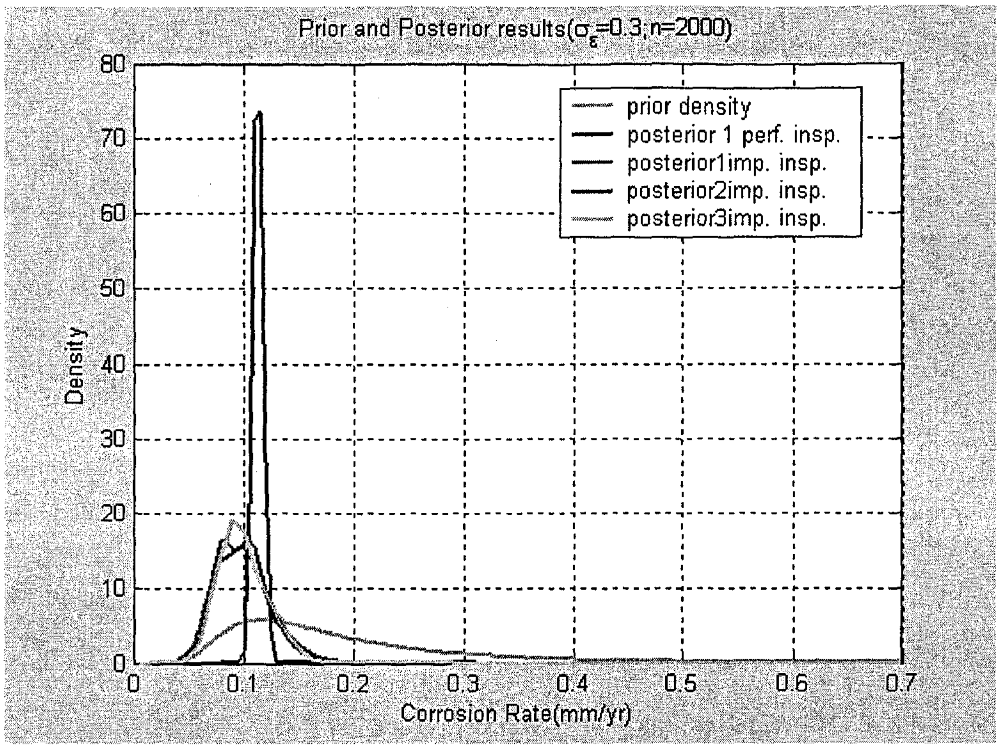


Figure 5.1: Prior and posterior densities for perfect and imperfect inspections (result of probability analysis).

After finding the prior and posterior deterioration mechanism functions, the ratio *ar/t* is estimated. Five hundred simulations where done to estimate the ratio *ar/t*. The MATLAB code used to estimate *ar/t* values while the equipment becoming older for this case study is given in Appendix A. Figure 5.2 show the estimated ratio *ar/t* with the increase in equipment age.

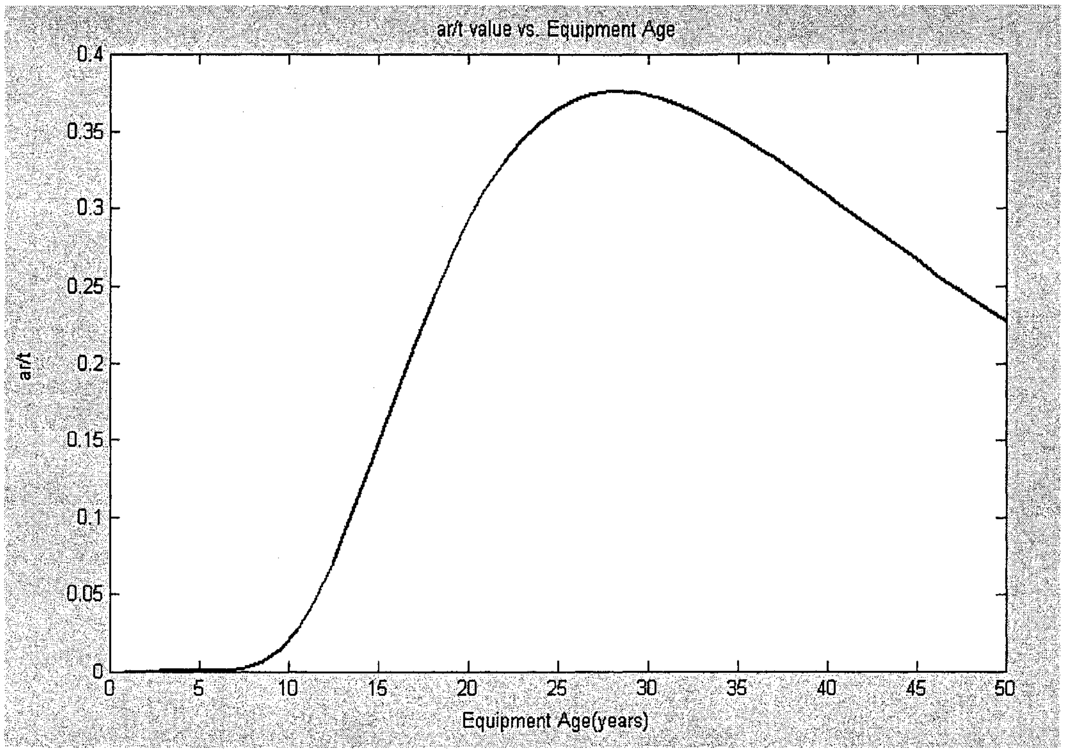


Figure 5.2 *ar/t* values (estimated using expression) with the increase in equipment age

Now the second step according to the API approach is to calculate the over-design factor. The over-design factor is estimated by:

$$\text{Over-design factor} = \frac{t_{original}}{t_{original} - C.A.}$$

$$= 20/\,(20\text{-}4) = 1.25$$

The third step according to the API 581(2000) is to estimate the correction factor. The correction factor is estimated based on the over design factor using table 4.1. It is found from the table that, for an over-design factor value between 1.1 and 1.5 the correction factor equals to one. So, the correction value is equal to one in this case study.

The fourth step according to the API approach is to estimate the material damage factor. A figure that shows the damage factor for different number of inspections is provided in section 4.6. The MATLAB code developed to estimate the change in damage factor with time is provided in appendix A. Figure 5.3 shows the change in the damage factor with time.

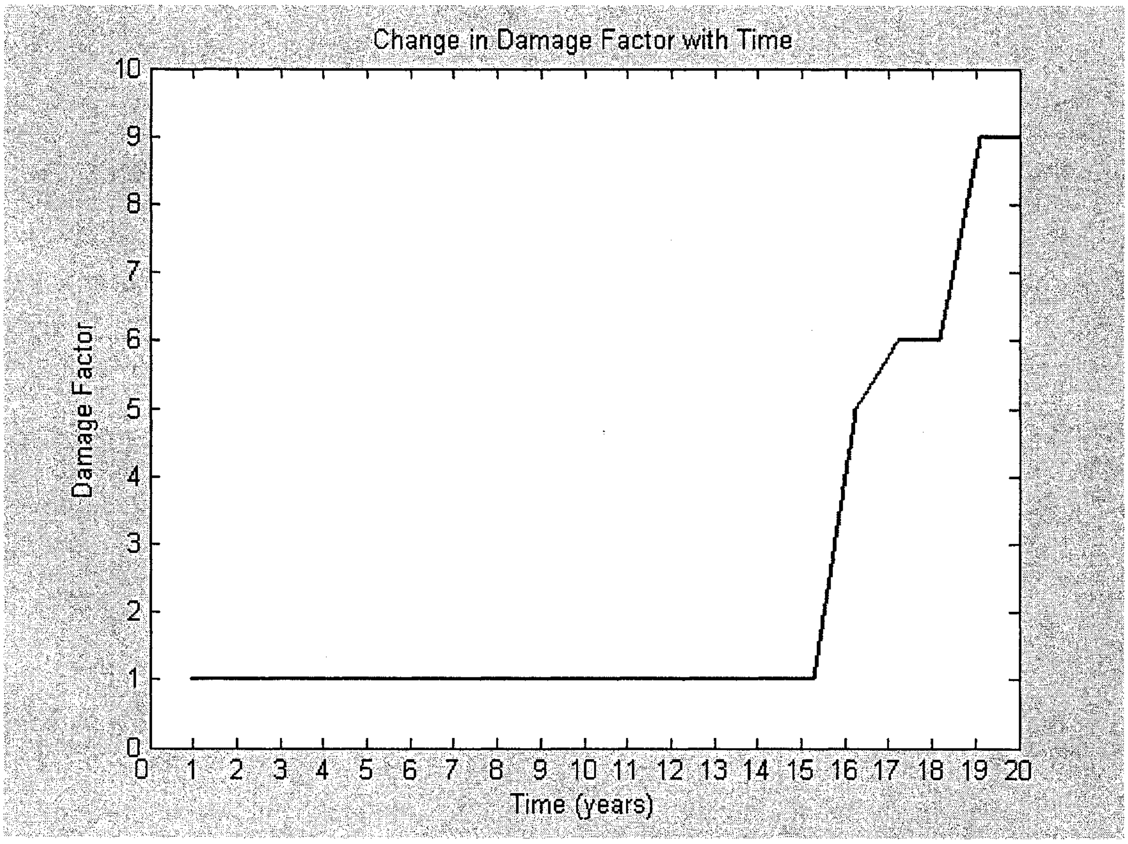


Figure 5.3 Change in the damage factor (estimated using expression) with time.

