BACHELOR THESIS & COLLOQUIUM – ME 1841038

EVALUATION OF FUZZY METHODS TO DETERMINE PROBABILITY OF FAILURE COMPARED WITH RBI ANALYSIS FOR PRESSURE VESSEL IN OIL AND GAS COMPANY

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DOUBLE DEGREE PROGRAM
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APPROVAL FORM

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Submitted to comply one of the requirement to obtain a Bachelor Engineering Degree
On
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ABSTRACT

Maintenance activities conduct to manage and preserve assets integrity. Risk assessment is used to develop interval inspection hence, maintenance strategy can arrange perfectly. On the other hand, prescriptive inspection is still used as the main consideration to determine the inspection schedule. The consequence is an ineffective inspection activity. Past expert judgement was a major consideration in resulting prescriptive schedule which probably has not been reassessed and updated at present. A quantitative assessment can cover the probability and consequence of failure through a detailed assessment. The assessment takes time to be developed which complex systems and formulas are adjusted to the actual condition. Somehow, this task might be conducted by an external party who has expert knowledge. Therefore, within this schedule vacancy, any deterioration might occur in the system. A qualitative assessment can be done to estimate risk. Local engineers, who have basic knowledge of corrosion and other damage factors, can do the qualitative assessment. The result shall update the previous prescriptive methods. In processing qualitative assessment, fuzzy methods are chosen due to their ability to cover linguistic tasks and numerical value. In this paper, fuzzy logic was used to determine the probability of failure of equipment. The result was compared to API 581 RBI assessment. At the latter, risk value from both methods was evaluated to determine the inspection interval. Both types of equipment have close results from inspection interval calculation. Mostly, the inspection interval from the fuzzy method was earlier than RBI methods. From this calculation, the fuzzy results can be used as an estimation for the local engineer's consideration to determine any inspection based on qualitative assessment. If the result compared with an 8-years prescriptive inspection interval, inspection interval from qualitative assessment earlier conducted. It means asset integrity could be maintained more precisely. The equipment is pressure vessels in the utility area to support the boiler system from an Indonesian oil and gas company.

Keywords: Fuzzy Logic, Pressure Vessel, Qualitative Assessment, RBI

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EVALUASI METODE FUZZY UNTUK PENENTUAN PROBABILITAS KEGAGALAN DENGAN PERBANDINGAN ANALISA RBI UNTUK BEJANA BERTEKANAN DI PERUSAHAAN MINYAK DAN GAS

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ABSTRAK

Kegiatan pemeliharaan terus dilakukan untuk mengelola dan menjaga integritas aset. Penilaian risiko digunakan untuk mengembangkan inspeksi interval karenanya strategi pemeliharaan dapat mengatur dengan sempurna. Di sisi lain, inspeksi preskriptif masih digunakan sebagai pertimbangan utama untuk menentukan jadwal inspeksi. Konsekuensinya adalah kegiatan inspeksi tidak efektif. Pertimbangan ahli di masa lalu adalah pertimbangan utama dalam menghasilkan jadwal preskriptif yang mungkin belum dinilai kembali dan diupgrade saat ini. Penilaian kuantitatif mencakup probabilitas dan konsekuensi kegagalan melalui penilaian terperinci. Penilaian membutuhkan waktu untuk dikembangkan, sistem dan formula yang kompleks disesuaikan dengan kondisi aktual. Entah bagaimana, tugas ini mungkin dilakukan oleh pihak eksternal yang memiliki pengetahuan ahli. Oleh karena itu, dalam kekosongan jadwal ini, setiap kerusakan mungkin terjadi dalam sistem. Penilaian kualitatif dapat dilakukan untuk memperkirakan risiko. Insinyur lokal yang memiliki pengetahuan dasar tentang korosi dan faktor-faktor kerusakan lainnya dapat melakukan penilaian kualitatif. Hasilnya harus memperbarui metode preskriptif sebelumnya. Dalam memproses penilaian kualitatif, metode fuzzy dipilih karena kemampuannya melingkupi tugas linguistik dan nilai numerik. Dalam makalah ini, logika fuzzy digunakan untuk menentukan probabilitas kegagalan peralatan dan hasilnya dibandingkan dengan penilaian dari API 581 RBI. Yang terakhir, nilai risiko dari kedua metode dievaluasi untuk menentukan interval inspeksi. Dari dua jenis peralatan memiliki kemiripan hasil perhitungan interval inspeksi. Sebagian besar interval inspeksi dari metode fuzzy lebih awal daripada metode RBI. Dari perhitungan ini, hasil fuzzy dapat digunakan sebagai estimasi untuk pertimbangan insinyur lokal untuk menentukan inspeksi berdasarkan penilaian kualitatif. Jika hasilnya dibandingkan dengan interval inspeksi preskriptif 8 tahunan, interval inspeksi dari penilaian kualitatif didapatkan hasil jadwal inspeksi lebih awal. Ini berarti integritas aset dapat dipertahankan lebih tepat. Peralatan yang dikaji dalam makalah ini adalah bejana tekan di area utilitas untuk mendukung sistem boiler dari perusahaan minyak dan gas Indonesia.

Kata Kunci: Bejana Bertekanan, Logika Fuzzy, Penilaian Kualitatif, RBI

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PREFACE

Thank the Almighty God who has given His favor to the author for completing this bachelor thesis entitled "Evaluation of Fuzzy Method to Determine Probability of Failure Compared With RBI Analysis for Pressure Vessel in Oil and Gas Company". This paper is structured to meet the final tasks of the bachelor program at Sepuluh November Institute Science and Technology Surabaya.

The author would like to thank profusely to all those who have helped and contributed to completing the writing of this bachelor thesis.

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The author fully realizes that there is no such perfect writing. Therefore, the author expects criticism and constructive suggestion for this research. Finally, the author hopes that the writing of this paper can be useful for readers by assisting to expand their insight about fuzzy and RBI assessment.

Surabaya, January 20th 2020

Author

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CHAPTER I

INTRODUCTION

1.1 Background

LNG companies operate with complex equipment which support production of LNG. These equipment have to be monitored through maintenance schedule in term to maintain sustainability of its lifetime and reliable during periods of operation. Prescriptive inspection depends on time-based which number of next year inspection can be resulted from past engineers' judgement. Though this methods has lack due to maintenance cost, oil and gas industry worldwide using it as main determination of inspection schedule.

Maintenance costs being fluently high due to routine inspection, moreover, wrong inspection activities may lead to ineffective inspection (Perumal, 2014). Mechanical integrity has to be ensured by inspected at the intervals provided in international codes or based on a risk-based assessment (Shishesaz, et al., 2013). Present method to determine time interval for inspection is time-based which has been used in a long time. This determination has not been renewed or reassessed. Hence, an appropriate calculation of risk-based is required to replace traditional methods. It may allow previously established inspection interval to be updated.

A big number of companies are started to realize RBI assessment as an advantage to minimize maintenance costs and maximize the efficiency of inspection activities. Mostly RBI assessment is conducted by the contractor. Although API 581 RBI has already proven methods, in practical condition RBI assessment needs time to develop. Therefore within this schedule vacancy, a qualitative assessment could be done as research to estimate the risk of assets. It helps to analyze the probability of any damage to occur or spread by doing a prevention activity. Therefore, local engineers with basic knowledge of corrosion are able to do the assessment.

Also, this prescriptive methods shall be evaluated. A qualitative assessment can be a solution to this problem. Fuzzy logic is able to cover from linguistic tasks to a numerical value. Therefore, it is possible to do a risk assessment using the fuzzy method. In this paper, the determination of the inspection interval is explained with fuzzy logic compared with RBI analysis. The relevant uncertainties and producing a more precise method are confidently distributed by fuzzy approach (Selvik, et al., 2011).

This paper describes the methodology of a risk-based assessment conducted on 8 pressure vessels used in the utility area for supplying steam in the boiler system at an Indonesian oil and gas company. Qualitative assessment using fuzzy logic to determine the probability of failure is compared with API 581 RBI. At the latter, calculation from both methods was evaluated in terms to develop the inspection interval.

1.1 Problem Formulation

This research attempts to solve problems in the oil and gas industries which being struggled on maintaining the assets. Problem formulations are arranged below:

1. How to determine risk value for selected pressure vessels refer to API 581?
2. How to determine probability of failure for selected pressure vessels using fuzzy logic?
3. How to determine inspection interval based on API 581 and fuzzy logic?

1.2 Research Objective(s)

These followings are the objectives of this research as the main goals to be achieved, explained below.:

1. To assess value of risk of selected pressure vessels based on RBI API 581
2. To determine probability of failure of pressure vessels using fuzzy logic methods
3. To provide recommendation for time inspection based on inspection interval from RBI API 581 and fuzzy logic methods.

1.3 Scope of Problem(s)

To clarify this research, the limitation should be established. The limitations of this research are defined below:

1. Selected pressure vessel at utilities section in the Indonesian LNG Company, which are:
   a. Continuous Blowdown Tank
   b. Blow Off Drum
2. Fuzzy methods only covered probability of failure.
3. Consequences of failure is *area-based*.
4. Standard code for RBI assessment is from API (American Petroleum Institute) RP 581

1.4 Research Benefit(s)

From this paper, benefits that can be earned are defined as below:

1. This paper delivers qualitative assessment using fuzzy logic as alternative methods to determine probability of failure for pressure vessels
2. This paper gives recommendation in determining inspection interval using RBI methods for company where the data has taken from
3. The result of this paper can be a reference to any assessment using risk-based with typical topic for further development
4. This paper can be a research reference in risk assessment on university level

CHAPTER II
LITERATURE STUDY

2.1 LNG Company

Oil and gas company has expanded around the world and become a well-known business engaging in exploration, production, refinement, and distribution of oil and gas. Extracted oil and gas from exploration must be processed before distributed to consumers. Therefore, many companies are integrated to suppress the cost and maintain the quality of resulted oil and gas in an example, Chevron Corporation, and Exxon Mobile. Regularly, integrated companies categorized into two, which are upstream, which focusing on exploration and production, then downstream, focusing on refinement and marketing activities (corrosionpedia.com, 2019). In Indonesia, Pertamina which wholly owned by Indonesia's government supervises all production and monitors the distribution of oil and gas across the nation (Pertamina, 2019). Hence, Pertamina has many subsidiary companies that have jobs to support production, process, and refinement of energy, the latter will be distributed to people equally in every region in Indonesia.

The company focuses on providing services on processing, and refining gas from gas producer until becoming LPG and LNG also store them, the rest will be returned to Pertamina policy. Maintaining assets quality is prior to things due to service companies. Hence, maintenance has to be done regularly. Inspection Section in Technical Department is the main role to observe and analyze any deterioration occur either inside or outside of the equipment by conducting any inspection strategies which are internal inspection, external inspection or on-stream inspection. In this case, the equipment is pressure vessels consisted of continuous blowdown tank, blow off tank and deaerator.

2.2 Utilities

Pressure vessels are located in the utility section. Their function is to support boiler operation which directly contributed to producing LNG. From processing sour gas, which the first gas gotten from a gas producer, becomes sweet gas which is LNG and LPG, it is not missed from utility role. The LNG plant utilities comprise several things below:

a. Power generation and distribution system
b. Water system (freshwater, demineralized water)
c. Cooling water system
d. Heating system
e. Fuel gas system
f. Instrument and tool air system
g. Nitrogen system.

Utilities are prior things to be supplied to the system during the production of LNG, as input or output need to be maintained well and will be processed in the utility section. Several types of equipment below support utility section which contributed to supplying steam to boilers, releasing steam to the atmosphere or as a heat exchanger. This equipment is categorized as pressure vessel:

a. Continuous blowdown drum/ tank
b. Blow off drum/ tank
c. Deaerator
d. Surface Condenser
e. Etc.

2.2.1 Continuous Blowdown Drum/ Tank

The continuous blowdown tank is a flash tank that continuously removes water from a steam drum in order to control solids' content. Dissolved solid formed from the water that is not evaporated and stay still. The solids should be removed before it formed scales and became harder to maintain. Due to high temperature and water contents corrosion can occur. The presence of the solid impurities accelerates acids and alkalis to be created which influences an internal surface of the tank.

The flows from the flash tank are used to heat feed water so heat recovery can be achieved by installing heat exchangers. Controlling the blowdown process is essential to prevent explosions and other problems caused by temperature and pressure differences.

Figure 2.1. Continuous blowdown tank
Source:magnetrol.com

2.2.2 Blow Off Drum/ Tank

Similar to blowdown tank, blow off-tank blows the fluid off directly to sewage or atmosphere. The difference between blow off tank and blowdown tank is the output. Unnecessary fluids from the water drum will be released to atmosphere and sludge (impurities) will be released to a sewer. In fact, continuous blowdown tank and blow off tank are just named matter that depends on company desire.

Figure 2.2 Blow Off Tank
Source: Company file

2.2.3 Pressure Vessel Worldwide Accident

Pressure vessel stores very substances depend on the function of each industry. High temperature and higher pressure than atmospheric conditions able to cause disaster. The higher the operating pressure, the bigger the size of the vessel. The more energy will be released in the event of a rupture, the higher damage consequences occurred. The consequences of these accidents can damage the environment even human health. As economical aspects, loss of revenue, and cost of maintenance are a major concern as a result of incidents (Steihauser et al. 2014). Although many companies have practically complied with laws and regulations and use the latest technologies, accidents can happen involving pressure vessels particularly in Canada (Journey Energy Pipeline, Edmonton,2017) and United States (ExxonMobil refinery, Baton, Rouge, 2016). For instance, regarding the U.S Chemical Safety Board website, a pressure vessel accident occurred at Loy Lange Box Company reported on March 3, 2017. A massive explosion with 2000 pounds weight launch itself to air, killed one worker and other people injured by the initial explosion. The vessel flew a hundred feet before landed on a nearby company caused the fatal injury of three members of the company (U.S. Chemical Safety Board, 2017).

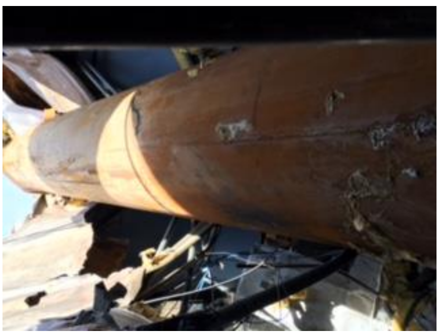

Figure 2.3 Loy Lange Box Accident
Source: csb.gov

Pressure vessel explosion occurred at a refinery in Skikda, Algeria on January 20, 2014. The accident caused 23 workers to die and damaged the whole area. In Houston Texas, in 2004 at a chemical plant, pressure vessel exploded. The accident shattered the entire city while leaving a large number of workers and citizens injured, damaged much public accommodation and residential building nearby.

Figure 2.4 Skikda LNG Accident
Source: timrileylaw.com

According to an analysis of accident conducted by Health and Safety Executive (HSE), mostly these accidents occurred because of several problems, there are (Croner-i, 2016):

a. Poor equipment and or system design
b. Poor installation
c. Lack on maintenance of equipment
d. Poor quality of repairs and modifications
e. An unsafe system of work

Law and regulation are only acting as mitigation and prevention. On-field, maintenance, and practical issues are handled by engineers. Therefore, any development is needed, one of which is risk analysis resulting in a risk-based inspection. Risk analysis must be done in terms to decrease any incident and giving correct inspection activities and schedule as a result of effectiveness and budgeting purpose. It cannot be concluded if the risk analysis has done so there will be no such incident in the future, risk analysis gives a significant decrease on any incident to occur in the future and acting as mitigation and prevention due to increasing quality of inspection and correct inspection interval for established equipment.

2.3 Bathtub Curve

This curve (Figure 2.5) describes a particular form of the deterioration function which divide into three parts. The reliability engineering widely used this “bathtub curve”. The first condition showed a decreasing failure rate, known as an early failure or infant mortality, then the constant failure rate appeared as the second condition. This condition also called “useful life”. The last condition is an increasing failure rate known as a wear-out failure. Mortality failure also called burn-in condition which typically occurs when a product is first to introduce in the early operation of a particular system. Random rate of failures corresponds to failures occurring during the useful life of the system. And for wear-out conditions, failures correspond to a failure occurring when the equipment or system operates beyond its design lifetime.

Most equipment or systems are suitable with a bathtub curve. In reliability engineering, these three conditions are analyzed using the Weibull equation correspond to continuous probability distribution functions. (Maisonnier, 2018)

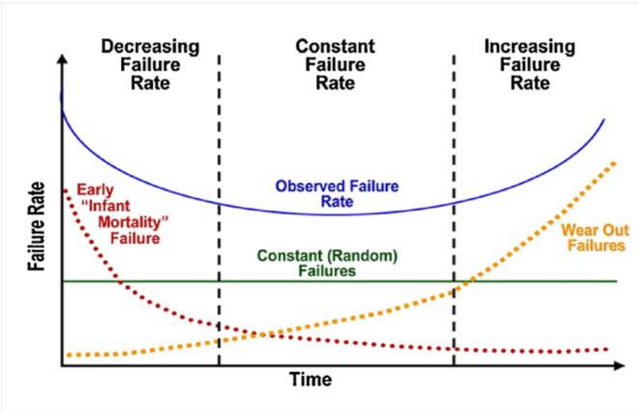

Figure 2.5 The bathtub curve
Source: allthingsnuclear.org

2.4 Damage Mechanisms

Determining damage mechanisms that occur on material construction surfaces are prime steps in terms to do RBI assessment. Besides observing and analyzing physical conditions, the inspection techniques need to be evaluated in order to quantify the damage.

a. Thinning damage
b. Component lining damage
c. External damage
d. Stress corrosion cracking
e. High Temperature Hydrogen Attack
f. Mechanical Fatigue
g. Brittle Fracture, including low temperature brittle fracture low alloy embrittlement, 885^{o}F embrittlement and sigma phase embrittlement

Damage mechanisms above are a must to be analyzed on each component of the vessel. When more than one damage mechanism occurs, the damage factor for each mechanism is calculated and combined in terms to determine the total damage factor.