The last step in the API approach is to find the optimal inspection time. From figure 5.3, it is clear that the damage factor for the molecular sieve vessel material starts to increase after fifteen years, so the inspection should be carried on at that time. The optimal inspection time is found to be after 15.3 years.

By combining the API approach with the stochastic gamma model approach developed by Kallen (2002), we can go further more to find the expected replacement and failure times. Replacement and failure probabilities are provided in section 4.5. The MATLAB code for the molecular sieve vessel case study which is provided in appendix A calculates the optimal replacement and failure times for 500 simulations. It was found that the expected replacement and failure times are found to be 40.50yr and 199.0yr., respectively.

5.2 Case 2: Distillate Hydrotreater Reactor

The distillate hydrotreater reactor commissioned in 1988. Two inspections were carried on the distillate hydrotreater reactor in the years 1992 and 2002. The case study data for the distillate hydrotreater reactor is shown in Table 5.4.

Table 5.4: Distillate hydrotreater reactor

Component type	Vessel
Material Type	Low alloy steel
Service start	1988
Initial material thickness	40 mm*
Drum diameter	3977 mm
Tensile strength	420 MPa
Yield strength	350 MPa
Operating pressure (inlet)	59 Kg/cm^2
Operating pressure (outlet)	36 Kg/cm^2
Corrosion rate	0.19 mm/yr**
Corrosion Allowance	6.0 mm**

Inspections carried on previously	1992 : 38.9 mm wall thickness 2002 : 37.5 mm wall thickness

*The value of the material thickness is changed to give a realistic value of the failure time.

** These values were assumed since it was not mentioned clearly in Geary (2002). It was estimated after carrying sensitivity analysis that studies the effect of changing the input data like wall thickness and corrosion rate on the optimal replacement and failure times. The sensitivity analysis is provided in Appendix B.

Several damage mechanisms are assumed to be active like: H_2 corrosion, H_2S corrosion, high temperature hydrogen attack, and SCC (Geary, 2002). Most of these damage mechanisms are listed in the stress corrosion cracking deterioration mechanism.

Finding the optimal inspection time according to the API approach comes in five steps. The first step is to calculate the ratio *ar/t* where. The API approach finds this ratio by taking an average value for the corrosion rate and estimating that this value will remain constant with time. Now after combining the API approach with the probabilistic approach developed by Kallen (2002), the gamma function is used to estimate the material corrosion rate behavior with the increasing age of the equipment for n number of simulations which gives more accurate results.

The stochastic gamma function described in section 4.3 is used to generate the prior and posterior deterioration mechanism functions which are used to find the ratio *ar/t*. More details about the prior and posterior density functions and how they are developed please see chapter four. The MATLAB code used to estimate the prior and posterior density functions for this case study is given in Appendix A. The prior and posterior density functions for 2000 simulations with measurement error of 0.3 times of standard deviation are shown in figure 5.4.

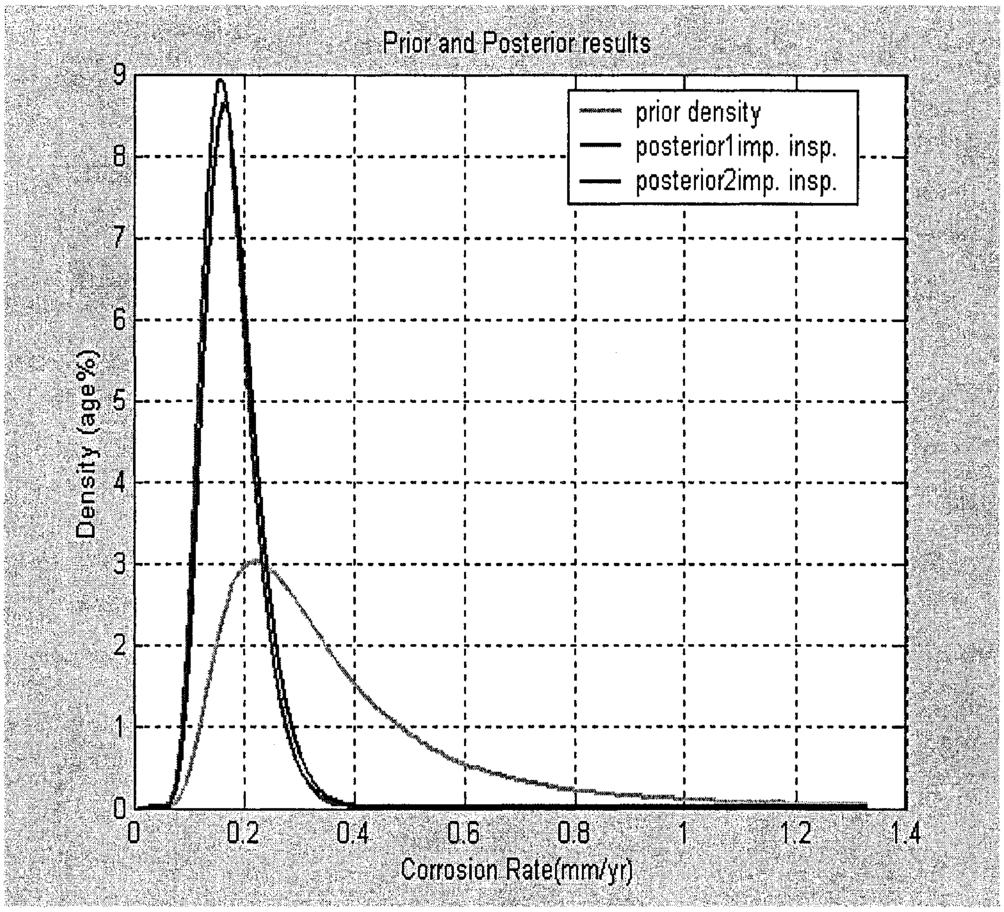


Figure 5.4: Prior and posterior densities for imperfect inspections (result of probability analysis).

After finding the prior and posterior deterioration mechanism functions, the ratio *ar/t* is estimated. Five hundred simulations where done to estimate the ratio *ar/t*. The MATLAB code used to estimate *ar/t* values while the equipment becoming older for this case study is given in Appendix A. Figure 5.5 show the estimated ratio *ar/t* with the increase in equipment age.