According to NACE (National Association of Corrosion Engineers), there are eight forms of corrosion which quoted from Fontana & Greene (1967), stated as below (NACE International, 1967):

a. Uniform Attack
b. Galvanic or Two-Metal Corrosion
c. Crevice Corrosion
d. Pitting
e. Intergranular Corrosion
f. Selective leaching
g. Erosion corrosion
h. Stress-corrosion cracking

2.5 Inspection Activities

There are three types of inspection activities according to API 510 for pressure vessels, one of these activities shall be applied as inspection techniques depend on particular interval inspection. Therefore internal inspection, on-stream inspection, and external inspection shall be selected from an assessment.

2.5.1. Internal Inspection

An internal inspection is conducted inside the vessel by shutting it down and do sterilization before the engineer comes in. Check of internal pressure boundary surfaces shall be provided for checking the damage. The objective of these techniques is to find damage that cannot be found by regular monitoring.

2.5.2. On-Stream Inspection

An inspection while the equipment still working or on-stream. It is similar to visual inspection but the goal of on-stream inspection to know the actual thickness that measured by not shutting down the operation process.

Table 2.1 Comparison Internal Inspection and On-stream Inspection

Internal Inspection	On-Stream Inspection
Shutdown	Equipment still working
Need to do preparation for the equipment (cleaning and sterilization)	Not necessary
More Cost	Less cost even none

2.5.3. External Inspection

External inspections are conducted to check physical conditions of the outside surface of the vessel, insulation systems, painting and coating systems, supports, and associated structure and to check for leakage, hot spots, vibration, the allowance for expansion, and the general alignment of the vessel on its supports conducted by inspector or other qualified personnel in accordance to API

510. Welding used to attach on components need to give attention due to cracking or other defects.

2.6 Standard Code and Regulation

It is mandatory to follow international standards and regulations due to the prevention of accidents and safety to workers, companies, and the environment. Mostly standard and regulation are created as a safety factor and will be revised if something anomalies or accident happened. On doing maintenance, several standards are required to follow even from the first step of designing of the vessels.

a. ASME VIII Division 1, "*Rules for Construction of Pressure Vessels*"

American Society of Mechanical Engineers (ASME) established rules for the new construction of steam boiler and pressure vessel for concerning the technical aspects. This code contains mandatory requirements, specific prohibition and no-mandatory guidance for construction activities. This code supports data of calculation minimum thickness which either may not found in the inspection report or vessel general specification or the data suggested is not confident to be assessed.

b. API 510, "*Pressure Vessel Inspection Code: In-Service Inspection, Rating, Repair, and Alteration*"

API 510 is the main foundation of a standard on substituting internal inspection to on-stream inspection for pressure vessels. Also in this code explained about inspection interval for each risk classification resulted from RBI calculation.

c. API Recommended Practice 571, " *Damage Mechanisms Affecting Fixed Equipment in the Refining Industry*"

This code provides general guidance of damage mechanisms affecting common alloys used in the refining and petrochemical industry. This code can be a reference to inspection personnel to help identify likely causes of damage due to determine inspection strategies monitoring program to ensure vessels integrity.

d. API Recommended Practice 580, *" Risk-Based Inspection"*

In API RP 580, RBI is explained in briefly of the basic minimum and recommended elements in developing, implementing, and maintaining risk-based inspection. It also provides guideline issues included introduction to the concept and principle of RBI.

e. API Recommenden Practice 581, " *Risk-Based Inspection Methodology*"

This code provides a quantitative procedure to conduct an RBI assessment to establish an inspection interval for pressurized fixed equipment. In API RP 581 consists of the probability of failure (POF) combined with the consequence of failure (COF) in determinating risk classification.

f. Peraturan Menteri ESDM No. 38 Tahun 2017 Pasal 17:

This regulation stated that the certificate of proper function and commissioning certificate are valid for a maximum of 4 years or less when the equipment is modified or doubtful ability. (Verse 1) For instance, equipment with the remaining life is less than 4 years, certificate of proper function and commissioning certificate are valid for one-half of the remaining life.

2.7 Corrosion Rate and Remaining Life Assessment

A corrosion rate is a major factor in determining risk based on API 581 RBI. It used as input to determine the damage factor of equipment. Also, the corrosion rate can estimate the remaining life of an equipment.

2.7.1. Corrosion Rate Calculation

The corrosion rate is calculated from measured thickness data. Two variations of thickness data, in minimal, from different inspection intervals, shall be available due to increased accuracy of calculated corrosion rate.

There are two types of corrosion rate, short-term rate, and long-term rate. The long-term corrosion rate is a difference between initial thickness data and actual thickness reading divided by the time interval between the readings. However, the short-term corrosion rate is a difference between previous thickness reading and actual thickness reading divided by the time interval between the readings. The formula can be described as below:

$$Corrosion\ rate\ (LT) = \frac{t\ initial - t\ actual}{time\ between\ t\ initial\ and\ t\ actual\ (years)} \quad (2.1)$$

$$Corrosion\ rate\ (ST) = \frac{t\ previous - t\ actual}{time\ between\ t\ previous\ and\ t\ actual\ (years)} \quad (2.2)$$

Where,

a) $t_{initial}$ is the initial thickness at the same CML as t_{actual}. It is either the first thickness measurement at this CML or the thickness at the start of a new corrosion rate environment, in in. (mm)
b) t_{actual} is the actual thickness of a CML, in in. (mm), measured during the most recent inspection
c) $t_{previous}$ is the previous thickness measured during the prior inspection. It is at the same location as t_{actual} measured during a previous inspection, in in. (mm).

If the result of short-term corrosion rate calculation is significantly different from the long-term rate, the component may be evaluated using the short term rate.

2.7.2. Remaining Life Calculation

Previous corrosion rate calculation is the component to determine the remaining life of the equipment. Remaining life is a difference between two thickness readings divided by the corrosion rate (short-term or long-term rate). Same with corrosion rate, remaining life calculation has a short-term rate and long-term rate, configured in the equation (2.3).

$$Remaining\ Life = \frac{t\ actual - t\ required}{corrosion\ rate\ (ST\ or\ LT)} \qquad (2.3)$$

Where,

a) t_{actual} is the actual thickness of a CML, in in. (mm), measured during the most recent inspection

b) $t_{required}$ is the required thickness at the same CML or component, in in. (mm), as the tactual measurement. It is computed by the design formulas (e.g. pressure and structural) and does not include corrosion allowance or manufacturer's tolerances.

2.8 Risk-Based Inspection Assessment

RBI can determine inspection intervals. An RBI assessment determines risk by combining the probability and the consequence of equipment failure. When an owner/user chooses to conduct an RBI assessment, it shall include a systematic evaluation of both the probability of failure and the consequence of failure following API 580. API 581 details an RBI methodology that has all of the key elements defined in API 580. Identifying and evaluating potential damage mechanisms, current equipment condition, and the effectiveness of the past inspections are important steps in assessing the probability of a pressure vessel failure. Identifying and evaluating the process fluid(s), potential injuries, environmental damage, equipment damage, and equipment downtime are important steps in assessing the consequence of a pressure vessel failure.

2.8.1. Probability of Failure

Calculation of probability of failure divided into two sections which are the determination of damage factors and management systems factors. API 581 has provided damage mechanisms and questionnaires for management systems factors. The calculation of POF is arranged in the equation (2.4) .

$$P_f(t) = gff_{total} . D_f(t) . F_{MS} \qquad (2.4)$$

Where,

a) P_f (t) is the probability of failure

b) Gff is generic failure frequency

c) D_f (t) is the total damage factor

d) F_{MS} is the value of calculated management systems factor

2.8.2. Generic Failure Frequency (*gff*)

Generic failure frequency represents an industry failure rate to occurred in a year. This value is estimated using records from all plants within various companies and plants in the oil and gas industry. Gff provided by API 581 as a representative of failure due to degradation from operational service-affecting to the environment. The values are represented in several discrete hole sizes for various types of processing equipment (pressure vessels, drums, towers, piping systems, tankage, etc.). Table 2.2 provides the value of gff for vessel type of equipment. These values will be used in the RBI calculation furthermore.

Table 2.2. Gff value of vessel/finfan type equipment

Equipment Type	Component Type	gff as a function of Hole Size (Failures/ year)				gff total (failures/ year)
		Small	Medium	Large	Rupture	
Vessel/FinFan	KODRUM	8E-06	2E-05	2E-06	6E-07	3,06E-05

2.8.3. Damage Factors

The damage factor is determined based on the applicable damage mechanisms (local and general corrosion, cracking, creep, etc.) relevant to the materials of construction and the process service, the physical condition of the component, and the inspection techniques used to quantify the damage. The damage factor modifies the industry generic failure frequency and makes it specific to the component under evaluation.

Methods for determining damage factors are provided for the following damage mechanisms:

i. Thinning (both general and local)
ii. Component Linings
iii. External Damage (corrosion and stress corrosion cracking)
iv. Stress Corrosion Cracking (internal based on process fluid, operating conditions and materials of construction)
v. High Temperature Hydrogen Attack
vi. Mechanical Fatigue (Piping Only)
vii. Brittle Fracture (including low-temperature brittle fracture, temper embrittlement, 885 embrittlement, and sigma phase embrittlement.)

The total damage factors (DF total) got from the summary of all damage mechanisms. The value can be calculated from equation (2.5).

$$D_{f-total} = D_{f-gov}^{thin} + D_{f-gov}^{extd} + D_{f-gov}^{scc} + D_{f-gov}^{htha} + D_{f-gov}^{brit} + D_{f-gov}^{mfat} \quad (2.5)$$

Where,

a) $D_{f-total}$ is total calculated damage factor

b) D_{f-gov}^{thin} is governing thinning damage factor
c) D_{f-gov}^{extd} is governing external damage factor
d) D_{f-gov}^{scc} is governing stress corrosion cracking (SCC) damage factor
e) D_{f-gov}^{htha} is governing high temperature hydrogen attack (HTHA) damage factor
f) D_{f-gov}^{brit} is governing brittle fracture damage factor
g) D_{f-gov}^{mfat} is governing piping mechanical fatigue damage facture

2.8.4. Management Systems Factor

The management systems adjustment factor, FMS, accounts for the influence of the facility's management system on the mechanical integrity of the plant equipment. This factor accounts for the probability that accumulating damage which results in loss of containment will be discovered in time and is directly proportional to the quality of a facility's mechanical integrity program. This factor is derived from the results of an evaluation of a facility's or operating unit's management systems that affect plant risk. The evaluation conducted through a questionnaire. RBI inspector gives a score for each question delivered to the management. FMS value is got from the calculation of the final total score which method provided in equation (2.6) and (2.7).

$$pscore = \frac{Score}{1000}.100 \text{ [unit is \%]} \qquad (2.6)$$

$$F_{MS} = 10^{(-0.02.pscore+1)} \qquad (2.7)$$

Where,
a) $pscore$ is calculated score
b) $Score$ is total score obtained from questionnaire
c) F_{MS} is the value of management systems factor

2.8.5. Consequences of Failure

Consequences of failure are analysed using different techniques on each categories. API 581 provides 4 categories:

i. Flammable and explosive consequence is calculated using event trees combined with computer modelling to determine various outcome of probabilities (pool fires, flash fire, vapor cloud explosions). Consequence areas can be determined based on personnel injuries and equipment damage due to explosion and thermal radiation.
ii. Toxic consequence is calculated using computer modelling to determine radius of consequence area due to overexposure of personnel injury to toxic concentrations within vapor cloud. Where the fluid is flammable and toxic, if the release is ignited, the toxic consequence is minor (assuming toxics are consumed in the fire).
iii. Non-flammable, non-toxic consequence are considered because can result in any serious consequences. Physical explosions amd Boiling Liquid

Expanding Vapor Explosions (BLEVE) considered as cause of serious personnel injuries and equipment damage.

iv. Financial consequence calculated losses due to business interuption and costs associated with environmental releases. Business interuption is estimated from the result of flammable and non-flammable consequence area. Environmental consequnece is determined directly from calculation of mass available for release or from release rate.

2.8.6. Representative Fluid and Associated Properties

A representative fluid is being identified and evaluated that mostly closed to the fluid contained in the pressurized system. This action needed because pure materials are rarely found in plant streams. Some assumptions are regularly involved in the selection of representative fluid. Fluid properties are described based on stored liquid or stored vapor or gas below:

i. Store Liquid
   a) Normal Boiling Point, *NBP*
   b) Density, ρ
   c) Auto-Ignition Temperature, *AIT*

ii. Stored Vapor or Gas
   a) Normal Boiling Point, *NBP*
   b) Molecular Wieght, *MW*
   c) Ideal Gas Specific Heat Capacity Ratio, *k*
   d) Constant Pressure Specific Heat, C_p
   e) Auto-Ignition Temperature, *AIT*

2.8.7. Release Hole Size Selection

Several release holes are provided in Table 2.3. This table contains a discrete set of a limited number of release hole sizes. The release hole size is limited to a maximum diameter of 406 mm. These diameters represent a practical number of the maximum value for release calculation.

Table 2.3 Release Hole Size
Source: API RBI 581 2016

Release Hole Size	Range Hole Diameters (mm)	Release Hole Diameter, dn (mm)
Small	0-6.4	d_1=6.4
Medium	>6.4-51	d_2=25
Large	>51-152	d_3=102
Rupture	>152	d_4= min [D,406]

2.8.8. Release Rate Calculation

Release rates depend upon the physical properties of the material, the initial phase, the process operating conditions, and the assigned release hole sizes. A correct release rate equation must be chosen based on the phase of the fluid. Either liquid or vapor/gas phase has a different equation. Also, each phase has two types of discharge, sonic or subsonic. The fluid streams inside the continuous blowdown tank and blow off-tank is a vapor. In this case, the vapor or gas equation will be used, equation (2.9) and (2.10).

$$P_{trans} = P_{atm}\left(\frac{k+1}{2}\right)^{\frac{k}{k-1}} \qquad (2.8)$$

Where,

a) P_{trans} is transition pressure,kPa
b) P_{atm} is atmospheric pressure,kPa
c) k is constant, $k = \frac{C_p}{C_p - R}$
d) C_p is specific heat capacity, J/kg-K

i. If the storage pressure, P_s, within the equipment item is greater than the transitqual to P transion pressure, P_{trans}.

$$W_n = \frac{C_d}{C_2}.A_n.P_s.\sqrt{\left(\frac{k.MW.g_c}{R.T_s}\right).\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \qquad (2.9)$$

ii. If the storage pressure is less than or P_{trans}.

$$W_n = \frac{C_d}{C_2}.A_n.P_s.\sqrt{\left(\frac{MW.g_c}{R.T_s}\right).\left(\frac{2.k}{k-1}\right).\left(\frac{P_{atm}}{P_s}\right)^{\frac{2}{k}}\left[1-\left(\frac{P_{atm}}{P_s}\right)\right]^{\frac{k-1}{k}}} \qquad (2.10)$$

Where,

a) W_n is the theoretical release rate associated with n^{th} release hole size, kg/s
b) C_d is the release hole coefficient of discharge. C_d =0.9 is recommended.
c) C_2, customary conversion factors which C2 = 1000 mm^2/m^2
d) A_n is the hole area associated with the n^{th} release hole size, mm^2
e) P_s is the storage or normal operating pressure, kPa
f) MW is the release fluid molecular weight, kg/kg-mol
g) g_c is the gravitational constant
h) R is the universal gas constant = 8.314 J/kg-mol-K
i) T_s is the storage or normal operating temperature, K

2.8.9. Fluid Inventory Available for Release Estimation

Fluid mass can be contributed from the leaking component's inventory combined with other attached components. In determining available mass, this section is divided into two sides. The first one is evaluating inventory group mass and next is component mass.

i. Inventory Group Mass : the component being evaluated is part of larger group of components. Equation (11) is describing inventory group mass.

$$mass_{inv} = \sum_{i=1}^{N} mass_{comp,i} \quad (2.11)$$

ii. Component Mass : assuming for large leaks, operator/ engineer intervention will occur within three minutes. Therefore additional mass is calculated based on three minutes of leakage from the component's inventory group. For instance, the maximum flow rate to be added to the release from surrounding components, W_{max8}, with limited diameter leak 203 mm (8 inch) using the hole area A_n= 32,450 mm^2 (50.3 $inch^2$). W_{max8} can be calculated using equation (2.9) or (2.10).

$$mass_{add,n} = 180.\min[W_n, W_{max8}] \quad (2.12)$$

Equation (13) is used to calculate maximum mass available.

$$mass_{avail,n} = \min[\{mass_{comp} + mass_{add,n}\}, mass_{inv}] \qquad (2.13)$$

Where,

a) $mass_{avail,n}$ is the available mass for release for each of the release hole sizes selected, associated with the n^{th} release hole size, kgs
b) $mass_{add,n}$ is the additional mass that can be addedd to the release as tcontributed from the surroundings equipment, kgs
c) $mass_{comp}$ is the inventory fluid mass for the component or piece of equipment being evaluated, kgs
d) $mass_{inv}$ is the inventory group fluid mass , kgs
e) W_{max8} is the maximum flow rate of additional mass that can be added to the release as contributed from the surrounding equipment in the inventory group, kgs

2.8.10. Release Type (Continuous or Instantaneous)

The release is modeled into two types, instantaneous release and continuous release.

i. Instantaneous Release: type of release which occurs so rapidly that the fluid distibute as single cloud or pool.
ii. Continuous Release: type of release which occurs over a longer period of time. The fluid is distributed in the shape of an elongated ellipse.

Two criterias that a pressure vessel is categorized either instantaneous or continuous release type:

i. If the release hole size is 6.35 mm (0.25 inch) or less, then the release type is continuous.
ii. If $t_n \leq 180$ sec and the release mass is greater than 4,536 kgs (10,000 lbs), then the release is instantaneous; otherwise, the release is continuous.

Equation (2.14) is used to determine time required to release 4,536 kgs (10,000 lbs).

$$t_n = \frac{C_3}{W_n} \qquad (2.14)$$

Where,

a) t_n is the time to release 10,000 lbs fluid mass, calculated for each of the n release hole sizes selected, seconds
b) C_3 , customary conversion factor which C_3=4,536 kg (10,000 lbs)
c) W_n is the theoretical release rate with the nth release hole size, kg/s

2.8.11. Impact or Detection and Isolation Systems on Release Magnitude Estimation

Detection, isolation, and mitigation systems are commonly installed to reduce the effects of a release of the fluids. API RP 581 is providing a simplified methodology for assessing the effectiveness of various types of detection, isolation, and mitigation systems. In this assessment, detection and isolation systems are designed to detect and isolate a leak, and ten to reduce the magnitude also the duration of the release. On the other hand, mitigation systems are designed to mitigate or reduce the consequence of a release. In Table 2.4 and Table 2.5 classified grade of detection and isolation in estimation leak duration. There is no total leak duration provided for rupture hole (largest release hole which greater than 102 mm in diameter).

Table 2.4. Detection System Rating Guide
Source: API RBI 581 2016

Type of Detection System	**Detection Classification**
Instrumentation designed specifically to detect material losses by changes in operating conditions (i.e., loss of pressure or flow) in the system.	A
Suitably located detectors to determine when the material is present outside the pressure-containing envelope	B
Visual detection, cameras, or deterctors with marginal coverage	C
Type of Isolation System	**Isolation Classification**
Isolation or shutdown systems activated directly from process instrumentation or detectors, with no operator intervention	A
Isolation or shutdown systems activated by operators in the control room or the suitable locations remote from the leak	B
Isolation dependent on manually-operated valves	C

Table 2.5. Leak Duration Based on Detection and Isolation Systems
Source: API RBI 581 2016

Detection System Rating	Isolation System Rating	Maximum Leak Duration, ld max
A	A	20 minutes for 6,4 mm leaks
		10 minutes for 25 mm leaks
		50 minutes fro 102 mm leaks
A	B	30 minutes for 6,4 mm leaks
		20 minutes for 25 mm leaks
		10 minutes fro 102 mm leaks
A	C	40 minutes for 6,4 mm leaks
		30 minutes for 25 mm leaks
		20 minutes fro 102 mm leaks
B	A or B	40 minutes for 6,4 mm leaks
		30 minutes for 25 mm leaks
		20 minutes fro 102 mm leaks
B	C	1 hour for 6,4 mm leaks
		30 minutes for 25 mm leaks
		20 minutes fro 102 mm leaks
C	A,B or C	1 hour for 6,4 mm leaks
		30 minutes for 25 mm leaks
		20 minutes fro 102 mm leaks

2.8.12. Release Rate and Mass for Consequence of Failure

In section 2.6.8 has been explained the definition of each release rate, continuous-release rate, and instantaneous release rate. For continuous releases, the release is modeled as a steady-state flow. Therefore, the release rate (kg/s; lb/s) is used as the input to the consequence analysis. On the other hand, the instantaneous release is using mass as the input to the consequence analysis. Continuous releases and instantaneous releases are calculated using equation (2.15), (2.16) and (2.17).

$$rate_n = W_n(1 - fact_{di}) \quad (2.15)$$

$$mass_n = min[\{rate_n . ld_n\}, mass_{avail,n}] \quad (2.16)$$

$$ld_n = min\left[\left\{\frac{mass_{avail,n}}{rate_n}\right\}, \{60. ld_{max,n}\}\right] \quad (2.17)$$

Where,

a) $rate_n$ is the adjusted or mitigated discharge rate used in the consequence calculation associated with the n^{th} release hole size, kg/s

b) $fact_{di}$ is the release magnitude reduction factor, based on the detection isolations systems present in the unit

c) $mass_n$ is the adjusted or mitigaed discharge mass used in the consequence calculation associated with n^{th} release hole size, kgs

d) ld_n is the actual leak duration based on the available mass and the calculated release rate, associated with the n^{th} release hole size, seconds

e) $ld_{max,n}$ is the maximum leak duration associated with n^{th} release hole size, seconds

$fact_{di}$ is determined from previous assessment of detection and isolation systems ratings. API 581 provide the value of reduction factor based on both the ratings combination, in Table 2.6.

Table 2.6. Adjustments to Release Based on Detection and Isolation Systems Source: API RBI 581 2016

System Classification		Release Magnitude Adjustment	Reduction Factor, $fact_{di}$
Detection	**Isolation**		
A	A	Reduce release rate or mass by 25%	0.25
A	B	Reduce release rate or mass by 20%	0.20
A or B	C	Reduce release rate or mass by 10%	0.10
B	B	Reduce release rate or mass by 15%	0.15
C	C	No adjustment to release rate or mass	0.00

2.8.13. Non-Flammable Non-Toxic Consequence

Personnel injury and damage to equipment still can be the consequence of the releases of non-flammable and non-toxic materials. But not as severe as other consequences. In this case, steam represents a hazard to personnel nearby. Generally, steam is at 100°C immediately after exiting a hole in an equipment item. A mixture between steam and air, cool and condense within a few feet, depending upon its pressure. After reaching concentration about 20%, the mixture cools down to about 60°C. In this case, an assumption is used that injury occurs above 60°C. This temperature number is selected for injury to personnel as this is the temperature above the Occupational Safety and Health Administration (OSHA) requirement. Consequence area of a continuous release of steam can be calculated using equation (2.18) and for consequence area of instantaneous release using equation (2.19).

$$CA_{inj,n}^{CONT} = C_9.rate_n \qquad (2.18)$$

$$CA_{inj,n}^{INST} = C_{10}(mass_n)^{0.6384} \qquad (2.19)$$

Where,

a) $CA_{inj,n}^{CONT}$, consequence area for continuous release rate
b) $CA_{inj,n}^{INST}$, consequence area for instantaneous release rate
c) C_9, customary conversion factors which C_9=0.123 m^2.sec/kg
d) C_{10}, customary conversion factors which C_{10}= 9.744 $m^2/kg^{0.006384}$

For non-flammable releases of steam, the continuous/ intanstantaneous blending factor for steam leaks is calculated using equation (2.20).

$$fact_n^{IC} = min\left[\left\{\frac{rate_n}{C_5}\right\}, 1.0\right] \qquad (2.20)$$

Where,

a) $fact_n^{IC}$ is blending factor
b) C_5 , customary conversion factor which C_5= 25.2 kg/sec

The non-flammable and non-toxic consequences area are combined using equation (2.21).

$$CA_{inj,n}^{leak} = CA_{inj,n}^{INST}.fact_n^{IC} + CA_{inj,n}^{CONT}(1 - fact_n^{IC}) \qquad (2.21)$$

There is no need to calculate a component damage area for non-flammable and non-toxic releases of steam.

$$CA_{cmd,n}^{nfnt} = 0.0 \qquad (2.22)$$

2.8.14. Final Component Damage Consequence Area Calculation

The final step to conclude the result of consequence area by using equation (2.25).

$$CA_{cmd} = \max\left[CA_{cmd}^{flam}, CA_{cmd}^{tox}, CA_{cmd}^{nfnt}\right] \qquad (2.23)$$

$$CA_{inj} = \max\left[CA_{inj,n}^{flam}, CA_{inj,n}^{tox}, CA_{inj,n}^{nfnt}\right] \qquad (2.24)$$

$$CA = \max\left[CA_{cmd}, CA_{inj}\right] \qquad (2.25)$$

Where,

a) CA_{cmd}, consequence area for component damage
b) CA_{inj}, consequence area for personnel injury

In this paper, the flammable and toxic consequences are not being assessed. The reason is that the steam as the fluid streams inside the system. The steam doesn't content any flammable and toxic content, basically only water content.

2.9 Risk Calculation

Total calculated risk is obtained from calculated probability of failure and consequence area. The latter probability failure, damage factor and consequence of area will be plotted in the risk matrix according to terms provided in API 581.

$$R(t) = P_f(t).CA \qquad (2.26)$$

Where,

a) $R(t)$ is calculated risk, m^2/year

b) $P_f(t)$ is the probability of failure, /year

c) CA is the calculated consequence of area, m^2

2.10 Fuzzy Logic

Fuzzy logic is one method to approach risk assessment. Fuzzy logic enables to do mitigation due to differences that may occur during the risk assessment process. Mamdani type of fuzzy method is being used in this paper. There are 4 steps in the fuzzy logic method. They are fuzzification, implication, aggregation, and defuzzification.

a. Fuzzification, performs conversion from crisp input values to fuzzy sets (Mohsin, et al., 2019). There are 5 type of membership function: triangular, tapezoidal, gaussian , singleton, and piecewise linear. Triangular and trapezoidal has advantages on easiness in determining range. Gaussian is a natural type and has a smooth function on each points (Grima, et al., 2000)
b. Implication, store all of the fuzzy rules which later will be used as a foundation of correlation between inputs and outputs from a system. Multi consequences will be set into single consequence in fuzzy inference system method (Turksen & Celikyilmaz, 2006). General form of implication is IF-THEN.
c. Aggregation, is procedure to collect the result of implication from fuzzy set input that has been processed to output. The result of single implication represents actual value (Iancu, 2011).
d. Defuzzification, converts fuzzy set to single value which the final result from fuzzy inference system method.

Fuzzy logic can handle linguistic terms and numerical data which able to result in a better decision (Singh & Pokhrel, 2017). The objective of using a fuzzy logic system is to overcome the uncertainty of the assessed component (Sa'idi, et al., 2014). In the practical field, lack of information or incomplete data can lead to blurriness and uncertainty so it cannot be separated as an aspect of knowledge (Jamshidi, et al., 2013). Due to this condition, fuzzy has the reliability to work on uncertainty and imprecision data which has no sharp boundaries (Zadeh, 1965). Therefore in this paper, the fuzzy method is using to calculate the probability of failure.

2.10.1. Weighting Scheme

The first step after collecting data from questionnaire is doing weghting scheme. There are 4 respondents are selected to fill the questionnaire. Questions categories provided in Table 2.7.

Table 2.7 Weighting Score and Classifications

Categories	Classification	Score
Title	Lead Engineer	3
	Engineer	2
	Inspector	1
Service Time	>30 years	5
	20-30	4
	10-20	3
	5-10	2
	<5	1
Education level	Master	5
	Bachelor	4
	Junior College	3
	Technical Secondary	2
	School Level	1
	40-49	3
	30-39	2
	<30	1

The experts gave evaluation based on their experience and knowledge. Therefore, a weighting scheme is introduced to represent the relative quality of a different expert. If an expert is considered better than others, the better one shall be given a greater score. (Dong, 2005)

All collected score calculated using equation (27) and (28) for developing a weighting scheme.

$$Total\ Score = \sum Q_n \qquad (2.27)$$

$$Expert\ Weighting = \frac{Total\ Score\ E1}{Total\ Score\ Overall} \qquad (2.28)$$

Where,

a) Q is score for every question refer to the weighting table

2.10.2. Damage Mechanisms

There are 66 damage mechanisms according to API 571,” Damage Mechanisms Affecting Fixed Equipment in the Refining Industry”, in Table 2.8. Then, 7 types of damage mechanisms are assessed and selected because they have more probability to occur than others. The assessment is conducted by observation and literature study due to pressure vessel fluid content, material construction, operational parameters, and inspection history. The damage mechanisms are:

a. Thinning Damage
b. Boiler Water Corrosion
c. Soil Corrosion
d. Microbiologically Induced Corrosion
e. Erosion Corrosion
f. Thermal Fatigue
g. External Corrosion

A metal equipment is going to be corroded (thinning damage) sooner or later. As the operational hour goes, as does the corrosion rate. In the same condition and cyclic process, the number of corrosion rate is constant. Therefore, it was chosen because the damage mechanisms in the pressure vessel are overall only caused by general thinning damage.

Boiler water corrosion has a probability to occur because the pressure vessels contain boiler water as the fluid. Corrosion in boiler feedwater is usually the result of dissolved gases, oxygen and carbon dioxide, which lead to oxygen pitting corrosion and carbonic acid corrosion, respectively. (American Petroleum Institute, 2011). This may occur because of impurities inside the boiler feed water or an unperfect filtration process.

So does soil corrosion and microbiologically induced corrosion, they are caused by impurities in the water content. Soil corrosion and MIC can occur in the bottom side of the pressure vessel.

Thermal fatigue is the result of cyclic stress caused by variations in temperature. The damage is in the form of cracking. Even though the operational temperature of pressure vessels relatively constant, it unlikely to occur. But it has a greater possibility than other damage mechanisms shown in the table.

Erosion can be occurred because there is a relative of movement between, or impact from solids, liquids, vapor or any combination thereof. It caused the removal of surface material. Mostly, corrosion contributes to this situation, it is very rare that only erosion itself.

External corrosion or atmospheric corrosion highly occurs because moisture associated with atmospheric conditions. Dry places cause very little corrosion. This damage mechanism affects the outer layer of the pressure vessel.

All of these damages, mechanisms were selected based on a qualitative assessment by looking at the biggest probabilities from other 66 damage mechanisms. All selected damage mechanisms had probabilities which not equal to zero.

Each expertise assessed each damage mechanism that might occur in the pressure vessels based on their knowledge and experience. Expertises were selected because they are familiar with the condition and process system of the pressure vessels.

Table 2.8 Damage Mechanisms According to API 571

DM#	Damage Mechanism	DM#	Damage Mechanism
1	Sulfidation	32	Sigma Phase/ Chi Embrittlement
2	Wet H2S Damage (Blistering/HIC/SOHIC/SSC)	33	885ºF (475ºC) Embrittlement
3	Creep/ Stree Rupture	34	Softening
4	High temp H2/H2S Corrosion	35	Reheat Cracking
5	Polythronic Acid Cracking	36	Sulfuric Acid Corrosion
6	Napthenic Acid Corrosion	37	Hydrofluoric Acid Corrosion
7	Ammonium Bisulfide Corrosion	38	Flue Gas Dew Point Corrosion
8	Ammonium Chloride Corrosion	39	Dissimilar Metal Weld (DMW) Cracking
9	HCl Corrosion	40	Hydrogen Stress Cracking in HF
10	High Temperature Hydrogen Attack	41	Dealloying (Dezincification/ Denickelification)
11	Oxidation	42	CO_2 Corrosion
12	Thermal Fatigue	43	Corrosion Fatigue
13	Sour Water Corrosion (acidic)	44	Fuel Ash Corrosion
14	Refractory Degradation	45	Amine Corrosion
15	Graphitization	46	Corrosion Under Insluation (CUI)
16	Temper Embrittlement	47	Atmoshperic Corrosion
17	Decarburization	48	Ammonia Stress Corrosion Cracking
18	Caustic Cracking	49	Cooling Water Corrosion
19	Caustic Corrosion	50	Boiler Water / Condensate Corrosion
20	Erosion/ Erosion-Corrosion	51	Microbiologically Induced Corrosion (MIC)
21	Carbonate SCC	52	Liquid Metal Embrittlement
22	Amine Cracking	53	Galvanic Corrosion
23	Chloride Stress Corrosion Cracking	54	Mechanical Fatigue
24	Carburization	55	Nitriding
25	Hydrogen Embrittlement	56	Vibration-Induced Fatigue
26	Steam Blanketing	57	Titanium Hydriding
27	Thermal Shock	58	Soil Corrosion
28	Cavitation	59	Metal Dusting
29	Graphitic Corrosion	60	Strain Aging
30	Short term Overheating-Stress Rupture	61	Sulfate Stress Corrosion Cracking
31	Brittle Fracture	62	Phosphoric Acid Corrosion

Continue to next section

Table 2.8 Damage Mechanisms According to API 571

Continue from previous section

63	Phenol (carbolic acid) Corrosion	65	Oxygen-Enhanced Ignition and Combustion
64	Ethanol Stress Corrosion-Cracking	66	Organic Acid Corrosion of Distillation Tower Overhead Systems

2.10.3. Membership Function

A numerical approximation system was proposed to systematically convert linguistic terms to the corresponding fuzzy number (Dong, 2005). Triangular Fuzzy Number (TFN) is used over other methods in determining fuzzy value. Each TFN represents the level of probability level. The linguistics to express 4 expert opinions about the probability of failure for pressure vessels are "Low"," Medium"," Medium High", and "High". Each level is formed in identical shape and ratio. In this section, membership functions are formed using default distribution programmed in MATLAB. Table 2.9 describes the details.