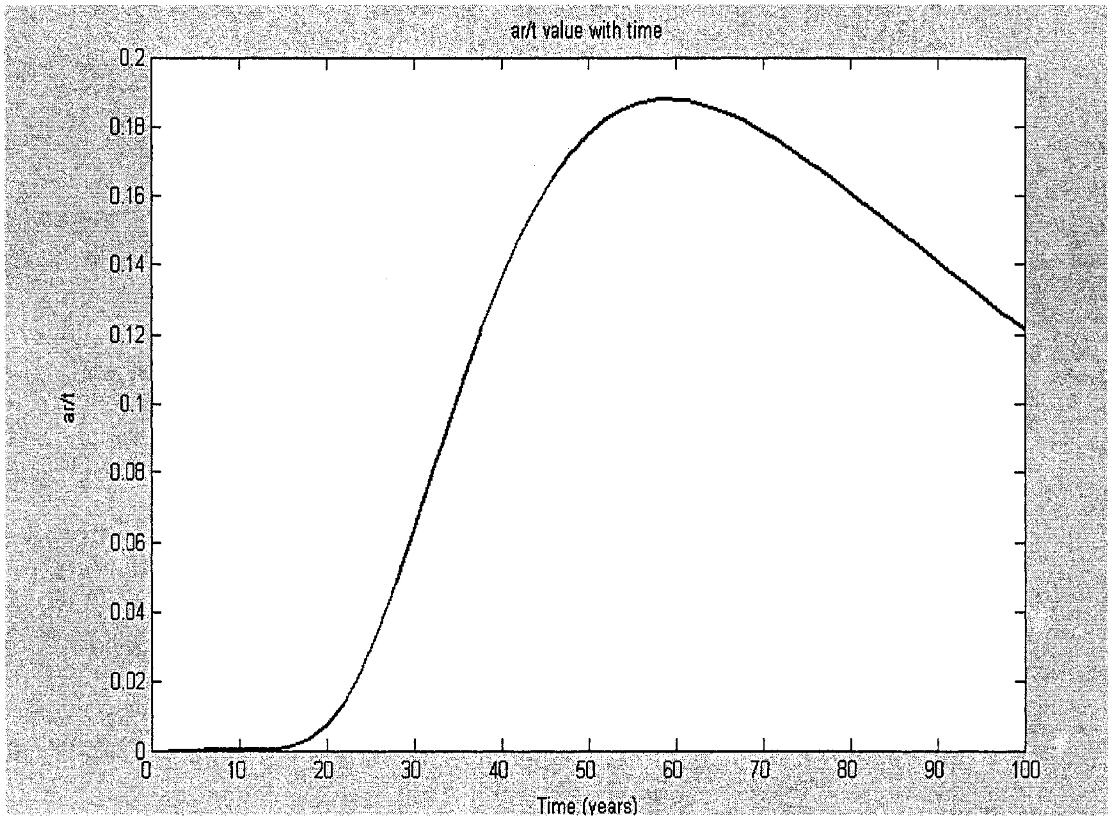


Figure 5.5 *ar/t* values (estimated using expression) with time

Now the second step according to the API approach is to calculate the over-design factor. The over-design factor is estimated by:

$$\text{Over-design factor} = \frac{t_{original}}{t_{original} - C.A.}$$

$$= 40/(40\text{-}6) = 1.18$$

The third step according to the API 581(2000) is to estimate the correction factor. The correction factor is estimated based on the over design factor using table 4.1. It is found from the table that, for an over-design factor value between 1.1 and 1.5 the correction factor equals to one. So, the correction value is equal to one in this case study.

The fourth step according to the API approach is to estimate the material damage factor. The figure that shows the damage factor for different number of inspections is provided in section 4.6. The MATLAB code developed to estimate the change in damage factor while the equipment becoming older is provided in appendix A. Figure 5.6 shows the change in the damage factor with the equipment age.

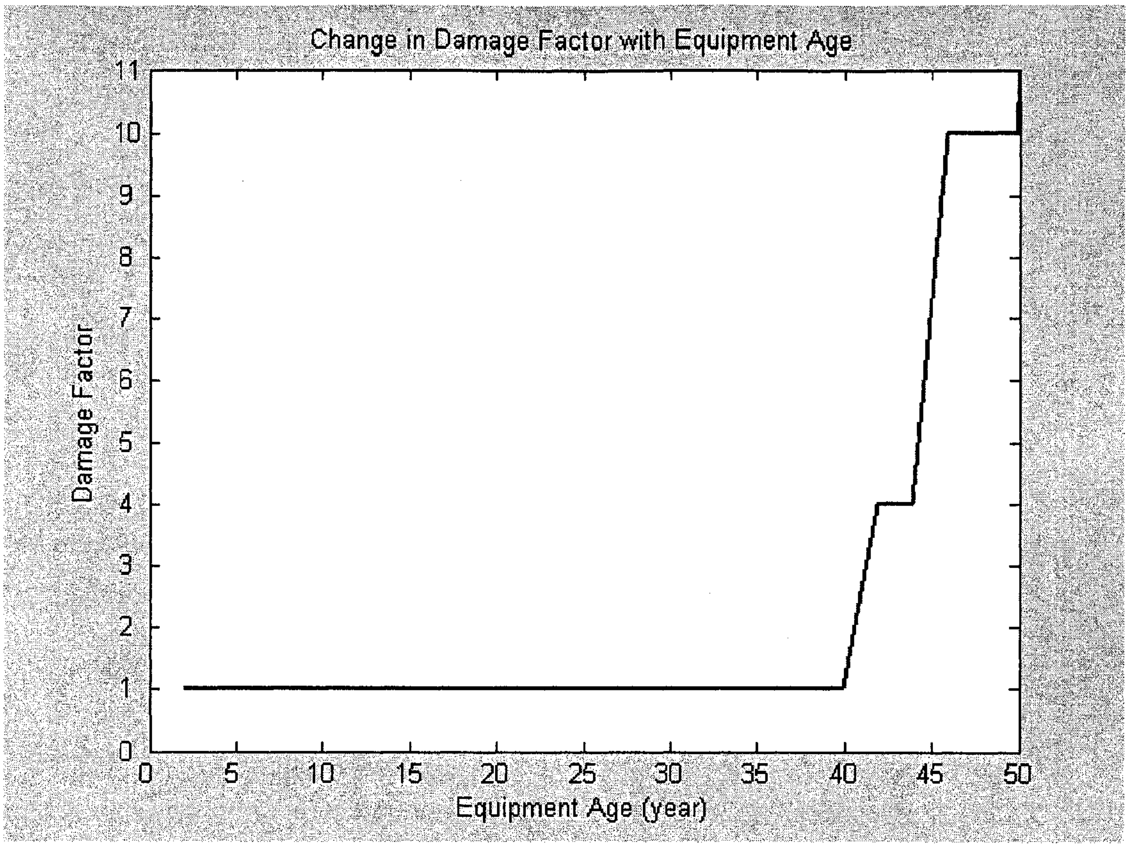


Figure 5.6: Change in the damage factor (estimated using expression) with the equipment age.

The last step in the API approach is to find the optimal inspection time. From figure 5.6, it is clear that the damage factor for the distillate hydrotreator reactor material starts to increase when the equipment age exceeds 40 years which means after 21 years, so the inspection should be carried on at that time. The optimal inspection time is found to be after 21.88 years. The damage factor change with time is shown in figure 5.7.

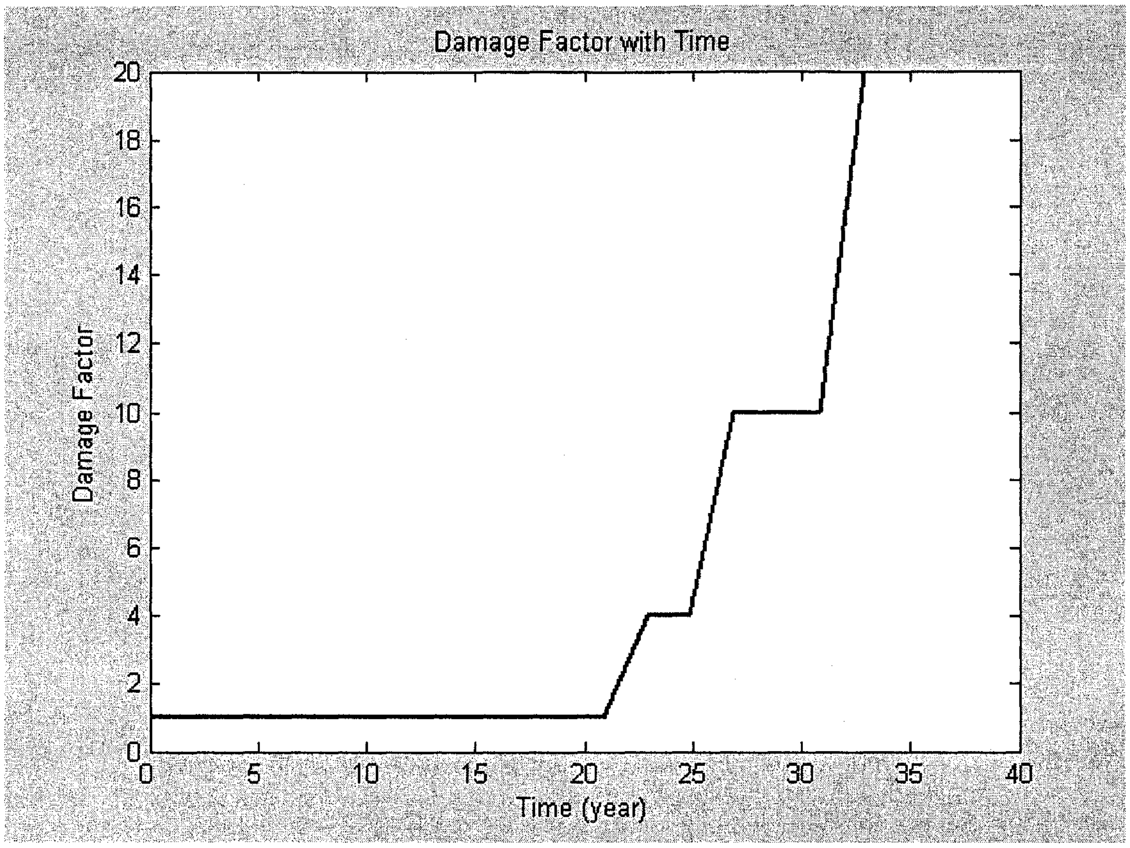


Figure 5.7: Change in the damage factor (estimated using expression) with time.