Table 2.9 Membership functions

No.	Damage Mechanism	Probabilities	TFN
1	Low (L)	Low (L)	(0, 0, 0.33)
2	Medium (M)	Medium (M)	(0, 0.33, 0.67)
3	Medium High (MH)	Medium High (MH)	(0.33, 0.67, 1)
4	High (H)	High (H)	(0.67, 1, 1)

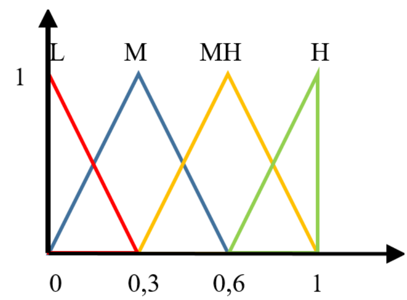

Figure 2.6 Graphical of membership function

2.10.4. Concordance Matrix

The graph formed by membership function is being analyzed to determine the union area and intersection area. Calculation of degree of agreement between experts opinion developed ratio between the intersection area and union area.

The concordance matrix was obtained by combining all degrees of agreements. Furthermore, a symmetric matrix with diagonal equal to 1 can be obtained because there are 4 selected experts. The matrix consisted of 4 rows and 4 columns for both union and intersection area matrix. (Leal & Naked, 2019)

$$CM = \frac{IA}{UA} \qquad (2.29)$$

Where,

a) DA is degree of agreement
b) IA is intersection area
c) UA is union area

2.10.5. Relative Concordance

Relative concordance is calculated for each specialist. The calculation is using formula in equation (30). (Leal & Naked, 2019)

$$RC_n = \sqrt{\left(\frac{1}{n-1}\right) * \sum (CM)^2} \qquad (2.30)$$

Where,

a) RC_n is the relative concordance for the nth experts
b) n is the amount number of experts

2.10.6. Relative Grade of Concordance

In relation to other exoerts opinion, the degree of realative agreement of each specialist is obtaine by calculate using formula in equation (31). (Leal & Naked, 2019)

$$RGC_n = \frac{RC_n}{\sum RC} \qquad (2.31)$$

Where,

a) RGC_n is the relative grade of concordance for the nth experts

2.10.7. Consensus Coefficient of the Specialist

In equation (32), formula is provided for calculating consesus coefficitent of each specialist. (Leal & Naked, 2019)

$$CCS_n = \frac{RGC_n * EW_n}{\sum (RGC * EW)} \qquad (2.32)$$

Where,

a) CCS_n is the consensus coeficient for the nth expert
b) EW_n is expert wieghting value for the nth expert

2.10.8. Triangular Fuzzy Number

Fuzzy value is obtained by multiplying the coefficient and default triangular fuzzy number for each qualitative assessment done by experts. The result is a new coordinate for new fuzzy value. (Leal & Naked, 2019)

$$TFN_n = \sum(CCS_n * n) \quad (2.33)$$

Where,

a) TFN_n is the triangular fuzzy umber coordinates fro the n^th expert opinion
b) n is the TFN relative to the linguistic terms used by the experts in qualitative assessment

2.11 Inspection Plan

Calculation of RBI results in an inspection plan by comparing risk targets and calculated risk. Each company has a risk target. If the results are overestimated, the inspection interval can be determined by a risk matrix. The risk matrix shows the risk category of equipment being assessed. API 510 has described several terms and conditions for each risk category for pressure vessels to determine the inspection interval.

In this assessment, fuzzy methods used to obtain the probability of failure. The calculation of the consequence area from RBI assessment was combined with Fuzzy-POF to obtain a risk value. So, the result of the inspection interval calculation is able to compare.

2.12 Risk Matrix

The calculated probability of failure and consequence of area are plotted on the risk matrix. POF is plotted on one axis while COF is plotted on others. The owner has a responsibility to define the category ranges and risk targets used. API 581 provides two types of risk matrix which are balance and unbalance.

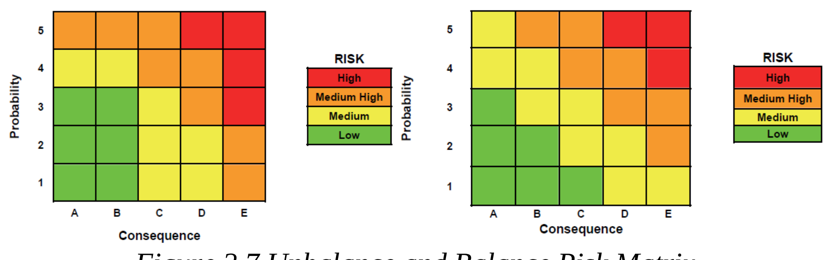

Figure 2.7 Unbalance and Balance Risk Matrix
Source: API RBI 581 2016

In API 581, category ranges of POF and CA are defined in Table 2.10. the indicators were used to plot PoF and CA in the risk matrix. Then it could be identified the risk category.

Table 2.10. Probability of Failure and Consequence of Failure Category
Source: API RBI 581 2016

Category	Probability Catergory		Consequence Category	
	Probability Range	Damage Factor Range	Category	Range (m2)
1	Pf ≤3.06E-05	Df ≤ 1	A	CA ≤ 9.29
2	3.06E-05< Pf ≤3.06E-04	1< Df ≤ 10	B	9.29< CA ≤ 92.9
3	3.06E-04< Pf ≤3.06E-03	10< Df ≤ 100	C	92.9< CA ≤ 929
4	3.06E-03< Pf ≤3.06E-02	100< Df ≤ 1,000	D	929< CA ≤ 9,290
5	Pf > 3.06E-02	Df > 1,000	E	CA > 9,290

CHAPTER III

METHODOLOGY

Figure 3.1 describes the flowchart of RBI and fuzzy logic calculation sequences.

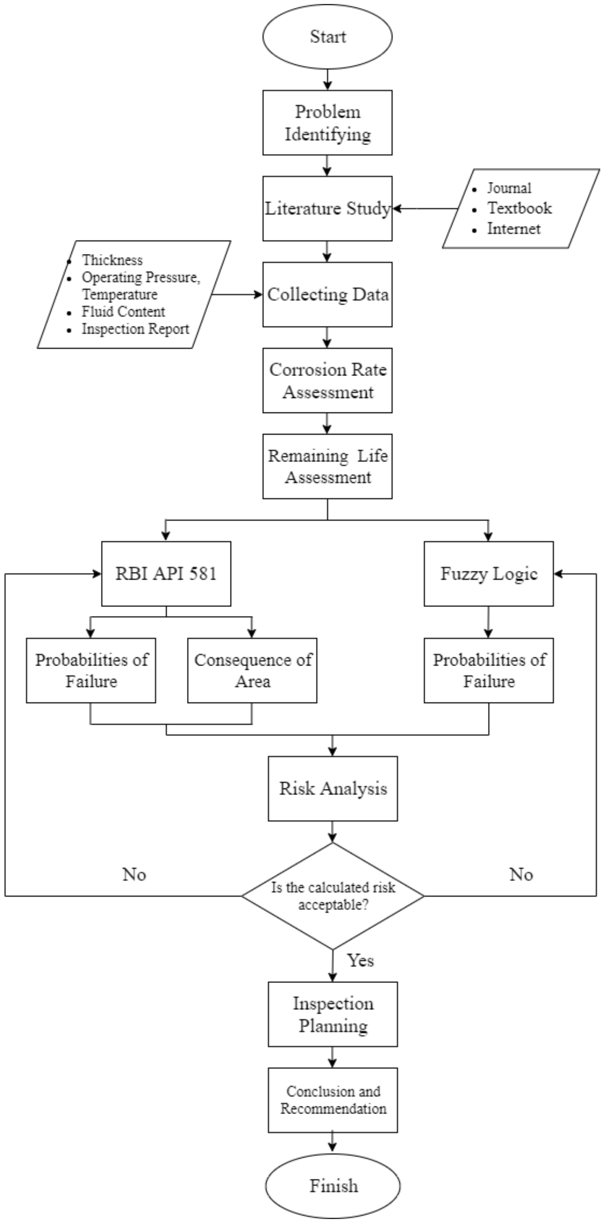

Figure 3.1 Reseacrh Flowchart

3.1 Problem Identifying

First identifying the problem about what, when, where, why and how the problem existed before doing the next step of the assessment. The objective is to give perspectives and directions to collect information that is needed.

3.2 Literature Study

References from established journals, articles, textbooks and standards are needed as supporting data to develop solution and ideas in terms of proposing recommendation of the problem.

3.3 Collecting Data

Quantitative assessment needs data such as thickness, temperature, pressure, contents of the fluid, inspection report, and type of material construction. All of them are required to be able to do a full assessment in resulting in a reliable risk calculation.

3.4 Corrosion Rate Assessment

A company shall record and save any inspection report regarding the actual thickness of the equipment. It is used to calculate the corrosion rate of the equipment. Through this method, it can be estimated when the equipment thickness reaches its maximum corrosion allowance. After it reached, the equipment can't be used for operational any longer.

3.5 Remaining Life Assessment

As one of the terms in substituting internal inspection to on-stream inspection, the remaining life of the asset has to be assessed. The calculation of the corrosion rate by comparing the actual thickness measurement, it develops the remaining life. Remaining life has to comply with the standards so the goal can be achieved.

3.6 Risk-Based Inspection (RBI) Calculation

Calculation of risk-based inspection below is refer to API 581, explained in part 3.6.1 and 3.6.2

3.6.1 Probability of Failure

In this section, equipment was being assessed according to its type, operational parameters, operational history, and management systems factor. API 581 provided a complex assessment to estimate the probability of failure for each equipment. General failure frequency (gff), damage factor, and management systems factor are three main division to be assessed in this section.

3.6.2 Consequences of Failure

Level 1 consequence analysis is performed in this paper. A consequence of failure calculated in detail refers to representative fluid in the system. A consequence of failre is calculated with a result of area-based.

The followings are steps that has to be done, stated as below:

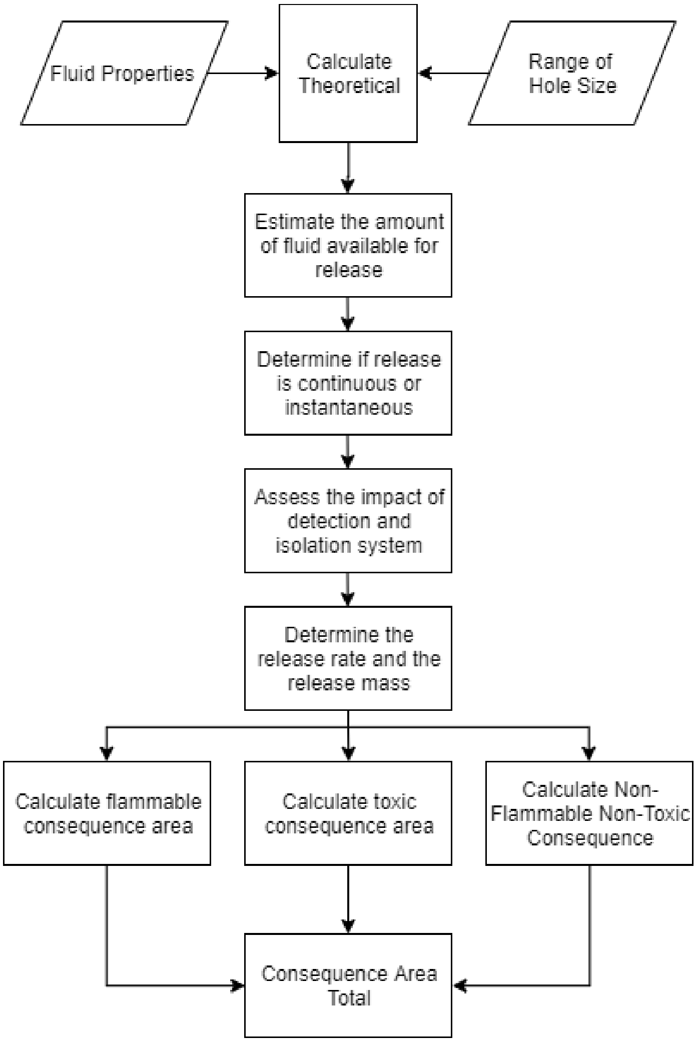

Figure 3.2 Consequence of Failure Flow Diagram

3.7 Fuzzy Logic

Risk assessment is completed with a fuzzy logic method. This paper is using a fuzzy inference system through software, MATLAB, to do a simulation of determining the probability of failure assessment. The latter will be compared with the risk target of the company.

Initial data is gotten from a qualitative assessment. Some questionnaires are collected from responsible inspection engineers. Respondents are divided based on their qualification through a weighting process. All the responds are responsible to determine the probabilities level of each damage mechanisms.

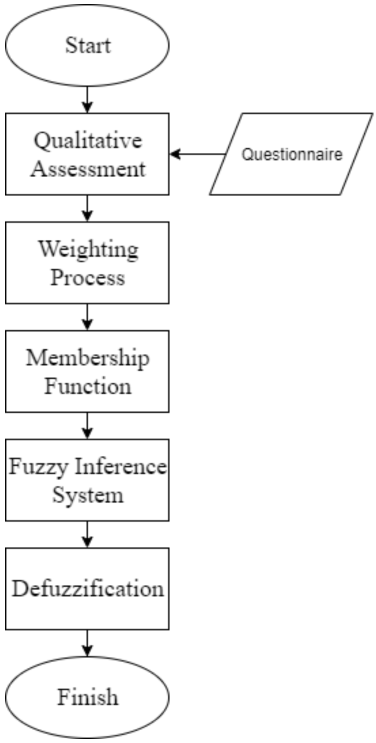

Figure 3.3 Fuzzy Logic Method Flow Diagram

3.7.1. Probabilities of Failure

Fuzzy logic is used to determine the probability of failure of the equipment. There are 7 damage mechanisms. Each damage mechanism categorized into one probabilities level. Each probabilities level was determined by the qualitative assessment. An estimate probabilities from the qualitative assessment were resulted by using complex calculation and matrix.

3.8 Risk Analysis

Risk got from doing multiplication of probability of failure and consequence of failure. Analyzing risk matrix that has been plotted by POF and COF to determine the category of risk, “Low Risk”, “Medium Risk”, and “ High Risk”. Each category has its interval inspection limit refer to API 510.

3.9 Inspection Planning

Inspection schedule as a result from RBI calculation either from RBI API 581 or fuzzy logic. It was served on a risk matrix while comparing calculated risk and required risk target.

3.10 Conclusion and Recommendation

From the result, data will be analyzed consider any mitigation plan will be done in the future to prevent or reduce error.

CHAPTER IV
SYSTEM DESCRIPTION

4.1. Utilities Configuration

Utility plants provide steam, water, air, nitrogen, and electricity into the production process of LNG and LPG. Several groundwater wells supply the water needs which has capacity 182-220 m^2/hour and pressure 2-4 kg/ cm^2. Water is used either for cooling systems or transforming to steam. Composition of groundwater is being used are explained as below:

Table 4.1. Groundwater Composition
Source: Company Utilities Data

Analysis Sample Point	Unit	Raw Water	Well #7	Well #8	Well #10	Well #12	Well #16
pH	Umhos/cm	5.38	2.97	4.24	4.29	5.44	4.87
Conductivity	Pt-Co scale	44.2	122.3	51.3	78.4	45.2	40.0
Color	mg/L	2.00	0.00	0.00	9.00	5.00	6.00
Total Solid	mg/L	67.0	87.0	44.0	92.0	42.0	44.0
Chloride,Cl	mg/L	2.30	1.00	0.60	1.50	1.30	1.10
Sulfate, SO4	mg/L	11.0	45.0	13.0	28.0	7.00	12.0
Silica, SiO4	mg/L	14.96	13.50	13.09	12.35	14.18	12.65
Nitrate, NO3	mg/L	0.07	0.20	0.03	0.05	0.01	0.04
Ammonia, NH3	mg/L	0.30	0.39	0.16	1.03	0.47	0.38
Total Hardness	mg/L	7.15	7.63	6.35	6.90	8.2	8.33
Iron, Fe	mg/L	3.19	4073	1.80	12.71	3.24	1.71
Copper, Cu	mg/L	0.07	<0.2	<0.2	<0.2	<0.2	<0.2
Calcium, Ca	mg/L	1.81	1.92	1.66	1.78	1.70	2.13
Magnesium, Mg	mg/L	0.81	0.68	0.53	0.59	0.95	0.72
Zinc, Zn	mg/L	0.02	0.02	<0.01	<0.01	<0.01	<0.01
Manganese	mg/L	0.07	0.08	0.04	0.03	0.09	0.06
Lead,Pb	mg/L	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Chromium, Cr	mg/L	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06
Mercury, Hg	mg/L						
Aluminum, Al	mg/L	0.081	1.918	0.188	0.084	0.047	0.077

Heated water distributes to 2 tanks, blow off the tank and continuous blowdown tank. Continuous blowdown tank inlet is on 3-5 cm height from the bottom side of the steam drum while blow off-tank inlet is on the bottom side of the water drum. High temperatures applied in the system transform water into steam. Configuration of the system can be seen in Figure 4.1.