By combining the API approach with the stochastic gamma model approach developed by Kallen (2002), we can go further more to find the expected replacement and failure times. Replacement and failure probabilities are provided in section 4.5. The MATLAB code for the molecular sieve vessel case study which is provided in appendix A calculates the optimal replacement and failure times for 500 simulations. It was found that the expected replacement and failure times are found to be 32.25 years and 209.91 years, respectively.

CHAPTER 6
DISCUSSION & CONCLUSIONS

Inspection refers to the planning, implementation and valuation of examinations to determine the physical and metallurgical condition of an equipment item (Wintel et al, 2001). Inspection is an initiator for actions such as the repair or replacement of deteriorating equipment, or change to the operating conditions.

Risk based inspection is a logical and structured process of planning and evaluation. Risk based inspection involves the planning of an inspection on the basis of the information obtained from a risk analysis for equipment items (Wintel et al, 2001). The objective of the risk analysis is to identify the potential degradation mechanisms and threats to the integrity of the equipment, and to assess the consequences and risks of failure. The information and associated uncertainties captured from the risk analysis about potential deterioration are used to develop an integrity management strategy and appropriate inspection plan. The inspection plan targets the high risk equipment and aims to detect potential degradation before the equipment been threatened.

Risk based inspection programs can be implemented on three different levels: qualitative, semi quantitative, and quantitative. The qualitative risk based inspection approach uses engineering experience and judgment as the bases for the risk analysis. The risk analysis for the qualitative risk based inspection approach is a straight forward assignment of the likelihood of failure and its consequences to their proper categories and placing them in the risk matrix. The semi-quantitative risk assessment approach combines aspects derived from both quantitative and qualitative approaches; it has the speed of the qualitative approach and the rigor of the quantitative approach. Risk ranking in the semi-quantitative risk based inspection is achieved through a risk matrix of failure probability and its consequence. The quantitative risk assessment approaches uses logic models evaluated probabilistically to provide a quantitative insight to identify the risk index. These models depicts combinations of the probability of occurring of events that results in sever accidents and its consequences. Estimating the probability of failure in the quantitative risk assessment approaches depends basically on historical failure data. Another way in estimating the probability of failure is based on reliability concept. Choosing the appropriate risk based inspection approach depends on the available resources and data, complexity of process and facilities, study frame time, and the objective of the study. Despite the used approach, risk based inspection program deals with four basic risk categories: flammable events which can cause damage through thermal radiation and blast overpressure, risk of release of toxic materials, environmental risk, and economic risk.

The process of risk based inspection forms a part of an integrated strategy for managing the integrity of the systems and equipment of the installation as a whole. Risk based inspection aims to manage the likelihood and consequences of failure at an acceptable level, thus avoid unreasonable risks of harm to people and the environment and increase the operational safety of a process plant; increases the plant availability; and reduces the direct inspection cost of the plant by avoiding unnecessary inspection and maintenance actions.

The key element in planning inspection based on carrying a risk assessment is the damage rate. Therefore, the risk based inspection program should take account of all deterioration mechanisms that can cause damage to equipment items.

This study presents a quantitative risk-based inspection model that combines a risk-based inspection program modeled by Kallen (2002) and a risk-based inspection program developed by the American Petroleum Institute (API). This probabilistic risk based inspection model uses a stochastic model instead of a deterministic model to evaluate the cumulative damage to the material of component. It uses a gamma distribution to model the material degradation and a Bayesian updating. The gamma distribution used to model two main deterioration mechanisms: thinning and stress corrosion cracking; however, the gamma model needs to be expanded to model all deterioration mechanisms. The gamma distribution seems to describe the material degradation process well; however, other mathematical models like the Weibull distribution model can be used. The Bayesian updating method allows the updating of the probability density function for the material degradation. This stochastic model uses only the inspection data to extrapolate the material condition in the future and to estimate the optimal replacement and failure times. On the contrast, the deterministic models need large number of input data. The uncertainty created by imperfect inspections is taken into consideration in the stochastic risk based inspection model. The error in inspection is normally distributed with mean zero and a standard deviation that reflects the accuracy of the inspection method. The risk is calculated using the probability of failure due to material deterioration and the consequence is assessed in terms of the damage factor. The risk function is used to determine an optimal inspection and replacement interval. In this study, the risk based inspection model is used to determine the optimal inspection, replacement, and failure times for two cases of study: molecular sieve vessel, and distillate hydrotreater reactor. For the molecular sieve vessel the next inspection is due after 11 years from now, and for the distillate hydrotreater reactor the next inspection is due after 10 years from now. The optimal inspection intervals given by the model for the case studies considered are reasonable; it is not too short so unnecessary inspections are avoided, nor it is too long so the risk of failure due to deterioration mechanisms will not become large. Applying the risk based model developed by Kallen (2002) gives slightly longer intervals for inspection. While applying the API risk based inspection model normally leads to much shorter inspection intervals; the API model usually recommends four or six years inspection intervals with different inspection activities regarding to the case studied. On the other hand, combining the two risk based models results in reliable inspection intervals that satisfies both features recommended by Kallen and the American Petroleum Institute (API). So we can certainly say that, results of the case studies presented in the study show that the method produces reliable estimates for the inspection intervals. The most important disadvantage of the method is that it is computationally exhaustive. For the molecular sieve vessel case study, the simulation using 500 samples took more than 10 hours, while for the distillate hydrotreater reactor case study, it took around 8 hours on a personal computer with an Intel Pentium 4 and 256 MB RAM. On the other hand, the method can be easily programmed and does not need a large amount of input data.