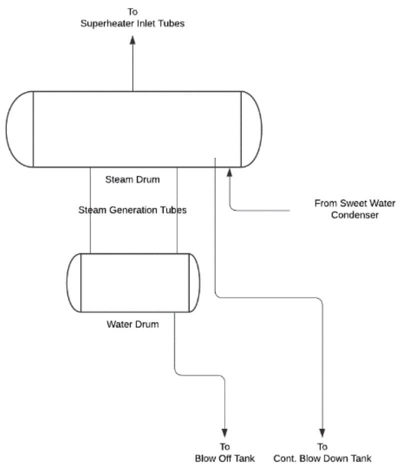

Figure 4.1 Distribution diagram of steam in utilities

4.2. Boiler Blowdown System

Blowdown is a drain water process which comes from boilers. The goal is to maintain a boiler water level conform with specification and standard so that scale, corrosion, carryover, and other problems can be minimized. Suspended solids can be removed during this process that occurs because of contaminated feed water and sediment as a result of internal chemical treatment.

Blowdown is a necessary process. Feed boiler water commonly contaminated with impurities such as dissolved solids. These impurities stay in the system and the latter will result in sediment also cause damage in pipe and steam trap. This sediment can transform into mud causing boiler efficiency drop and heat transfer drop. Therefore, boiler water in the system should be blowdown routinely to control the dissolved solids concentration.

This blowdown process often ignored. Imperfect blowdown process cause increased fuel consumption, additional chemical treatment, and heat loss. Moreover, high-temperature steam can be used for re-heating. This high-temperature steam flow back to the system to recover low-pressure steam that works as an economizer.

Two types of boiler blowdown which are continuous blowdown (CBD) and intermittent blowdown (IBD). Blowdown disposed of water has high temperature and high pressure, therefore, shall be cooled before releasing to the environment which using seawater as the cooler.

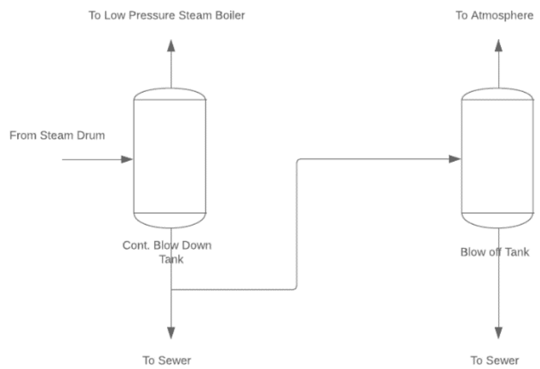

Figure 4.2 Diagram of continuous blowdown tank and blow off tank

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CHAPTER V

COLLECTED DATA

5.1 Equipment Data Sheet and Inspection Report

The equipment data sheet consists of actual condition data. Measured data and notes of equipment were written on a sheet for future engineer observation and company archives. A collection of a certain amount of equipment data sheets saved in one report called an inspection report. The folder keeps certain information that has similarities. Furthermore, separating into some category makes the job searching and analyzing easier.

Type of equipment, equipment dimensions, construction material, year built, temperature (operating and design), pressure (operating and design), and actual thickness reading were some prior information need to be listed in the equipment datasheet. Some information was collected from manufacturer specification.

5.2 Data Sheet Pressure Vessel

All of the equipment data were identified to analyze the risk grade of each equipment. Corrosion rate and remaining life were using measured thickness data below as input of formula (2.1) and (2.2) from Chapter II. Design parameters were used to identify consequence areas in the risk-based inspection calculation section. All of the data were collected due to actual measurements that had been done by local engineers or external parties. Those files were saved in the inspection report. Summary of equipment collected data attached in the attachment section.

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CHAPTER VI

RISK-BASED INSPECTION ASSESSMENT

6.1 Corrosion Rate Calculation

As have been mentioned in section 2.5.1, corrosion rates are calculated from measured thickness data using equation (2.1) and (2.2). In an example, one equipment was measured and resulted in actual-measurement thickness. Three thickness measurement was taken in 1998, 2015, and 2018. Within 1998 and 2018, thickness measurement was taken several times. But in this case, 1998 was taken as initial measurement data and 2015 and 2018 were taken as two latest measurement data. Each part of the equipment corrosion rate shall be calculated. Thickness measurement data from one blow-off tank shell part, 31-C-3, is exposed in Table 6.1.

Table 6.1 Summary of Thickness Measurement

Year	Thickness Measurement (mm)
1998	8,70
2015	8,01
2018	7,86

The data is being used as the input to the equation,

a. $$Corrosion\ rate\ (LT) = \frac{t\ initial - t\ actual}{time\ between\ t\ initial\ and\ t\ actual\ (years)}$$

$$= \frac{8{,}70\ mm - 7{,}86\ mm}{20\ years}$$

$$= 0{,}042\ mm/\ year$$

b. $$Corrosion\ rate\ (ST) = \frac{t\ previous - t\ actual}{time\ between\ t\ previous\ and\ t\ actual\ (years)}$$

$$= \frac{8{,}70\ mm - 8{,}01\ mm}{3\ years}$$

$$= 0{,}050\ mm/\ year$$

Short term and long term corrosion rates shall be compared which has the biggest number. The minor assessment shall be done to check the data integrity. Somehow, the biggest rate is generally chosen. On the other hand, short term corrosion rate is more preferable than long term corrosion rate due to the latest update of thickness measurement data.

Table 6.2 Summary of Corrosion Rates for Short Term

No. Tag	Equipment	Corrosion Rate (ST)	
		Shell	**Head**
31-C-3	Blow-Off Tank	0,05	0,013
31-C-8	Blow-Off Tank	0,07	0,093
31-C-10	CBD Tank	0,03	0,063
31-C-11	Blow Off Tank	0,01	0,03
31-C-13	Blow-Off Tank	0,003	0,0097
31-C-14	Blow-Off Tank	0,053	0,117
31-C-21	CBD Tank	0,027	0,027
31-C-22	CBD Tank	0,033	0,023

Table 6.3 Summary of Corrosion Rates for Long Term

No. Tag	Equipment	Corrosion Rate (LT)	
		Shell	**Head**
31-C-3	Blow-Off Tank	0,042	0,036
31-C-8	Blow-Off Tank	0,057	0,074
31-C-10	CBD Tank	0,078	0,085
31-C-11	Blow Off Tank	0,085	0,115
31-C-13	Blow-Off Tank	0,048	0,074
31-C-14	Blow-Off Tank	0,092	0,091
31-C-21	CBD Tank	0,023	-0,003
31-C-22	CBD Tank	0,014	0,009

6.2 Remaining Life Calculation

The corrosion rate is used as input to the remaining life calculation of an asset. The corrosion rate has to be calculated differently for each equipment. One corrosion rate is not universally used. Required thickness is being used as the lowest standard of operational equipment thickness. Required thickness for the example equipment is 2,4 mm.

$$Remaining\ Life\ = \frac{t\ actual - t\ required}{corrosion\ rate\ (ST\ or\ LT)}$$

a. For long term rate,

$$= \frac{7{,}86\ mm - 2{,}4\ mm}{0{,}042\ mm/year}$$

$$= 130\ year$$

b. For short term rate,

$$= \frac{7{,}86\ mm - 2{,}4\ mm}{0{,}050\ mm/year}$$

$$= 109{,}2\ year$$

Remaining life and corrosion rate calculation are important. These data are used to determine the inspection interval compare with the risk category of this risk assessment. API 510 provided the terms and conditions.

Table 6.4 Summary of Remaining Life for Short Term

No. Tag	Equipment	Remaining Life (ST), years	
		Shell	**Head**
31-C-3	Blow-Off Tank	109,2	567,75
31-C-8	Blow-Off Tank	56,13	75,13
31-C-10	CBD Tank	129,33	71,92
31-C-11	Blow Off Tank	560	171,3
31-C-13	Blow-Off Tank	1795,8	64,08
31-C-14	Blow-Off Tank	96,49	50,43
31-C-21	CBD Tank	244,5	275,63
31-C-22	CBD Tank	223,2	375,86

Table 6.5 Summary of Remaining Life for Long Term

No. Tag	Equipment	Remaining Life (LT), years	
		Shell	**Head**
31-C-3	Blow-Off Tank	130	207,4
31-C-8	Blow-Off Tank	69,12	94,49
31-C-10	CBD Tank	49,74	53,91
31-C-11	Blow Off Tank	65,88	49,87
31-C-13	Blow-Off Tank	124,98	83,47
31-C-14	Blow-Off Tank	55,87	65
31-C-21	CBD Tank	308,84	-
31-C-22	CBD Tank	520,8	982,24

The lowest value of the remaining life from each part of the equipment was chosen to represent the whole equipment. When one part of the equipment was broken, the whole equipment couldn't be used anymore.

6.3 Generic Failure Frequency (*gff*)

Gff value obtained from the table provided in API 581. The table shown in this section is selected based on equipment type and component type. In the table, the pressure vessel is categorized as a knock out drum. Then all value in Table 6.6 used as input in POF calculation.

Table 6.6 Gff value of vessel/finfan type equipment

Equipment Type	Component Type	gff as a function of Hole Size (Failures/ year)				gff total (failures/ year)
		Small	Medium	Large	Rupture	
Vessel/FinFan	KODRUM	8E-06	2E-05	2E-06	6E-07	3,06E-05

6.4 Damage Factors

The major damage in the pressure vessels is caused by thinning damage. Fluid in the vessels has assessed nad not found any harmful content such as acid, sulfur, and amine. The operational temperature is generally constant around 100°C-200°C. Therefore, the damage caused by high temperatures is not applied in this system. Operational pressure is working in a constant cycle and relatively low. So, brittle and fatigue damage is not applied in the system because of constant temperature and pressure.

API 581 provided 6 categories to determine the damage factor. All the damage factors are calculated using equation (2.5) in Chapter 2.

$$D_{f-total} = D_{f-gov}^{thin} + D_{f-gov}^{extd} + D_{f-gov}^{scc} + D_{f-gov}^{htha} + D_{f-gov}^{brit} + D_{f-gov}^{mfat}$$

In the pressure vessel, 31-C-3, only thinning damage factor occured. Therefore, D_{f-gov}^{thin} = 0,1. So,

$$D_{f-total} = 0{,}1$$

Table 6.7 Summary of total damage factor

No. Tag	Equipment	Total Damage Factor
31-C-3	Blow-Off Tank	0,1
31-C-8	Blow-Off Tank	0,1
31-C-10	CBD Tank	0,595
31-C-11	Blow Off Tank	0,1
31-C-13	Blow-Off Tank	0,1
31-C-14	Blow-Off Tank	0,1053
31-C-21	CBD Tank	0,16294
31-C-22	CBD Tank	0,1

6.5 Management Systems Factor

The management system factor value is obtained from the calculation of the total score in each category in the questionnaire. The score is being used as input for the calculation of management systems factor. This FMS questionnaire evaluates equipment based on the types. There are two types of equipment, continuous blowdown tank, and knock-off drum. One tank and others in the same type have similarities in management systems. Table 6.8 described the scores.

$$pscore = \frac{Score}{1000}.100 \text{ [unit is \%]}$$

$$= \frac{936}{1000}.100$$

$$= 93.6\%$$

$F_{MS} = 10^{(-0.02.pscore+1)}$

$= 10^{(-0.02.93,6+1)}$
$= 0,134$

Table 6.8 Management System Factor Questionnaire Score of Blow off Tank

Category	**Score**
Leadership and Administration	67
Process Safety Information	72
Process Hazard Analysis	91
Management of Change	79
Operating Procedures	76
Safe Work Practices	75
Taining	97
Mechanical Integrity	116
Pre-Startup Safety Review	60
Emergency Response	64
Incident Investigation	63
Contractors	45
Mangement Systems Assessments	31
Total	936

Table 6.9 Summary of FMS value

No.	**Equipment**	**FMS**
1	Blow-Off Tank	0,134
2	CBD Tank	0,134

6.6 Probability of Failure

The probability of failure calculates all the probability that might occur in each part of the pressure vessels. There are two parts which are shell and head. Gff, damage factor and management factors are combined to obtain the value of POF.

$P_f(t) = gff_{total}.D_f(t).F_{MS}$

$= 3,06x10^{-5}x0,1x0,134$
$= 4,1x10^{-7}$

Table 6.10 Summary of POF calculation

No. Tag	Equipment	Probability of Failure	
		Head	Shell
31-C-3	Blow-Off Tank	4,E-07	4,E-07
31-C-8	Blow-Off Tank	4,E-07	4,E-07
31-C-10	CBD Tank	2,E-06	4,E-07
31-C-11	Blow Off Tank	4,E-07	4,E-07
31-C-13	Blow-Off Tank	4,E-07	4,E-07
31-C-14	Blow-Off Tank	4,E-07	4,E-07
31-C-21	CBD Tank	7,E-07	4,E-07
31-C-22	CBD Tank	4,E-07	4,E-07

6.7 Determine the Representative Fluid and Associated Properties

In this first step in determining the consequence of failure, representative fluid and other associated properties are being described in terms to make assessment simpler. Liquid and vapor or gas have their focus properties. The fluid in pressure vessels, which is assessed, is vapor.

i. Stored Vapor or Gas
   a) Normal Boiling Point, *NBP*
   b) Molecular Wieght, *MW*
   c) Ideal Gas Specific Heat Capacity Ratio, *k*
   d) Constant Pressure Specific Heat, C_p
   e) Auto-Ignition Temperature, *AIT*

Table 6.11 Summary of Vapor Content

No.	Parameters	Value
1	Representative Fluid	Steam
2	Fluid Type	Type 0*
3	Molecular Weight	18 kg/kg-mol
4	Density	1000 kg/m^3
5	Normal Boiling Point	100^{o}C
6	Ambient State	Gas*
7	k	1
8	Cp	$2x10^{13}$J/kmol-K
9	Phase of Fluid at Normal Operating Condition	Gas*
10	Phase of Fluid at Ambient Conditions	Gas*
11	Final Phase for Consequence	Model as Gas*

*these informations refer to table that provided by API 581

6.8 Release Hole Size Selection

The diameter of each release holes is provided by API 581. The size started from a small, medium, large and rupture. For a small hole, the diameter starts at 0 up to 6.4 mm, but the release holes number used for calculation..

Table 6.12 Release Hole Size
Source: API RBI 581 2016

Release Hole Size	Range Hole Diameters (mm)	Release Hole Diameter, dn (mm)
Small	0-6.4	d_1=6.4
Medium	>6.4-51	d_2=25
Large	>51-152	d_3=102
Rupture	>152	d_4= min [D,406]

6.9 Release Rate Calculation

Transition pressure and service pressure shall be compared first before calculating the release rate. The purpose is to determine the type of flow either subsonic or sonic. Sonic flow applied when storage pressure is greater than transition pressure. If reverse condition applied then it is subsonic flow. This is an example calculation of equipment 31-C-3.

$$P_{trans} = P_{atm}\left(\frac{k+1}{2}\right)^{\frac{k}{k-1}}$$

$$= 101{,}3\ kPa\left(\frac{1+1}{2}\right)^{\frac{1}{1-1}}$$

$$= 167{,}1\ kPa$$

Table 6.13 Comparison between P_{trans} and P_{atm}

No. Tag	Equipment	Transition Pressure	Storage Pressure
31-C-3	Blow-Off Tank	167,05 kPa	103 kPa
31-C-8	Blow-Off Tank	167,05 kPa	345,2 kPa
31-C-10	CBD Tank	167,05 kPa	448,2 kPa
31-C-11	Blow Off Tank	167,05 kPa	104 kPa
31-C-13	Blow-Off Tank	167,05 kPa	345,2 kPa
31-C-14	Blow-Off Tank	167,05 kPa	345,2 kPa
31-C-21	CBD Tank	167,05 kPa	343,2 kPa
31-C-22	CBD Tank	167,05 kPa	103 kPa

Table 6.14 Calculation of area for each release hole

Parameters	Release Hole Diameter (mm)			
	6,4	25	102	406
Area (mm^2)	32,183	491,071	8174,571	129514

Because in pressure vessel 31-C-3 is less than P_{trans} then the subsonic formula is being used. All of the release holes shall be calculated.

$$= \frac{0{,}9}{1000}.32{,}183mm^2.102{,}97kPa.\sqrt{\left(\frac{18.1}{8{,}3145.383{,}15}\right).\left(\frac{2.1}{1-1}\right).\left(\frac{101{,}3}{102{,}97}\right)^{\frac{2}{1}}\left[1-\left(\frac{101{,}3}{102{,}97}\right)\right]^{\frac{1-1}{1}}}$$

$$= 0{,}0395\ kg/s$$

$$W_n = \frac{C_d}{C_2}.A_n.P_s.\sqrt{\left(\frac{MW.g_c}{R.T_s}\right).\left(\frac{2.k}{k-1}\right).\left(\frac{P_{atm}}{P_s}\right)^{\frac{2}{k}}\left[1-\left(\frac{P_{atm}}{P_s}\right)\right]^{\frac{k-1}{k}}}$$

Table 6.15 Summary of release rate calculation

No. Tag	Equipment	Release Rate for Release Diameter ,Wn (kg/s)			
		6,4	**25**	**102**	**406**
31-C-3	Blow-Off Tank	0,0395	0,6035	10,0455	159,1559
31-C-8	Blow-Off Tank	0,45	6,866	114,3045	1810,986
31-C-10	CBD Tank	0,56	8,5931	143,0437	2266,317
31-C-11	Blow Off Tank	0,05	0,7726	12,86	203,75
31-C-13	Blow-Off Tank	0,45	6,866	114,3045	1810,986
31-C-14	Blow-Off Tank	0,45	6,866	114,3045	1810,986
31-C-21	CBD Tank	0,4318	6,5889	109,6818	1737,746
31-C-22	CBD Tank	0,1295	1,9767	32,9045	521,3237