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APPENDIX A
THE MATLAB CODE

A.1 Case Study 1: Molecular Sieve Vessel

The following MATLAB code is developed to draw the prior and posterior density functions for perfect and imperfect inspection, and to estimate the optimal replacement and failure times.

```
>> % component diameter [mm]
>> d=2374;

>> % actual thickness at service start [mm]
>> th=20;

>> % tensile strength [MPa]
>> TS=448.16;

>> % yeild strength [MPa]
>> YS=206.84;

>> % residual stress [MPa]
>> S=min(1.1*(TS+YS)/2,TS);

>> % operating pressure [MPa]
>> OP=11.1;

>> % S coefficient of variation
>> residualtress_cov=0.20;

>> % pressure coefficient of variation
>> pressure_cov=14;

>> % standard deviation residual stress
>> sigma_S=residual_cov*S;

>> % standard deviation pressure
>> sigma_pr=pressure_cov*OP;

>> % corrosion rate [mm/yr]
>> CR=0.1;

>> % coefficient of variation of CR
>> cov=0.12;

>> % corrosion allowance [mm]
>> CorrAllowance = 4.0;
```

```
>> % times between past inspections
>> t=[1986-1982 1992-1986 2000-1992];

>> % changes in wall thickness during these times
>> D=[(th-19.7) (19.7-19.1) (19.1-18.2)];

>> % total number of inspections
>> K=length(t);

>> % cov for each inspection
>> InspCOV=[0.5;0.5;0.5];

>> % standard deviation fpr each inspection
>> SigmaEpsilon=InspCOV.*D';

>> % the grid for the normal density of the measurement error
>> NormalLimit=round(max(SigmaEpsilon)*1000*3)/1000;
>> eps=[-NormalLimit:0.001:NormalLimit];

>> % built the gamma density estimation
>> n=100;
>> U= unifrnd(0,1,n,1);
>> G= zeros(n,1);
>> for i=1:n
if U(i)<=0.5
G(i)=1*CR;
elseif U(i)>0.5 & U(i)<=0.8
G(i)=2*CR;
else
G(i)=4*CR;
end
end
>> GInv = 1./G;
>> y = gamfit(GInv);
>> a=y(1);
>> b=1/y(2);

>> % define the grid over which the densities are calculated
>> GridDist=CR/20;
>> x= GridDist:GridDist:7*CR;
>> N=length(x);

>> % the prior is given by:
>> Prior = exp(a*log(b)-gammaln(a)+(-a-1)*log(x)-b./x);

>> % find the posterior for one perfect inspection
```

```
>> A = a+t(K)/cov^2;
>> B=b+D(K)/cov^2;
>> PostPerfInsp = exp(A*log(B)-gammaln(A)+(-A-1)*log(x)-B./x);

>> % find the posterior for one imperfect inspection
>> n=2000;
>> R=1;
>> E = zeros(n,R);
>> h = zeros(n,R);
>> for k =1:R
E(:,k) = normrnd(0,SigmaEpsilon(k),n,1);
if k==1
h(:,k) = E(:,k);
else
h(:,k) = E(:,k) - E(:,k-1);
end
end
>> likelihood = zeros(N,R);
>> LikeliProd = zeros(N,1);
>> for j=1:N
for k=1:R
likelihood(j,k) = (1/n)*sum(exp(-(t(k)/cov^2)*log(x(j)*cov^2)-
gammaln(t(k)/cov^2)+(t(k)/cov^2-1)*log(D(k)-min(D(k)-0.001,h(:,k)))-(D(k)-
min(D(k),h(:,k)))/(x(j)*cov^2)));
end
end
>> LikeliProd = prod(likelihood,2);
>> PostImpInsp = Prior'.*LikeliProd/(Prior*LikeliProd*GridDist);
>> PostImpInspCDF = cumsum(PostImpInsp)*GridDist;

>> % find the posterior for two imperfect inspections
>> R2=2;
>> h2= zeros(n,R2);
>> E2 = zeros(n,R2);
>> for k2 =1:R2
E2(:,k2) = normrnd(0,SigmaEpsilon(k2),n,1);
if k2==1
h2(:,k2) = E2(:,k2);
else
h2(:,k2) = E2(:,k2) - E2(:,k2-1);
end
end
>> likelihood = zeros(N,R2);
>> LikeliProd = zeros(N,1);
>> for j=1:N
for k2=1:R2
```

```
likelihood2(j,k2) = (1/n)*sum(exp(-(t(k2)/cov^2)*log(x(j)*cov^2)-
gammaln(t(k2)/cov^2)+(t(k2)/cov^2-1)*log(D(k2)-min(D(k2)-
0.001,h2(:,k2)))-(D(k2)-min(D(k2),h2(:,k2)))/(x(j)*cov^2)));
end
end
>> LikeliProd2 = prod(likelihood2,2);
>> PostImpInsp2 = Prior'.*LikeliProd2/(Prior*LikeliProd2*GridDist);
>> PostImpInspCDF2 = cumsum(PostImpInsp2)*GridDist;

>> % find the posterior for three imperfect inspections
>> R3=3;
>> E3 = zeros(n,R3);
>> h3= zeros(n,R3);
>> for k3 =1:R3
E3(:,k3) = normrnd(0,SigmaEpsilon(k3),n,1);
if k3==1
h3(:,k3) = E3(:,k3);
else
h3(:,k3) = E3(:,k3) - E3(:,k3-1);
end
end
>> likelihood = zeros(N,R3);
>> LikeliProd = zeros(N,1);
>> for j=1:N
for k3=1:R3
likelihood3(j,k3) = (1/n)*sum(exp(-(t(k3)/cov^2)*log(x(j)*cov^2)-
gammaln(t(k3)/cov^2)+(t(k3)/cov^2-1)*log(D(k3)-min(D(k3)-
0.001,h3(:,k3)))-(D(k3)-min(D(k3),h3(:,k3)))/(x(j)*cov^2)));
end
end
>> LikeliProd3 = prod(likelihood3,2);
>> PostImpInsp3 = Prior'.*LikeliProd3/(Prior*LikeliProd3*GridDist);
>> PostImpInspCDF3 = cumsum(PostImpInsp3)*GridDist;
>> % open a figue and plot the prior and posterior
>> plot(x,Prior,'g-',x,PostPerfInsp,'k-',x,PostImpInsp,'r-',x,PostImpInsp2,'b-
',x,PostImpInsp3,'c','LineWidth',2);
>> grid
>> legend('prior density','posterior 1 perf. insp.',['posterior',num2str(k),'imp.
insp.'],['posterior',num2str(k2),'imp. insp.'],['posterior',num2str(k3),'imp.
insp.'],0);
>> title(['Prior and Posterior
results(\sigma_\epsilon=',num2str(mean(SigmaEpsilon)),';n=',num2str(n),')']);
>> xlabel('Corrosion Rate(mm/yr)');
>> ylabel('Density');

>> % built a function to calculate the expected time of preventive
```

```
>> % replacement, the expected time of failure and the time horizon over
>> % which calculations are done

>> % N is number of samples
>> N=500;

>> % p: normal distributed samples for pressure
>> p= normrnd(OP,sigma_pr,N,1);

>> % s: normal distributed samples for residual stress
>> s = normrnd(S,sigma_S,N,1);

>> % m: vector of safety margins
>> m = th-p*th./(2*s);

>> c = zeros(N,1);
>> for i=1:N
u=unifrnd(0,1);
c(i) = x(min(find(PostImpInspCDF3>u)));
end
>> MaxT = max(m./c);
>> rho = CorrAllowance./m;
>> dT =1;
>> PrepData = zeros(N,3);
>> function y = simulprep(cov,m,rho,CR,dT,MaxT)
>> a = 1/cov^2;
>> b = 1/(CR*cov^2);
>> ExpFailTime = 1-gammainc(b*m,a*dT);
>> ExpReplTime = 1-gammainc(b*rho.*m,a*dT);
>> for i=2*dT:dT:round(1.5*MaxT)
ExpFailTime = ExpFailTime+i*(gammainc(b*m,a*(i-1*dT))-
gammainc(b*m,a*i));
ExpReplTime = ExpReplTime+i*(gammainc(b*rho.*m,a*(i-1*dT))-
gammainc(b*rho.*m,a*i));
end
>> TimeHorizon = round(1.2*ExpFailTime);
>> y=[ExpReplTime ExpFailTime TimeHorizon];
>> G=y(:,2);

>> % find The Optimal Inspection Time [yr]
>> ar=10*Prior.*x
>> q=ar/th
>> xx=x*ExpectedFailureTime;
>> plot(xx,q,'LineWidth',2);
>> title(['ar/t value vs. Equipment Age']);
>> xlabel('Equipment Age (years)');
```

```
>> ylabel('ar/t');

>> I=1;
>> Inspection0=zeros(19,1);
>> for J=1:19
if (J<=4)
I=I;
elseif (J==5)
I=I+1;
elseif (J==6)
I=I+4;
elseif (J==7)
I=I+14;
elseif (J==8)
I=I+70;
elseif (J==9)
I=I+160;
elseif (J==10)
I=I+150;
elseif (J==11)
I=I+120;
elseif (J==12)
I=I+130;
elseif (J==13)
I=I+100;
elseif (J==14)
I=I+150;
elseif ((J>14)&&(J<19))
I=I+150;
else
I=I+400;
end
Inspection0(J,1)=I;
end

>> I1=1;
>> Inspection1=zeros(19,1);
>> for J=1:19
if (J<=5)
I1=I1;
elseif (J==6)
I1=I1+1;
elseif (J==7)
I1=I1+4;
elseif (J==8)
I1=I1+14;
```

```
elseif (J==9)
I1=I1+50;
elseif (J==10)
I1=I1+40;
elseif (J==11)
I1=I1+40;
elseif (J==12)
I1=I1+50;
elseif ((J>12)&&(J<18))
I1=I1+100;
else
I1=I1+150;
end
Inspection1(J,1)=I1;
end

>> I2=1;
>> Inspection2=zeros(19,1);
>> for J=1:19
if (J<=7)
I2=I2;
elseif (J==8)
I2=I2+3;
elseif (J==9)
I2=I2+6;
elseif ((J>9)&&(J<13))
I2=I2+10;
elseif ((J>12)&&(J<17))
I2=I2+40;
elseif ((J>16)&&(J<19))
I2=I2+100;
else
I2=I2+270;
end
Inspection2(J,1)=I2;
end

>> I3=1;
>> Inspection3=zeros(19,1);
>> for J=1:19
if (J<=8)
I3=I3;
elseif ((J>8)&&(J<11))
I3=I3+2;
elseif (J==11)
I3=I3+1;
```

```
elseif (J==12)
I3=I3+3;
elseif (J==13)
I3=I3+11;
elseif (J==14)
I3=I3+30;
elseif (J==15)
I3=I3+10;
elseif (J==16)
I3=I3+20;
elseif (J==17)
I3=I3+50;
elseif (J==18)
I3=I3+120;
else
I3=I3+300;
end
Inspection3(J,1)=I3;
end

>> I4=1;
>> Inspection4=zeros(19,1);
>> for J=1:19
if (J<=9)
I4=I4;
elseif (J==10)
I4=I4+1;
elseif (J==11)
I4=I4;
elseif (J==12)
I4=I4+2;
elseif (J==13)
I4=I4+6;
elseif (J==14)
I4=I4+10;
elseif (J==15)
I4=I4+10;
elseif (J==16)
I4=I4+20;
elseif (J==17)
I4=I4+50;
elseif (J==18)
I4=I4+120;
else
I4=I4+310;
end
```

```
Inspection4(J,1)=I4;
end

>> I5=1;
>> Inspection5=zeros(19,1);
>> for J=1:19
if (J<=10)
I5=I5;
elseif (J==11)
I5=I5+1;
elseif (J==12)
I5=I5+1;
elseif (J==13)
I5=I5+3;
elseif (J==14)
I5=I5+4;
elseif (J==15)
I5=I5+10;
elseif (J==16)
I5=I5+20;
elseif (J==17)
I5=I5+50;
elseif (J==18)
I5=I5+120;
else
I5=I5+290;
end
Inspection5(J,1)=I5;
end

>> I6=1;
>> Inspection6=zeros(19,1);
>> for J=1:19
if (J<=11)
I6=I6;
elseif (J==12)
I6=I6+1;
elseif (J==13)
I6=I6+3;
elseif (J==14)
I6=I6+4;
elseif (J==15)
I6=I6+11;
elseif (J==16)
I6=I6+20;
elseif (J==17)
```

```
I6=I6+50;
elseif (J==18)
I6=I6+120;
else
I6=I6+290;
end
Inspection6(J,1)=I6;
end

>> % Number of inspections=3.
>> DamageFactor=zeros(1,140);
>> for Z=1:140
if (qqqq(Z)<=0.02)
DF=Inspection3(1)
elseif ((qqqq(Z)>0.02)&&(qqqq(Z)<=0.04))
DF=Inspection3(2)
elseif ((qqqq(Z)>0.04)&&(qqqq(Z)<=0.06))
DF=Inspection3(3)
elseif ((qqqq(Z)>0.06)&&(qqqq(Z)<=0.08))
DF=Inspection3(4)
elseif ((qqqq(Z)>0.08)&&(qqqq(Z)<=0.10))
DF=Inspection3(5)
elseif ((qqqq(Z)>0.10)&&(qqqq(Z)<=0.12))
DF=Inspection3(6)
elseif ((qqqq(Z)>0.12)&&(qqqq(Z)<=0.14))
DF=Inspection3(7)
elseif ((qqqq(Z)>0.14)&&(qqqq(Z)<=0.16))
DF=Inspection3(8)
elseif ((qqqq(Z)>0.16)&&(qqqq(Z)<=0.18))
DF=Inspection3(9)
elseif ((qqqq(Z)>0.18)&&(qqqq(Z)<=0.20))
DF=Inspection3(10)
elseif ((qqqq(Z)>0.20)&&(qqqq(Z)<=0.25))
DF=Inspection3(11)
elseif ((qqqq(Z)>0.25)&&(qqqq(Z)<=0.30))
DF=Inspection3(12)
elseif ((qqqq(Z)>0.30)&&(qqqq(Z)<=0.35))
DF=Inspection3(13)
elseif ((qqqq(Z)>0.35)&&(qqqq(Z)<=0.40))
DF=Inspection3(14)
elseif ((qqqq(Z)>0.40)&&(qqqq(Z)<=0.45))
DF=Inspection3(15)
elseif ((qqqq(Z)>0.45)&&(qqqq(Z)<=0.50))
DF=Inspection3(16)
elseif ((qqqq(Z)>0.50)&&(qqqq(Z)<=0.55))
DF=Inspection3(17)
```

```
elseif ((qqqq(Z)>0.55)&&(qqqq(Z)<=0.60))
DF=Inspection3(18)
elseif ((qqqq(Z)>0.60)&&(qqqq(Z)<=0.65))
DF=Inspection3(19)
end
DamageFactor(1,Z)=DF
end

>> plot(xx,DamageFactor,'LineWidth',2);
>> title(['DamageFactor vs. Time']);
>> xlabel('Time(year)');
>> ylabel('DamageFactor');

>> % Mean Expected Failure Time [yr]
>> ExpectedFailureTime=mean(G)

ExpectedFailureTime =

  199.0760

>> % Minimum Expected Failure Time [yr]
>> EFT=min(G)

EFT =

  103.2876

>> % find Expected Replacement Time [yr]
>> J=y(:,1);
>> ExpectedReplacementTime=mean(J)

ExpectedReplacementTime =

   40.5072
```