6.10 Estimate the Fluid Inventory Available for Release

Fluid inventory available for release estimation is calculated using 8 inch or 203 mm of diameter. The equation is using previous sonic or subsonic flow formula.

$$W_n = \frac{C_d}{C_2}.A_n.P_s.\sqrt{\left(\frac{MW.g_c}{R.T_s}\right).\left(\frac{2.k}{k-1}\right).\left(\frac{P_{atm}}{P_s}\right)^{\frac{2}{k}}\left[1-\left(\frac{P_{atm}}{P_s}\right)\right]^{\frac{k-1}{k}}}$$

$$= \frac{0,9}{1000}.32{,}450mm^2.102{,}97kPa.\sqrt{\left(\frac{18.1}{8{,}3145.383{,}15}\right).\left(\frac{2.1}{1-1}\right).\left(\frac{101{,}3}{102{,}97}\right)^{\frac{2}{1}}\left[1-\left(\frac{101{,}3}{102{,}97}\right)\right]^{\frac{1-1}{1}}}$$

$$= 39{,}877\ kg/s$$

Table 6.16 Summary of release rate maximum calculation

Parameters	Equipment							
	31-C-3	**31-C-8**	**31-C-10**	**31-C-11**	**31-C-13**	**31-C-14**	**31-C-21**	**31-C-22**
An Max (8 inch), mm2	32.450							
Wn Max (8 inch),kg/s	39,877	453,75	567,83	51,05	453,75	453,75	435,4	130,62

In determining mass component of the pressure vessel, basic mass density formula is used.

$$\rho = \frac{m}{V}$$

$$m = \frac{\rho}{V}$$

Known capacity of blow off tank, 31-C-3, is 12 m^3. For the fluid density , ρ, is using 997,95 kg/m^3.

$$m = \frac{997,95\ kg/m3}{12\ m3}$$
$$= 11.975\ kg$$

Table 6.17 Summary of mass component calculation

No. Tag	Equipment	Mass Component (kg)
31-C-3	Blow-Off Tank	11.975
31-C-8	Blow-Off Tank	7.984
31-C-10	CBD Tank	5.888
31-C-11	Blow Off Tank	4.690
31-C-13	Blow-Off Tank	7.984
31-C-14	Blow-Off Tank	7.984
31-C-21	CBD Tank	5.888
31-C-22	CBD Tank	11.975

i. The information inventory group mass is provided in table based on the type of equipment. For knock out drum, the liquid content maintained at 10% as the maximum value from mass component.
$mass_{inv} = \sum_{i=1}^{N} mass_{comp,i}$

Table 6.18. Summary of mass component calculation
Source: API RBI 2018

Equipment Description	Component Type	Example	Default Liquid Volume Percent
Knock-out Pots and Dryers	KODRUM	Compressor Knock-outs, Fuel Gas KO Drums, Flare Drums, Air Dryers	10% Liquid; Much Less liquid inventory expected in knock-out drums

Table 6.19 Summary of mass inventory calculation

No. Tag	Equipment	Mass Inventory (kg)
31-C-3	Blow-Off Tank	1198
31-C-8	Blow-Off Tank	798,4
31-C-10	CBD Tank	588,8
31-C-11	Blow Off Tank	469
31-C-13	Blow-Off Tank	798,4
31-C-14	Blow-Off Tank	798,4
31-C-21	CBD Tank	588,8
31-C-22	CBD Tank	1198

ii. Component mass is calculated by using 3 minutes multiple by the minimum value between release rate from each diamater and release rate maximum with 203 mm or 8 inch diameter.

$$\begin{aligned} mass_{add,n} &= 180.\min[W_n, W_{max8}] \\ &= 180.\min[0{,}0395; 39{,}8768] \\ &= 180.\,0{,}0395 \\ &= 7{,}119\ kg \end{aligned}$$

Table 6.20 Summary of mass addition calculation

No. Tag	Equipment	Mass Addition for Release Diameter, $mass_{add,n}$ (kgs)			
		6,4	**25**	**102**	**406**
31-C-3	Blow-Off Tank	7,119	108,623	1808,188	7177,831
31-C-8	Blow-Off Tank	81,002	1235,992	20574,812	81674,33
31-C-10	CBD Tank	101,368	1546,753	25747,875	102209,46
31-C-11	Blow Off Tank	9,113	139,06	2314,854	9189,107
31-C-13	Blow-Off Tank	81,002	1235,992	20574,812	81674,332
31-C-14	Blow-Off Tank	81,002	1235,992	20574,812	81674,332
31-C-21	CBD Tank	77,726	1186,005	19742,721	78371,29
31-C-22	CBD Tank	23,318	355,802	5922,816	23511,372

Mass available of the pressure vessel is calculated by taking the minimum value between mass inventory and mass component plus mass addition.

$$\begin{aligned} mass_{avail,n} &= \min[\{mass_{comp} + mass_{add,n}\}, mass_{inv}] \\ &= \min[\{11975 + 7{,}119\}, 1198] \\ &= 1198\ kg \end{aligned}$$

Table 6.21 Summary of mass available calculation

No. Tag	Equipment	Mass Available for Release Diameter, $mass_{avail,n}$ (kg)			
		6,4	**25**	**102**	**406**
31-C-3	Blow-Off Tank	1197,5			
31-C-8	Blow-Off Tank	798,36			
31-C-10	CBD Tank	588,79			
31-C-11	Blow Off Tank	469,037			
31-C-13	Blow-Off Tank	798,36			
31-C-14	Blow-Off Tank	798,36			
31-C-21	CBD Tank	588,79			
31-C-22	CBD Tank	1197,54			

6.11 Determine the Release Type (Continuous or Instantaneous)

Continuous and instantaneous release type are determined through calculation. These are the terms to categorize the release type:

i. If the release hole size is 6.35 mm (0.25 inch) or less, then the release type is continuous.

ii. If $t_n \leq 180$ sec and the release mass is greater than 4,536 kgs (10,000 lbs), then the release is instantaneous; otherwise, the release is continuous.

Equation (14) in chapter 2 is used to determine time required to release 4,536 kgs (10,000 lbs). An example calculation for equipment 31-C-3 is described below:

$$t_n = \frac{C_3}{W_n}$$

$$= \frac{4536\ kg}{0{,}0395\ kg/s}$$

$$= 11.464{,}453\ s$$

Table 6.22 Summary of time required calculation

No. Tag	Equipment	Time Required for Release Diameters ,t_n(s)			
		6,4	**25**	**102**	**Rupture**
31-C-3	Blow-Off Tank	11.464,453	7516,616	451,546	28,5
31-C-8	Blow-Off Tank	10.079,757	660,587	39,683	2,505
31-C-10	CBD Tank	8054,611	527,867	31,711	2,001
31-C-11	Blow Off Tank	89.590,580	5871,408	352,713	22,262
31-C-13	Blow-Off Tank	10.079,757	660,587	39,683	2,505
31-C-14	Blow-Off Tank	10.079,757	660,587	39,683	2,505
31-C-21	CBD Tank	10.504,596	688,429	41,356	2,610
31-C-22	CBD Tank	35.015,287	2294,762	137,853	8,701

Table 6.23 Summary of type of release

No. Tag	Equipment	Type of Release for Release Diameters			
		6,4	**25**	**102**	**Rupture**
31-C-3	Blow-Off Tank	Continuous	Continuous	Continuous	Instantaneous
31-C-8	Blow-Off Tank	Continuous	Continuous	Instantaneous	Instantaneous
31-C-10	CBD Tank	Continuous	Continuous	Instantaneous	Instantaneous
31-C-11	Blow Off Tank	Continuous	Continuous	Continuous	Instantaneous
31-C-13	Blow-Off Tank	Continuous	Continuous	Instantaneous	Instantaneous
31-C-14	Blow-Off Tank	Continuous	Continuous	Instantaneous	Instantaneous
31-C-21	CBD Tank	Continuous	Continuous	Instantaneous	Instantaneous
31-C-22	CBD Tank	Continuous	Continuous	Instantaneous	Instantaneous

6.12 Estimate the Impact or Detection and Isolation Systems on Release Magnitude

The estimation of impact or detection and isolation system on release magnitude has been provided by API 581. In the system, detection equipment such as pressure gauge and temperature gauge are provided. Therefore, any losses or abnormal condition must be detected. Also, all operators are working on a remote space were able to monitor ongoing operation in the system. So, grade B for both detection and isolation system for pressure vessel in this assessment.

Table 6.24. Detection and Isolation System Rating Guide
Source: API RBI 581 2016

Type of Detection System	**Detection Classification**
Suitably located detectors to determine when the material is present outside the pressure-containing envelope	B
Type of Isolation System	**Isolation Classification**
Isolation or shutdown systems activated by operators in the control room or the suitable locations remote from the leak	B

Table 6.25 Leak Duration Based on Detection and Isolation Systems
Source: API RBI 581 2016

Detection System Rating	**Isolation System Rating**	**Maximum Leak Duration, ld max**
B	A or B	40 minutes for 6,4 mm leaks
		30 minutes for 25 mm leaks
		20 minutes fro 102 mm leaks

6.13 Determine the Release Rate and Mass for Consequence of Failure

Each grade in the detection and isolation system affected the calculation. In this case, the reduction factor is equal to 0.15 because both systems are marked as grade B. This factor is used to calculate release rate and release mass. Pressure vessel 31-C-3 is being used as an example of the calculation. The release rate is used for calculating a continuous type of release hole, but also as an input for release mass calculation.

Table 6.26 Adjustments to Release Based on Detection and Isolation Systems
Source: API RBI 581 2016

System Classification		**Release Magnitude Adjustment**	**Reduction Factor, $fact_{di}$**
Detection	**Isolation**		
B	B	Reduce release rate or mass by 15%	0.15

$$rate_n = W_n(1 - fact_{di})$$
$$= 0{,}0395\ (1 - 0{,}15)$$
$$= 0{,}0336$$

Table 6.27 Summary of release rate for each release diameters

No. Tag	Equipment	Release Rate for Release Diameters ,$rate_n$ (kg/s)			
		6,4	**25**	**102**	**Rupture**
31-C-3	Blow-Off Tank	0,0336	0,5129	8,5387	135,2825
31-C-8	Blow-Off Tank	0,3825	5,8366	97,1588	1539,3381
31-C-10	CBD Tank	0,4787	7,3041	121,5872	1926,369
31-C-11	Blow Off Tank	0,043	0,6567	10,9313	173,1896
31-C-13	Blow-Off Tank	0,3825	5,8366	97,1588	1539,3381
31-C-14	Blow-Off Tank	0,3825	5,8366	97,1588	1539,3381
31-C-21	CBD Tank	0,367	5,6	93,2295	1477,084
31-C-22	CBD Tank	0,1101	1,68	27,969	443,125

Table 6.28 Maximum Leak Duration
Source: API 581 2016

Release Size (mm)	Maximum Leak Duration, *ldmax*
6,4	2400
25	1800
102	1200
Rupture	-

The Leak duration for each release size is being calculated. Leak duration is needed for calculating release mass. Release mass calculation applied when the release type of a certain hole is instantaneous.

$$ld_n = min\left[\left\{\frac{mass_{avail,n}}{rate_n}\right\}, \{60.\,ld_{max,n}\}\right]$$
$$= min\left[\left\{\frac{1197{,}54\ kg}{135{,}2825\ kg/s}\right\}, \{60.\,ld_{max,n}\}\right]$$
$$= 8{,}8521\ s$$

Table 6.29 Summary of leak duration for instantaneous type

No. Tag	Equipment	Duration for Instantaneous Type (s)	
		102	**Rupture**
31-C-3	Blow-Off Tank	-	8,852
31-C-8	Blow-Off Tank	8,2171	0,5186
31-C-10	CBD Tank	4,8425	0,3056
31-C-11	Blow Off Tank	-	2,7082

Continue to next section

Table 6.29 Summary of leak duration for instantaneous type

Continued from previous section

31-C-13	Blow-Off Tank	8,2171	0,5186
31-C-14	Blow-Off Tank	8,2171	0,5186
31-C-21	CBD Tank	6,3155	0,3986
31-C-22	CBD Tank	42,8169	2,7025

$$
\begin{aligned}
mass_n &= min\left[\{rate_n . ld_n\}, mass_{avail,n}\right] \\
&= min[\{0{,}0336 .8{,}8521\}, 1197{,}5] \\
&= 1197{,}5403 \text{ kg}
\end{aligned}
$$

Table 6.30 Summary of mass rate calculation

No. Tag	Equipment	Mass Rate, $mass_n$ (kg)	
		102	**Rupture**
31-C-3	Blow-Off Tank	-	1197,54
31-C-8	Blow-Off Tank	798,3602	
31-C-10	CBD Tank	588,7907	
31-C-11	Blow Off Tank	-	469,0366
31-C-13	Blow-Off Tank	798,3602	
31-C-14	Blow-Off Tank	798,3602	
31-C-21	CBD Tank	588,7907	
31-C-22	CBD Tank	1197,54	

6.14 Determine Non-Flammable Non-Toxic Consequence

Heating water will produce steam. This steam is not an explosive and toxic material. All the content has been assessed in the previous section therefore flammable and toxic consequence part was not assessed. Consequence area for continuous and instantaneous release rate is calculated for each release holes.

For continuous release rate:

$$
\begin{aligned}
CA_{inj,n}^{CONT} &= C_9 . rate_n \\
&= 0{,}123 \frac{m2s}{kg} x \; 0{,}0336 \; kg/s \\
&= 0{,}004 \; m2
\end{aligned}
$$

For instantaneous relase rate:

$$
\begin{aligned}
CA_{inj,n}^{INST} &= C_{10} (mass_n)^{0.6384} \\
&= 9{,}744 \; m2/kg (1197{,}5403 \; kg)^{0.6384} \\
&= 899{,}3271 \; m2
\end{aligned}
$$

Table 6.31 Summary of consequence area for conituous and instantaneous calculation

No. Tag	Equipment	Consequence Area for Continuous and Instantaneous per Release Diameter (m2)			
		6,4	**25**	**102**	**Rupture**
31-C-3	Blow-Off Tank	0,004	0,0063	1,050	899,3271
31-C-8	Blow-Off Tank	0,047	0,718	694,2263	694,2263
31-C-10	CBD Tank	0,059	0,898	571,5843	571,5843
31-C-11	Blow Off Tank	0,005	0,081	1,345	494,3513
31-C-13	Blow-Off Tank	0,047	0,718	694,2263	694,2263
31-C-14	Blow-Off Tank	0,047	0,718	694,2263	694,2263
31-C-21	CBD Tank	0,045	0,689	571,5843	571,5843
31-C-22	CBD Tank	0,014	0,207	899,3271	899,3271

Intanstaneous release rate

The blending factor is used as a combination to merge consequence are for continuous and instantaneous. The final result is a single consequence area for an equipment.

$$fact_n^{IC} = min\left[\left\{\frac{rate_n}{C_5}\right\}, 1.0\right]$$
$$= min\left[\left\{\frac{0,336}{25,2}\right\}, 1.0\right]$$
$$= 0,001$$

Table 6.32 Summary of blending factor calculation

No. Tag	Equipment	Blending Factor, $fact_n^{IC}$			
		6,4	**25**	**102**	**Rupture**
31-C-3	Blow-Off Tank	0,001	0,02	0,339	1
31-C-8	Blow-Off Tank	0,015	0,232	1	1
31-C-10	CBD Tank	0,019	0,29	1	1
31-C-11	Blow Off Tank	0,002	0,026	0,434	1
31-C-13	Blow-Off Tank	0,015	0,232	1	1
31-C-14	Blow-Off Tank	0,015	0,232	1	1
31-C-21	CBD Tank	0,015	0,222	1	1
31-C-22	CBD Tank	0,004	0,067	1	1

One of the consequence area categories is CA leak for personnel injury, another one is for component damage. All of the previous results are combined using blending factor in resulting consequence area for personnel injury.

$$CA_{inj,n}^{leak} = CA_{inj,n}^{INST}.fact_n^{IC} + CA_{inj,n}^{CONT}(1 - fact_n^{IC})$$

$= (899{,}3271\ x\ 1) + \left(0{,}004\ x\ (1 - 0{,}001)\right) + \left(0{,}063\ x(1 - 0{,}02)\right) + (1{,}05\ x\ (1 - 0{,}339))$
$= 900{,}0875\ m2$

Table 6.33 Summary of CA leak calculation

No. Tag	Equipment	Consequence of Leak for Personnel Injury, $CA_{inj,n}^{leak}$ (m2)
31-C-3	Blow-Off Tank	900,09
31-C-8	Blow-Off Tank	694,824
31-C-10	CBD Tank	572,28
31-C-11	Blow Off Tank	495,197
31-C-13	Blow-Off Tank	694,824
31-C-14	Blow-Off Tank	694,824
31-C-21	CBD Tank	572,165
31-C-22	CBD Tank	899,5335

In the calculation scheme, API 581 gives a note that there is no need to calculate a component damage area for non-flammable and non-toxic releases of steam. So,
$CA_{cmd,n}^{nfnt} = 0.0$