A.2 Case Study 2: Distillate Hydrotreater Reactor

The following MATLAB code is developed to draw the prior and posterior density functions imperfect inspections, and to estimate the optimal replacement and failure times.

```
>> clear
>> % component diameter [mm]
>> d= 3977;

>> % actual thickness at service start [mm]
>> th=40;

>> % tensile strength [MPa]
>> TS= 420;

>> % yeild strength [MPa]
>> YS=350;

>> % residual stress [MPa]
>> S=min(1.1*(TS+YS)/2,TS);

>> % operating pressure [MPa]
>> OP=4.7;

>> % S coefficient of variation
>> residualstress_cov=0.25;

>> % pressure coefficient of variation
>> pressure_cov=0.13;

>> % standard deviation flow stress
>> sigma_S=flowstress_cov*S;

>> % standard deviation pressure
>> sigma_pr=pressure_cov*OP;

>> % corrosion rate [mm/yr]
>> CR=0.19;

>> % coefficient of variation of CR
>> cov=0.6;

>> % corrosion allowance [mm]
```

```
>> CorrAllowance = 6.0;

>> % times between past inspections
>> t=[2002-1992  1992-1988];

    >> % changes in wall thickness during these times
>> D=[(th-38.9) (38.9-37.5)];

>> % total number of inspections
>> K=length(t);

>> % cov for each inspection
>> InspCOV=[0.5;0.5];

>> % standard deviation fpr each inspection
>> SigmaEpsilon=InspCOV.*D';

>> % the grid for the normal density of the measurement error
>> NormalLimit=round(max(SigmaEpsilon)*1000*4)/1000;
>> eps=[-NormalLimit:0.001:NormalLimit];

>> % built the gamma density estimation
>> n=100;
>> U= unifrnd(0,1,n,1);
>> G= zeros(n,1);
    >> for i=1:n
            if U(i)<=0.5
            G(i)=1*CR;
            elseif U(i)>0.5 & U(i)<=0.8
            G(i)=2*CR;
    else
            G(i)=4*CR;
            end
end
>> GInv = 1./G;
    >> y = gamfit(GInv);
>> a=y(1);
>> b=1/y(2);

>> % define the grid over which the densities are calculated
>> GridDist=CR/20;
    >> x= GridDist:GridDist:7*CR;
>> N=length(x);

>> % the prior is given by:
>> Prior = exp(a*log(b)-gammaln(a)+(-a-1)*log(x)-b./x);
```

```
>> % find the posterior for one perfect inspection
    >> A = a+t(K)/cov^2;
>> B=b+D(K)/cov^2;
>> PostPerfInsp = exp(A*log(B)-gammaln(A)+(-A-1)*log(x)-B./x);

>> % find the posterior for one imperfect inspection
>> n=2000;
    >> R=1;
>> E = zeros(n,R);
>> h = zeros(n,R);
>> for k =1:R
     E(:,k) = normrnd(0,SigmaEpsilon(k),n,1);
      if k==1
            h(:,k) = E(:,k);
            lse
            h(:,k) = E(:,k) - E(:,k-1);
            end
end
    >> likelihood = zeros(N,R);
>> LikeliProd = zeros(N,1);
    >> for j=1:N
            for k=1:R
likelihood(j,k) = (1/n)*sum(exp(-(t(k)/cov^2)*log(x(j)*cov^2)-
    gammaln(t(k)/cov^2)+(t(k)/cov^2-1)*log(D(k)-min(D(k)-0.001,h(:,k)))-(D(k)-
    min(D(k),h(:,k)))/(x(j)*cov^2)));
            end
            end
    >> LikeliProd = prod(likelihood,2);
    >> PostImpInsp = Prior'.*LikeliProd/(Prior*LikeliProd*GridDist);
    >> PostImpInspCDF = cumsum(PostImpInsp)*GridDist;

    >> % find the posterior for two imperfect inspections
    >> R2=2;
    >> h2= zeros(n,R2);
    >> E2 = zeros(n,R2);
    >> for k2 =1:R2
            E2(:,k2) = normrnd(0,SigmaEpsilon(k2),n,1);
            if k2==1
            h2(:,k2) = E2(:,k2);
            else
            h2(:,k2) = E2(:,k2) - E2(:,k2-1);
            end
            end
    >> likelihood = zeros(N,R2);
    >> LikeliProd = zeros(N,1);
```

```
>> for j=1:N
        for k2=1:R2
likelihood2(j,k2) = (1/n)*sum(exp(-(t(k2)/cov^2)*log(x(j)*cov^2)-
   gammaln(t(k2)/cov^2)+(t(k2)/cov^2-1)*log(D(k2)-min(D(k2)-0.001,h2(:,k2)))-
   (D(k2)-min(D(k2),h2(:,k2)))/(x(j)*cov^2)));
        end
        end
>> LikeliProd2 = prod(likelihood2,2);
>> PostImpInsp2 = Prior'.*LikeliProd2/(Prior*LikeliProd2*GridDist);

>> % open a figue and plot the prior and posterior
>> plot(x,Prior,'g-',x,PostImpInsp,'r-',x,PostImpInsp2,'b-','LineWidth',2);
>> grid
>> legend('prior density',['posterior',num2str(k),'imp. insp.']
,['posterior',num2str(k2),'imp. insp.'],0);
>> title(['Prior and Posterior results  (\sigma_\epsilon =',num2str (mean
(SigmaEpsilon)),';n=',num2str(n),')']);
>> xlabel('Corrosion Rate(mm/yr)');
>> ylabel('Density (age%)');

>> % built a function to calculate the expected time of preventive
>> % replacement, the expected time of failure and the time horizon over which
>> % calculations are done

>> %N is number of samples
>> N=500;

>> % p: normal distributed samples for pressure
>> p= normrnd(OP,sigma_pr,N,1);

>> % s: normal distributed samples for flow stress
>> s = normrnd(S,sigma_S,N,1);

>> % m: vector of safety margins
>> m = th-p*th./(2*s);

>> c = zeros(N,1);
>> for i=1:N
        u=unifrnd(0,1);
        c(i) = x(min(find(PostImpInspCDF2>u)));
        end
>> MaxT = max(m./c);
>> rho = CorrAllowance./m;
>> dT =1;
>> PrepData = zeros(N,3);
>> function y = simulprep(cov,m,rho,CR,dT,MaxT)
```

```
>> a = 1/cov^2;
>> b = 1/(CR*cov^2);
>> ExpFailTime = 1-gammainc(b*m,a*dT);
>> ExpReplTime = 1-gammainc(b*rho.*m,a*dT);
>> for i=2*dT:dT:round(1.5*MaxT)
ExpFailTime = ExpFailTime+i*(gammainc(b*m,a*(i-1*dT))-
gammainc(b*m,a*i));
ExpReplTime = ExpReplTime+i*(gammainc(b*rho.*m,a*(i-1*dT))-
gammainc(b*rho.*m,a*i));
        end
>> TimeHorizon = round(1.2*ExpFailTime);
>> y = [ExpReplTime ExpFailTime TimeHorizon];
>> G = y(:,2);

>> % find The Optimal Inspection Time [yr]
>> ar=10*Prior.*x
>> q=ar/th
>> xx=x*ExpectedFailureTime;
>> plot(xx,q,'LineWidth',2);
>> title(['ar/t value vs. Equipment Age']);
>> xlabel('Equipment Age (years)');
>> ylabel('ar/t');

>> I=1;
>> Inspection0=zeros(19,1);
>> for J=1:19
    if (J<=4)
    I=I;
    elseif (J==5)
    I=I+1;
    elseif (J==6)
    I=I+4;
    elseif (J==7)
    I=I+14;
    elseif (J==8)
    I=I+70;
    elseif (J==9)
    I=I+160;
    elseif (J==10)
    I=I+150;
    elseif (J==11)
    I=I+120;
    elseif (J==12)
    I=I+130;
    elseif (J==13)
    I=I+100;
```

```
    elseif (J==14)
    I=I+150;
    elseif ((J>14)&&(J<19))
    I=I+150;
    else
    I=I+400;
    end
    Inspection0(J,1)=I;
    end
>> I1=1;
>> Inspection1=zeros(19,1);
>> for J=1:19
    if (J<=5)
    I1=I1;
    elseif (J==6)
    I1=I1+1;
    elseif (J==7)
    I1=I1+4;
    elseif (J==8)
    I1=I1+14;
    elseif (J==9)
    I1=I1+50;
    elseif (J==10)
    I1=I1+40;
    elseif (J==11)
    I1=I1+40;
    elseif (J==12)
    I1=I1+50;
    elseif ((J>12)&&(J<18))
    I1=I1+100;
    else
    I1=I1+150;
    end
    Inspection1(J,1)=I1;
    end
>> I2=1;
>> Inspection2=zeros(19,1);
>> for J=1:19
    if (J<=7)
    I2=I2;
    elseif (J==8)
    I2=I2+3;
    elseif (J==9)
    I2=I2+6;
    elseif ((J>9)&&(J<13))
    I2=I2+10;
```

```
    elseif ((J>12)&&(J<17))
    I2=I2+40;
    elseif ((J>16)&&(J<19))
    I2=I2+100;
    else
    I2=I2+270;
    end
    Inspection2(J,1)=I2;
    end
>> I3=1;
>> Inspection3=zeros(19,1);
>> for J=1:19
    if (J<=8)
    I3=I3;
    elseif ((J>8)&&(J<11))
    I3=I3+2;
    elseif (J==11)
    I3=I3+1;
    elseif (J==12)
    I3=I3+3;
    elseif (J==13)
    I3=I3+11;
    elseif (J==14)
    I3=I3+30;
    elseif (J==15)
    I3=I3+10;
    elseif (J==16)
    I3=I3+20;
    elseif (J==17)
    I3=I3+50;
    elseif (J==18)
    I3=I3+120;
    else
    I3=I3+300;
    end
    Inspection3(J,1)=I3;
    end
>> I4=1;
>> Inspection4=zeros(19,1);
>> for J=1:19
    if (J<=9)
    I4=I4;
    elseif (J==10)
    I4=I4+1;
    elseif (J==11)
    I4=I4;
```

```
elseif (J==12)
I4=I4+2;
elseif (J==13)
I4=I4+6;
elseif (J==14)
I4=I4+10;
elseif (J==15)
I4=I4+10;
elseif (J==16)
I4=I4+20;
elseif (J==17)
I4=I4+50;
elseif (J==18)
I4=I4+120;
else
I4=I4+310;
end
Inspection4(J,1)=I4;
end
>> I5=1;
>> Inspection5=zeros(19,1);
>> for J=1:19
if (J<=10)
I5=I5;
elseif (J==11)
I5=I5+1;
elseif (J==12)
I5=I5+1;
elseif (J==13)
I5=I5+3;
elseif (J==14)
I5=I5+4;
elseif (J==15)
I5=I5+10;
elseif (J==16)
I5=I5+20;
elseif (J==17)
I5=I5+50;
elseif (J==18)
I5=I5+120;
else
I5=I5+290;
end
Inspection5(J,1)=I5;
end
```

```
>> I6=1;
>> Inspection6=zeros(19,1);
>> for J=1:19
   if (J<=11)
   I6=I6;
   elseif (J==12)
   I6=I6+1;
   elseif (J==13)
   I6=I6+3;
   elseif (J==14)
   I6=I6+4;
   elseif (J==15)
   I6=I6+11;
   elseif (J==16)
   I6=I6+20;
   elseif (J==17)
   I6=I6+50;
   elseif (J==18)
   I6=I6+120;
   else
   I6=I6+290;
   end
   Inspection6(J,1)=I6;
   end

>> % Number of inspections=2.
>> DamageFactor=zeros(1,140);
>> for Z=1:140
   if (qqqq(Z)<=0.02)
   DF=Inspection2(1)
   elseif ((qqqq(Z)>0.02)&&(qqqq(Z)<=0.04))
   DF=Inspection2(2)
   elseif ((qqqq(Z)>0.04)&&(qqqq(Z)<=0.06))
   DF=Inspection2(3)
   elseif ((qqqq(Z)>0.06)&&(qqqq(Z)<=0.08))
   DF=Inspection2(4)
   elseif ((qqqq(Z)>0.08)&&(qqqq(Z)<=0.10))
   DF=Inspection2(5)
   elseif ((qqqq(Z)>0.10)&&(qqqq(Z)<=0.12))
   DF=Inspection2(6)
   elseif ((qqqq(Z)>0.12)&&(qqqq(Z)<=0.14))
   DF=Inspection2(7)
   elseif ((qqqq(Z)>0.14)&&(qqqq(Z)<=0.16))
   DF=Inspection2(8)
   elseif ((qqqq(Z)>0.16)&&(qqqq(Z)<=0.18))
   DF=Inspection2(9)
```

```
    elseif ((qqqq(Z)>0.18)&&(qqqq(Z)<=0.20))
    DF=Inspection2(10)
    elseif ((qqqq(Z)>0.20)&&(qqqq(Z)<=0.25))
    DF=Inspection2(11)
    elseif ((qqqq(Z)>0.25)&&(qqqq(Z)<=0.30))
    DF=Inspection2(12)
    elseif ((qqqq(Z)>0.30)&&(qqqq(Z)<=0.35))
    DF=Inspection2(13)
    elseif ((qqqq(Z)>0.35)&&(qqqq(Z)<=0.40))
    DF=Inspection2(14)
    elseif ((qqqq(Z)>0.40)&&(qqqq(Z)<=0.45))
    DF=Inspection2(15)
    elseif ((qqqq(Z)>0.45)&&(qqqq(Z)<=0.50))
    DF=Inspection2(16)
    elseif ((qqqq(Z)>0.50)&&(qqqq(Z)<=0.55))
    DF=Inspection2(17)
    elseif ((qqqq(Z)>0.55)&&(qqqq(Z)<=0.60))
    DF=Inspection2(18)
    elseif ((qqqq(Z)>0.60)&&(qqqq(Z)<=0.65))
    DF=Inspection2(19)
    end
    DamageFactor(1,Z)=DF
    end

>> plot(xx,DamageFactor,'LineWidth',2);
>> title(['DamageFactor vs. Time']);
>> xlabel('Time(year)');
>> ylabel('DamageFactor');

>> % Mean Expected Failure Time [yr]
>> ExpectedFailureTime = mean(G)

ExpectedFailureTime = 209.9185

>> % Minimum Expected Failure Time [yr]
>> EFT = min(G)

EFT = 209.0292

>> % find Expected Replacement Time [yr]
>> J = y(:,1);
>> ExpectedReplacementTime = mean(J)

ExpectedReplacementTime = 32.2589
```

APPENDIX B
SENSIVITY ANALYSIS

Five factors were studied to see which are the factors that effect on the results (failure and replacement time) the most. The factors that were taken are the corrosion rate, corrosion allowance, pressure, diameter, and thickness.

The software (Design Expert 6) was used, two factorial design was used so two values of each factor are taken (high and low values). Sixteen runs were carried on to find how the failure and replacement time will change with the change in the values of the input data; this is shown in Table B.1.

Table B.1: Effect of changing the input data on the failure and replacement times.

Factor 1 A:Corrosion Rate mm/yr	Factor 2 B:Corrosion Allowance mm	Factor 3 C:Pressure GPa	Factor 4 D:Diameter mm	Factor 5 E:Thickness mm	Response 1 Failure Time year	Response 2 Replacement Time year
0.05	4.00	1.00	1000.00	45.00	900.62	81.8
0.15	4.00	1.00	1000.00	15.00	101.65	28.45
0.05	8.00	1.00	1000.00	15.00	301.395	161.78
0.15	8.00	1.00	1000.00	45.00	301.395	55.11
0.05	4.00	12.00	1000.00	15.00	297.45	81.78
0.15	4.00	12.00	1000.00	45.00	297.16	28.45
0.05	8.00	12.00	1000.00	45.00	887.93	161.8
0.15	8.00	12.00	1000.00	15.00	100.24	55.1133
0.05	4.00	1.00	4000.00	15.00	301.395	81.78
0.15	4.00	1.00	4000.00	45.00	301.395	28.45
0.05	8.00	1.00	4000.00	45.00	900.62	161.8
0.15	8.00	1.00	4000.00	15.00	101.65	55.11
0.05	4.00	12.00	4000.00	45.00	887.93	81.8
0.15	4.00	12.00	4000.00	15.00	100.24	28.45
0.05	8.00	12.00	4000.00	15.00	297.16	161.78
0.15	8.00	12.00	4000.00	45.00	297.16	55.11

Table B.2 shows that just two factors have significant effect on the failure time. These factors are the corrsion rate and the thickness. It is found too that there is an interaction between these two factors ;i.e.the factors effected with each other; increasing the corrosion rate with decreasing the thickness leads to decrease the failure rate time. See figure B.1.

Table B.2: ANOVA table for the failure time

Response: Failure Time

ANOVA for Selected Factorial Model

Analysis of variance table [Partial sum of squares]

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob. > F**
Model	1.42E+06	3	4.72E+05	28645.3	< 0.0001
A	*6.30E+05*	*1*	*6.30E+05*	*38202.3*	*< 0.0001*
E	*6.29E+05*	*1*	*6.29E+05*	*38188.3*	*< 0.0001*
AE	*1.57E+05*	*1*	*1.57E+05*	*9545.33*	*< 0.0001*
Residual	197.73	12	16.48		
Cor Total	1.42E+06	15			

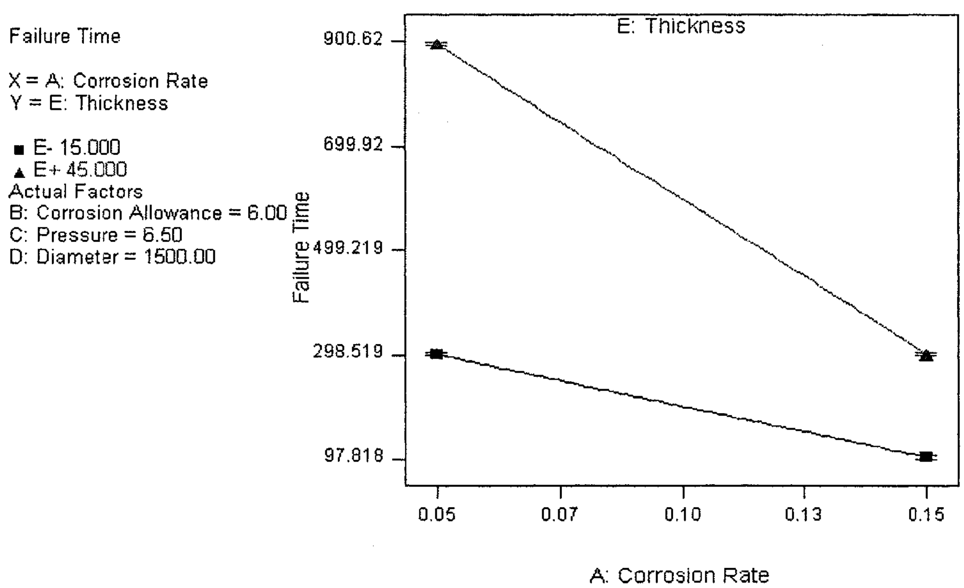

Figure B.1: Effect of changing the corrosion rate and material thickness on the failure time

For the replacement time Table B.3 shows that two factors have siginficant effect on the response. These factors are the corrosion rate and corrosion Alowance. It is also found that there is an interaction between the two factors. See figure B.2.

Table B.3: ANOVA table for the replacement time

Response: Replacement Time
ANOVA for Selected Factorial Model
Analysis of variance table [Partial sum of squares]

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**Prob. > F**
Model	39827.7	3	13275.9	1.97E+08	< 0.0001
A	*25606.1*	*1*	*25606.1*	*3.80E+08*	*< 0.0001*
B	*11376.5*	*1*	*11376.5*	*1.69E+08*	*< 0.0001*
AB	*2845.07*	*1*	*2845.07*	*4.22E+07*	*< 0.0001*
Residual	8.08E-04	12	6.74E-05		
Cor Total	39827.7	15			

Increasing the corrosion rate with decreasing the corrosion allowance leads to decrease the replacement time.

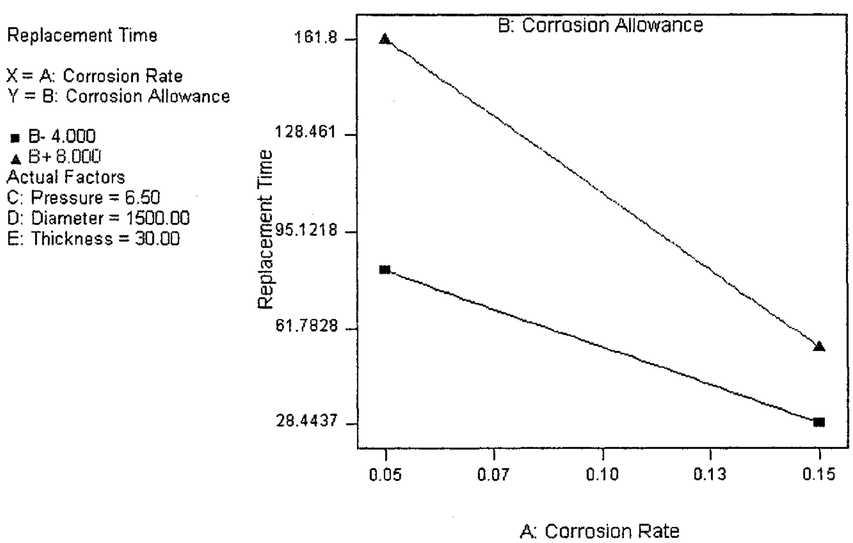

Figure B.2: Effect of changing the corrosion rate and corrosion allowance on the optimal replacement time