6.15 Final Component Damage Consequence Area

The final calculation to obtain the value of the consequence area. Because there is no component damage for non-flammable and non-toxic consequence so it is equal to zero.

$$CA_{cmd} = \max\left[CA_{cmd}^{flam}, CA_{cmd}^{tox}, CA_{cmd}^{nfnt}\right]$$

$$CA_{cmd} = 0$$

Only non-flammable and non-toxic consequence is assessed so CA nfnt the only have that has value.

$$CA_{inj} = \max\left[CA_{inj,n}^{flam}, CA_{inj,n}^{tox}, CA_{inj,n}^{nfnt}\right]$$

$$CA_{inj} = \max[0\ ;0\ ;900{,}087]$$

$$CA_{inj} = 900{,}087\ m2$$

The final consequence of area is gotten from comparing CA component damage and CA for personnel injury. In this case, blow-off tank, 31-C-3, is used as an example of the calculation.

$$CA = \max\left[CA_{cmd}, CA_{inj}\right]$$

$$CA = 900{,}087\ m2$$

Table 6.34 Summary of final consequence area calculation

No. Tag	Equipment	Total Consequence Area, CA (m2)
31-C-3	Blow-Off Tank	900,09
31-C-8	Blow-Off Tank	694,824
31-C-10	CBD Tank	572,28
31-C-11	Blow Off Tank	495,197
31-C-13	Blow-Off Tank	694,824
31-C-14	Blow-Off Tank	694,824
31-C-21	CBD Tank	572,165
31-C-22	CBD Tank	899,534

6.16 Risk Calculation

Risk is a multiplication between the probability of failure and consequence area. Probability failure for each part of the equipment has its value. But for a consequence, the area only provided one value for whole equipment. In this case, two values of risk gotten from head part and shell part for every pressure vessels.

$$R(t) = P_f(t).CA$$
$$= 4{,}1x10^{-7}.900{,}087\ m2$$
$$= 3{,}7x10^{-4}$$

Table 6.35 Summary of risk calculation

No. Tag	Equipment	Risk (m2/year)	
		Head	Shell
31-C-3	Blow-Off Tank	3,7E-04	3,7E-04
31-C-8	Blow-Off Tank	2,9E-04	2,9E-04
31-C-10	CBD Tank	1,4E-03	2,4E-04
31-C-11	Blow Off Tank	2,0E-04	2,0E-04
31-C-13	Blow-Off Tank	2,9E-04	2,9E-04
31-C-14	Blow-Off Tank	3,0E-04	2,9E-04
31-C-21	CBD Tank	3,8E-04	2,4E-04
31-C-22	CBD Tank	3,7E-04	3,7E-04

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CHAPTER VII

PROBABILITY OF FAILURE USING FUZZY LOGIC

7.1 Qualitative Assessment

The targets for qualitative assessment are engineers who responsible and know the condition of the pressure vessels. There are 4 engineers in total. The questionnaire is provided through a google form. Several questions about engineers' opinions due to the actual condition of the pressure vessels, including basic information of the engineers as input for the weighting scheme. The questionnaire contents were:

a. Respondent's Job Title
b. Job Service Time
c. Respondent's Educational Level
d. Respondent's Age
e. Pressure Vessel Damage Mechanism

7.1.1. Weighting Scheme

Expert engineers' opinions are being assessed based on their position, experience, educational level, and age. Table 7.1 explained the details. The final result of this section is the relative weighting score for each engineer. The detail questions and responses are provided in the attachment section. An example in calculating one expert's opinion is provided in table 7.1.

Table 7.1 Example of expert 1 weighting scheme

Expert 1		
Constitution	**Classification**	**Score**
Title	Lead Engineer	3
Service Time	<5 Year	1
Educational Level	Bachelor	4
Age	<30	1

$$Total\ Score\ En = \sum Q_n$$
$$= 3 + 1 + 4 + 1$$
$$= 9$$

$$Expert\ Weighting = \frac{Total\ Score\ En}{Total\ Score\ Overall}$$
$$= \frac{9}{33}$$
$$= 0{,}27273$$

Table 7.2 Summary of weighting calculation

No	Title	Service Time	Educational Level	Age	Weighting Score	Weighting Factor
1	Lead Engineer	<5	Bachelor	<30	9	0,27273
2	Engineer	<5	Bachelor	<30	9	0,27273
3	Inspector	<5	Bachelor	<30	7	0,21212
4	Engineer	<5	Bachelor	<30	8	0,24242
Total					33	1

7.1.2. Damage Mechanism

Seven damage mechanisms are selected as the main focus in determining the probability of failure. These damage mechanisms are marked by experts to determine the grade of probability through qualitative assessment. The damage mechanisms are:

a) Thinning Damage
b) Boiler Water Corrosion
c) Thermal Fatigue
d) Soil Corrosion
e) Erosion Corrosion
f) Microbiologically Induced Corrosion
g) External Corrosion

Experts gave their assessment in determining the probability of failure based on their knowledge and record of the equipment's operational procedure. The summary of qualitative assessment is provided in Table 7.3.

Table 7.3 Summary of qualitative assessment for each damage mechanisms

Indicator	E1	E2	E3	E4
Thinning Damage	M	M	L	H
Boiler Water Corrosion	MH	M	L	L
Thermal Fatigue	L	L	L	L
Soil Corrosion	L	L	L	M
Erosion Corrosion	MH	L	M	H
Microbiologically Induced Corrosion	L	L	M	L
External Corrosion	MH	MH	L	H

7.2 Membership Function

In this section, membership functions are formed using a default distribution of 4 types of probability level. Table 7.4 provides linguistic terms and their TFN coordinates. This membership function as a basic function to develop fuzzy value. The final fuzzy value is obtained from MATLAB software.

Table 7.4 Membership Functions

No.	Damage Mechanism	Probabilities	TFN
1	Low (L)	Low (L)	(0, 0, 0.33)
2	Medium (M)	Medium (M)	(0, 0.33, 0.67)
3	Medium High (MH)	Medium High (MH)	(0.33, 0.67, 1)
4	High (H)	High (H)	(0.67, 1, 1)

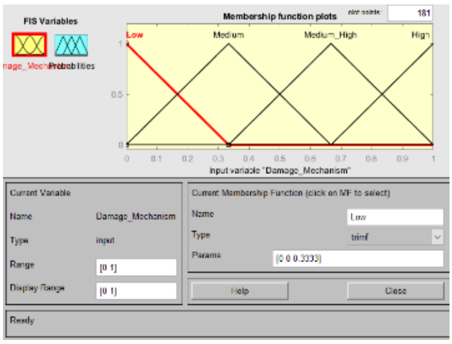

Figure 7.1 Membership function of damage mechanisms for input in MATLAB

Figure 7.2 Membership function of probability of failure for output in MATLAB

7.3 Fuzzy Calculation

In this section, a new coordinate for TFN is figured out by following several calculations. The basic membership function is going to be merged with concordance matrix which associated with the expert's qualitative assessment.

7.3.1. Concordance Matrix

Matrix was made by analyzing the membership function. Intersection area and union area of "medium" and "medium-high" grade are measured. The method used in this section is an inter-rater reliability method. Inter-rater reliability is a method to measure the consistency of the implementation of a rating system (R.T, 2011). In other words, it is a level of agreement between rates which gives score how much similarity exists in the ratings.

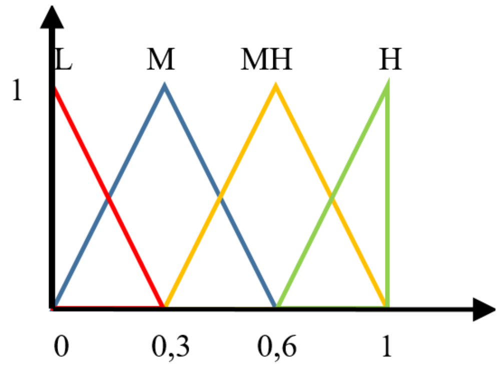

Figure 7.3 Graphical of membership function for concordance assessment

The similarity is found in medium and medium-high grade. Therefore, it was assessed due to the intersection and union area. Results of the assessment are found in the Table 7.5 and Table 7.6.

Table 7.5 Intersection area

Intersection Area				
Qualitative	**MH**	**M**	**M**	**MH**
MH	1	0,25	0,25	1
M	0,25	1	1	0,25
M	0,25	1	1	0,25
MH	1	0,25	0,25	1

Table 7.6 Union area

Union Area				
Qualitative	**MH**	**M**	**M**	**MH**
MH	1	1,75	1,75	1
M	1,75	1	1	1,75
M	1,75	1	1	1,75
MH	1	1,75	1,75	1

After the values of the intersection area and union area were obtained, concordance calculation was made using the equation. Medium-high grade in row one column one was calculated as an example.

$$CM = \frac{IA}{UA}$$

$$= \frac{1}{1}$$

$$= 1$$

Table 7.7 Summary of concordance matrix calculation

CM				CM^2			
1	0,143	0,143	1	1	0,02	0,02	1
0,143	1	1	0,143	0,02	1	1	0,02
0,143	1	1	0,143	0,02	1	1	0,02
1	0,143	0,143	1	1	0,02	0,02	1
		$\sum(CM)^2$		2	2,4	2,4	2,4

7.3.2. Relative Concordance

The value in relative concordance is obtained from previous concordance matrix calculation with the power of two. The result was multiplied with the calculation of the amount of opinion then they were squared.

$$RC_n = \sqrt{\left(\frac{1}{n-1}\right) * \sum(CM)^2}$$

$$= \sqrt{\left(\frac{1}{3-1}\right) * 2}$$

$$= 0{,}8248$$

Table 7.8 Summary of relative concordance calculation

Experts	RC_n
1	0,8248
2	0,8248
3	0,8248
4	0,8248
$\sum RC$	3,2991

7.3.3. Relative Grade of Concordance

Relative grade was calculated for each relative concordance by comparing the n^{th} relative concordance with the total relative concordance.

$$RGC_n = \frac{RC_n}{\sum RC}$$

$$= \frac{0{,}8248}{3{,}2991}$$

$$= 0{,}25$$

Table 7.9 Summary of relative grade of concordance calculation

Experts	RGC_n
1	0,25
2	0,25
3	0,25
4	0,25

7.3.4. Consensus Coefficient of the Expert

The consensus coefficient is calculated for every expert. The experts' weighting scheme is combined with relative concordance. An example of the calculation is provided using expert 1 calculation.

$$CCS_n = \frac{RGC_n * EW}{\sum(RGC * EW)}$$

$$= \frac{0{,}25 * 0{,}27273}{0{,}25}$$

$$= 0{,}2727$$

Table 7.10 Summary of consensus coefficient calculation

Experts	$RGC_n * EW$	**CCS$_n$**
1	0,068	0,2727
2	0,068	0,2727
3	0,053	0,2121
4	0,061	0,2424
$\sum(RGC * EW)$	0,25	

7.3.5. Triangular Fuzzy Number

The consensus coefficient was used to determine new TFN coordinates by doing multiplication with the basic membership function of each linguistic terms. Then, all multiplication result summed up with another calculation from other experts in the same type of damage mechanisms. Damage mechanisms were provided in the table as a complex calculation.

$$TFN_n = \sum(CCS_n * n)$$

a) Coordinate 1 for TFN

Table 7.11 Summary of TFN calculation for coordinate 1

Indicator	E1		E2		E3		E4		CCE x TFN				Σ (CCE x TFN)
	QA	TFN	QA	TFN	QA	TFN	QA	TFN	E1	E2	E3	E4	
Thinning Damage	M	0	M	0	L	0	H	0,67	0	0	0	0,16	0,162
Boiler Water Corrosion	MH	0,3	M	0	M	0	L	0	0,09	0	0	0	0,091
Thermal Fatigue	L	0	M	0	L	0	L	0	0	0	0	0	0
Soil Corrosion	L	0	L	0	L	0	M	0	0	0	0	0	0
Erosion Corrosion	MH	0,3	L	0	M	0	H	0,67	0	0	0	0,16	0,253
Microbiogically Induced Corrosion	L	0	L	0	M	0	L	0	0	0	0	0	0
External Corrosion	MH	0,3	MH	0,3	L	0	H	0,67	0,09	0,09	0	0,16	0,343

b) Coordinate 2 for TFN

Table 7.12 Summary of TFN calculation for coordinate 2

Indicator	E1		E2		E3		E4		CCE x TFN				Σ (CCE x TFN)
	QA	TFN	QA	TFN	QA	TFN	QA	TFN	E1	E2	E3	E4	
Thinning Damage	M	0,3	M	0,3	L	0	H	0,67	0	0,09	0	0,16	0,34
Boiler Water Corrosion	MH	0,67	M	0,3	M	0,3	L	0	0,18	0,09	0,07	0	0,34
Thermal Fatigue	L	0	M	0,3	L	0	L	0	0	0,09	0	0	0,09
Soil Corrosion	L	0	L	0	L	0	M	0	0	0	0	0	0
Erosion Corrosion	MH	0,67	L	0	M	0,3	H	0,67	0,18	0	0,07	0,16	0,414
Microbiogically Induced Corrosion	L	0	L	0	M	0,3	L	0	0	0	0,07	0	0,7
External Corrosion	MH	0,67	MH	0,67	L	0,3	H	0,67	0,18	0,18	0	0,16	0,53

c) Coordinate 3 for TFN

Table 7.13 Summary of TFN calculation for coordinate 3

Indicator	E1		E2		E3		E4		*CCE x TFN*				Σ (CCE x TFN)
	QA	TFN	QA	TFN	QA	TFN	QA	TFN	E1	E2	E3	E4	
Thinning Damage	M	1	M	L	L	0,3	H	1	0	0,18	0,07	0,24	0,68
Boiler Water Corrosion	MH	1	M	M	M	0,67	L	0,3	0,27	0,18	0,14	0,08	0,68
Thermal Fatigue	L	0,3	M	L	L	0,3	L	0,3	0	0,18	0,07	0,08	0,42
Soil Corrosion	L	0,3	L	L	L	0,3	M	0,67	0	0,09	0,07	0,16	0,41
Erosion Corrosion	MH	1	L	M	M	0,67	H	1	0,27	0,09	0,14	0,24	0,75
Microbiogically Induced Corrosion	L	0,3	L	M	M	0,67	L	0,3	0	0,09	0,14	0,08	0,40
External Corrosion	MH	1	MH	L	L	0,3	H	1	0,27	0,27	0,07	0,24	0,859

7.4 Fuzzy Inference System

The fuzzy inference system contains rules in determining the relation between two membership functions. In this case, damage mechanisms as input and probabilities as an output. This FIS is using an inline relationship. When damage mechanisms are low grade so does probabilities. There are total 4 rules in this FIS using IF_ THEN logic.

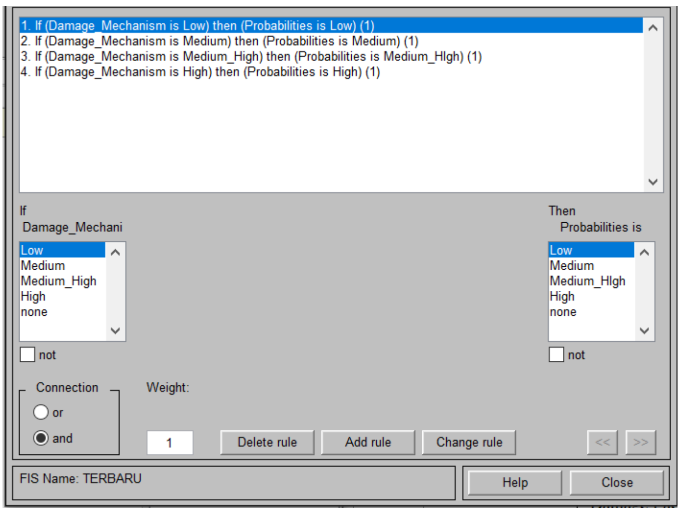

Figure 7.4 Rules in fuzzy inference system

7.5 Fuzzification System

The result from multiplication between the consensus coefficient with the default membership function of each linguistic terms was used to determine the input in the damage mechanism section. The example can be seen in Figure 7.5. If we input 0,343 as the result of thinning damage in the damage mechanisms section, the output showed 0,347 for probabilities. Table 7.14 showed the new coordinate of TFN as input and the result of probabilities in its column.

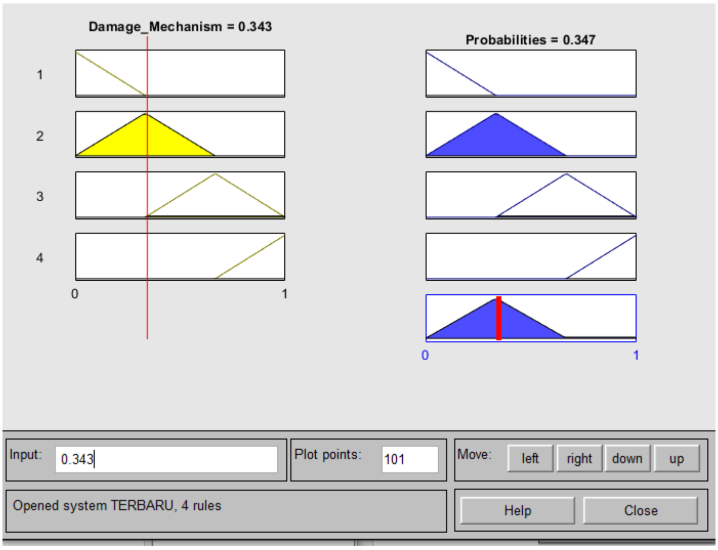

Figure 7.5 Fuzzication system

Table 7.14 Summary of fuzzy value

Indicator	Coordinate			Fuzzy Probabilities
	1	2	3	
Thinning Damage	0,162	0,343	0,677	0,347
Boiler Water Corrosion	0,091	0,343	0,677	0,347
Thermal Fatigue	0,000	0,091	0,424	0,239
Soil Corrosion	0,000	0,000	0,414	0,108
Erosion Corrosion	0,253	0,414	0,747	0,427
Microbiogically Induced Corrosion	0,000	0,071	0,404	0,219
External Corrosion	0,343	0,525	0,859	0,52
Probabilities				0,00015113

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CHAPTER VIII
INSPECTION INTERVAL

8.1 Inspection Interval

An inspection interval is an estimation of the inspection schedule. In this case, the inspection interval was obtained through risk assessment. Although fuzzy logic only used in determining the probability of failure, in this chapter the author would like to compare the result of obtainable inspection interval either from RBI and Fuzzy-RBI calculation.

8.1.1 Inspection Interval Based on API RBI 581

API RBI 581 has provided a calculation for the probability of failure and consequence area. In terms to plot the risk categories, API 581 divides three criteria. The first one is obtained from probability value, which ranges from 3.06E-05 up to 3.06E-02. Then the damage factor is looked up from 1 up to 1000. And last, the consequence range within 9,29 up to 9.290.

Table 8.1. Probability of failure and consequence of failure category
Source: API RBI 581 2016

Category	Probability Catergory		Consequence Category	
	Probability Range	Damage Factor Range	Category	Range (m2)
1	Pf ≤3.06E-05	Df ≤ 1	A	CA ≤ 9,29
2	3.06E-05< Pf ≤3.06E-04	1< Df ≤ 10	B	9,29< CA ≤ 92,9
3	3.06E-04< Pf ≤3.06E-03	10< Df ≤ 100	C	92,9< CA ≤ 929
4	3.06E-03< Pf ≤3.06E-02	100< Df ≤ 1,000	D	929< CA ≤ 9.290
5	Pf > 3.06E-02	Df > 1,000	E	CA > 9.290

In this section, pressure vessel, 31-C-3, is presented as an example. POF, DF, and CA from RBI assessment plotted in the risk matrix.

Table 8.2. Resulted damage factor and consequence of area

	Head	Shell	Category	
			Head	Shell
P(t):	0,00000041	0,00000041	1	1
DF total:	0,1	0,1		
CA:	900,09	900,09	C	C

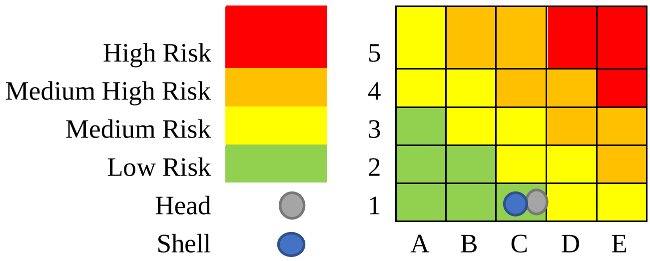

Figure 8.1. Risk Matrix for RBI Assessment
Source: API RBI 581 2016

Pressure vessel, 31-C-3, is categorized in low-risk grade according to RBI assessment. Then the inspection interval can be estimated from two scenarios in terms to obtain the best and reliable inspection schedule.

a) Inspection Planning

Table 8.3. Calculated risk and risk target

	Time	**Risk (m2/ year)**	**Risk Target (m2/ year)**
Last inspection date	25/10/2018	3,7E-04	0,5
RBI Date	11/11/2019	3,7E-04	0,5
Plan Date	25/10/2022	3,7E-04	0,5

Risk target = (Risk RBI Date). (Time Plan Date – RBI Date) $^{n-1}$
0,5 = (0,00037) . (2,95) $^{n-1}$
1351,96 = (2,95) $^{n-1}$
To determine value of n, an interpolation methods needs to be done.

Table 8.4. Interpolation

X_1	6	Y_1	664,64
X	X	Y	1351,96
X_2	7	Y_2	1963,44

$$X = X_1 + \left(\frac{Y - Y_1}{Y_2 - Y_1}\right)(X_2 - X_1)$$
= 6,5292 year

Calculated risk and risk company target are used to calculate inspection year. If the result of this calculation is over-estimated, the next step shall follow the standard in API 510.

8.1.2 Inspection Interval Using Fuzzy Methods

In this section, the probability of failure as the result of fuzzy logic is used to determine the inspection interval. RBI-consequence area is being used to determine the risk categories of the pressure vessel. The reason for using consequence area from RBI calculation because a consequence of area of equipment will always be the same through time to time. Consequence assessment is taken from the general specification of the equipment and type of fluids, so the value is hard to change unless a massive change applied to the system such as changing the type of fluid. Therefore, the value of CA is used the same as in the RBI assessment.

POF was calculated from 7 damage mechanisms that have more probability to occur than the other 66 damage mechanisms. They were assessed for giving POF value to two types of equipment but the damage mechanisms between two types of these pressure vessels are considered the same. Therefore only one value of POF was used. The summary calculation is displayed in Table 8.5.

Table 8.5. Summary of risk calculation from fuzzy-POF

No.	Equipment	Type	Probabilities	Consequence (m2)	Risk
1	31-C-3	Blow-Off	0,00015	900,087	0,136
2	31-C-8	Blow-Off	0,00015	694,824	0,105
3	31-C-10	CBD	0,00015	572,280	0,086
4	31-C-11	Blow-Off	0,00015	495,197	0,075
5	31-C-13	Blow-Off	0,00015	694,824	0,105
6	31-C-14	Blow-Off	0,00015	694,824	0,105
7	31-C-21	CBD	0,00015	572,165	0,086
8	31-C-22	CBD	0,00015	899,534	0,136

The same terms and conditions are used for plotting into the risk matrix to figure out the risk categories for each pressure vessel. Damage factor terms were not being used due to no assessment of damage factor.

Table 8.6. POF and CA category for fuzzy method

Probability Catergory		Consequence Category	
Category	Probability Range	Category	Range (m2)
1	Pf ≤3.06E-05	A	CA ≤ 9,29
2	3.06E-05< Pf ≤3.06E-04	B	9,29< CA ≤ 92,9
3	3.06E-04< Pf ≤3.06E-03	C	92,9< CA ≤ 929
4	3.06E-03< Pf ≤3.06E-02	D	929< CA ≤ 9.290
5	Pf > 3.06E-02	E	CA > 9.290

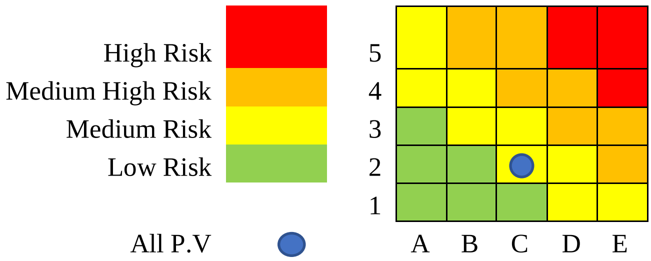

Figure 8.2. Risk matrix for fuzzy method

All the pressure vessels were cateforized in medium risk according to the result of fuzzy method.

a) Inspection Interval

Calculated risk of each pressure vessel was compared to the risk target of the company. The result is displayed in the Table 8.7.

Table 8.7. Summary of inspection interval from fuzzy method

No.	Equipment	Type	Fuzzy-Risk	Risk Target (m2/Year)	Inspection Interval (Years)
1	31-C-3	Blow-Off	0,136	0,5	3,676
2	31-C-8	Blow-Off	0,105	0,5	4,761
3	31-C-10	CBD	0,086	0,5	5,781
4	31-C-11	Blow-Off	0,075	0,5	6,681
5	31-C-13	Blow-Off	0,105	0,5	4,761
6	31-C-14	Blow-Off	0,105	0,5	4,71
7	31-C-21	CBD	0,086	0,5	5,782
8	31-C-22	CBD	0,136	0,5	3,678

8.2 Discussion

Fuzzy-PoFs were obtained on level 1,5 x 10-4 for every equipment. The fluid between one equipment to others is the same, so it assumed that damage mechanisms for all the equipment are the same therefore qualitative assessment only done once. For instance, RBI-PoFs were relatively the same. The POF was on the 10-7 level. If we compare both results, fuzzy-PoFs has a higher value. It was because RBI has a complex calculation process in determining PoF value. The result of the calculation was summarized in Table 8.8.

Interval inspection calculated with fuzzy was in range 3,67 years up to 6,96 years ahead. It was counted from the last inspection year. On the other hand, interval inspection calculated with API 581 RBI in the range 4 years up to 7 years. In practical conditions, RBI needs time to develop the program and formula for certain systems in a company. More complex a system, more time is needed. RBI assessors are developing and running their program and formula in 3 years in the company. Within 3 years, deterioration might occur in the system with no signs. Also, if an abnormal condition happened the personnel needs to re-assess the assets.

Table 8.8. Summary of PoF from RBI and Fuzzy Methods

No.	Equipment	Type	PoF-RBI (Head)	PoF-RBI (Shell)	Fuzzy-PoF
1	31-C-3	Blow-Off	4,E-07	4,E-07	1,5 E-4
2	31-C-8	Blow-Off	4,E-07	4,E-07	1,5 E-4
3	31-C-10	CBD	2,E-06	4,E-07	1,5 E-4
4	31-C-11	Blow-Off	4,E-07	4,E-07	1,5 E-4
5	31-C-13	Blow-Off	4,E-07	4,E-07	1,5 E-4
6	31-C-14	Blow-Off	4,E-07	4,E-07	1,5 E-4
7	31-C-21	CBD	7,E-07	4,E-07	1,5 E-4
8	31-C-22	CBD	4,E-07	4,E-07	1,5 E-4

Interval inspection calculated with fuzzy was in range 3,67 years up to 6,96 years ahead. It was counted from the last inspection year. On the other hand, interval inspection calculated with API 581 RBI in the range 4 years up to 7 years. In practical conditions, RBI needs time to develop the program and formula for certain systems in a company. More complex a system, more time is needed. RBI assessors are developing and running their program and formula in 3 years in the company. Within 3 years, deterioration might occur in the system with no signs. Also, if an abnormal condition happened the personnel needs to re-assess the assets.

If the result of this method was compared with an 8-years prescriptive inspection interval, inspection interval from qualitative assessment earlier conducted. It means asset integrity could be maintained more precisely. Previous engineer’s judgement about inspection interval had been out of date due to the equipment age and increasing risk.

In figure 8.3 exposed two types of inspection intervals. There are interval from RBI calculation and fuzzy methods. Mostly fuzzy logic resulted in lower interval inspection than RBI assessment. From this calculation, the fuzzy results can be used as an estimation for the local engineer's consideration to determine any inspection based on qualitative assessment. The resulting sensitivity could be increased with a more precision qualitative assessment of damage mechanisms.

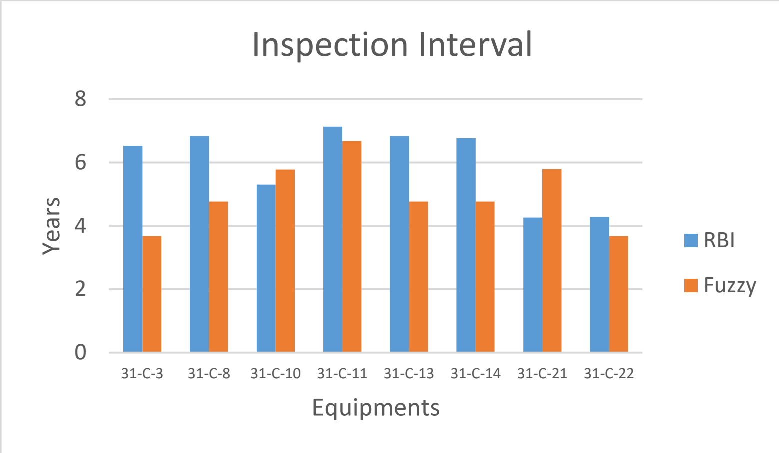

Figure 8.3 Resulted inspection interval comparison

Fuzzy logic is often used for mapping the level of certain factors such as probability, frequency of failure, and risk. So in this case, fuzzy logic used to obtain the probability of failure is considered correct and reliable enough. On the other hand, it is debatable when the method is used to determine the inspection interval because the maintenance strategy involved company budgeting. Therefore, this method is relatively hard implemented because not providing any further details.

For further usage, fuzzy logic methods are properly used when there is no quantitative assessment has been done before or the latest condition of the system has not been assessed. The resulting accuracy in this fuzzy method can be still debatable because it is purely based on personnel opinions. For the method itself, fuzzy logic is possible to use because of its ability to transform the linguistic task into a numerical value. From this point, local engineers are able to conduct this assessment based on their knowledge and experience. Simple and quick is the correct word to describe this method. The consequences are highly educated and experienced personnel is needed in terms to have a reliable assessment. Also, the number of respondents shall be increased as the reason to have various opinions.

CHAPTER IX

CONCLUSION AND RECOMMENDATION

9.1 Conclusion(s)

1. Calculated risk based on API 581 RBI for continuous blowdown tank and blow off-tank were the same. All equipment was on the low-risk levels (green). Table 9.1 is the summary of calculated risk based on API RBI 581.

Table 9.1 Summary of calculated risk based on API RBI 581

No Tag	Equipment	RBI Risk (m2/year)	
		Head	Shell
31-C-3	Blow-Off Tank	3,7E-04	3,7E-04
31-C-8	Blow-Off Tank	2,9E-04	2,9E-04
31-C-10	CBD Tank	1,4E-03	2,4E-04
31-C-11	Blow Off Tank	2,0E-04	2,0E-04
31-C-13	Blow-Off Tank	2,9E-04	2,9E-04
31-C-14	Blow-Off Tank	3,0E-04	2,9E-04
31-C-21	CBD Tank	3,8E-04	2,4E-04
31-C-22	CBD Tank	3,7E-04	3,7E-04

2. Experts' opinions were transformed from linguistic tasks to a numerical value by using membership functions. Then, the numerical value was merged with the result of the concordance matrix. New triangular fuzzy numbers were obtained from the calculation. Lastly, new coordinates of TFN were input to the membership function in MATLAB software then the probability for each damage mechanism was obtained. POF was calculated by combining all probabilities number of damage mechanisms. The fuzzy-PoF is $1,5 \times 10^{-4}$ for all equipment.
3. Inspection intervals from RBI assessment were obtained through interpolation between calculated risk and risk target. In the fuzzy method calculated risk compared directly with company risk target. Inspection interval obtained by the fuzzy method mostly lower than the RBI inspection interval. Table 9.2 is the summary of the inspection interval for both methods.

Table 9.2 Summary of inspection interval from RBI and fuzzy

No.	Equipment	Type	RBI (Years)	Fuzzy (Years)
1	31-C-3	Blow-Off	6,529	3,676
2	31-C-8	Blow-Off	6,837	4,761
3	31-C-10	CBD	5,300	5,781
4	31-C-11	Blow-Off	7,129	6,681
5	31-C-13	Blow-Off	6,837	4,761
6	31-C-14	Blow-Off	6,768	4,761
7	31-C-21	CBD	4,265	5,782
8	31-C-22	CBD	4,283	3,678

9.2 Recommendation(s)

1. The qualitative assessment shall be conducted by a responsible person or personnel who knows the actual conditions and has the knowledge to assess any deterioration occurred in the system. Respondents shall be collected as many as possible in terms to achieve the accuracy and reliability of the assessment.
2. The qualitative assessment shall be conducted before quantitative assessment such as RBI. This fuzzy method is an alternative in case a quantitative assessment takes a too long time or any sudden strategy shall be taken therefore any assessment shall be conducted as soon as possible. This method can be done by local engineers with basic knowledge of corrosion and other damage factors.
3. Research in determining fuzzy value for calculating risk shall be updated. Any modifications shall be applied. Hopefully, in the future the accuracy of fuzzy logic for qualitative assessment is accurate enough so any policies are right taken

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Christian Laurent was born in Surabaya on 26 October 1997. He is the first son of two siblings. He grew up in Surabaya. He completed his high school in SMA St. Louis 1 Surabaya (2013-2016). He continues in pursuins his Engineering Degree at Marine Engineering Department in Institut Teknologi Sepuluh Nopember, joining the Joint Degree Program with *Hoschshule Wismar*, Germany. During his study, he has been actively involved in some organizations, competitions, and activities. He was the staff of External Affairs of HIMASISKAL FTK-ITS for 2016/2017 period. He involved in three paper innovation competitions' committee in Marine Icon 2017, Petrolida Society of Petroleum Engineers (SPE) ITS 2018, and Marine Icon 2018. Also, He has been trusted to become a liaison officer in ASEAN University Network (AUN-QA) 2019. He has done internship two times in PT Daya Radar Utama Shipyard, Lampung, and PT Badak LNG, Bontang. He has involved in RBI assessment since the internship in PT Badak LNG to determine the assets' integrity and inspection interval. In this research of bachelor thesis, he has done an improvement by adding fuzzy logic as the methods to calculate qualitative assessment. During the research for the bachelor thesis, he was a member of Marine Reliability, Availability, Management, and Safety (RAMS) Laboratory.

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