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Application and Implementation of RBI at a Petrochemical Plant

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Abstract

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The aim of this thesis was to participate in the application and implementation of Risk Based Inspection (RBI) in the olefin production plant at the Borealis Porvoo site. The pressure equipment and piping, which were included in RBI implementation, are installed and operating in the hot end distillation process of the ethylene unit.

The main objective of this thesis was to conduct the equipment criticality classification (risk assessment). Considering the individual pressure equipment and piping, the criticality was assessed based on the risk they represent associated to safety, health, environment, economics, and company reputation. The objective of this thesis also included examining the means to improve risk management by inspection activities and a study of degradation mechanisms, which were identified to be present or to initiate in corrosion loops that were assessed. The pressure equipment and piping of the hot end distillation process have been clustered into corrosion loops with the help of a corrosion study, conducted by an external party.

The corrosion study´s results were reviewed, and the corrosion loops were validated and configured in the Integrity Management System (IMS). During the RBI implementation process, the Borealis Group´s specifications and guidelines were applied. The equipment criticality classification was managed in the IMS and conducted by using the integrated Pressure Equipment Integrity (PEI) module in the IMS. During the criticality classification process, a condition, inspection and in-service history study was conducted on the considered pressure equipment and piping. Essential and valuable experience was achieved of the RBI process at the Porvoo site. Important observations and conclusions were acquired from the conducted semi-quantitative RBI assessment associated with improvements of the criticality classification, the corrosion study as well as the utilization of the IMS PEI module. The conducted project shows that risk management at the olefin production plant can be optimized and improved by applying and implementing RBI on the related pressure equipment and piping. Essential factors regarding the improvement of risk management by inspection activities, were gathered in a table based on the theory studied in this thesis.

Keywords: process industry, asset integrity management, RBI, risk assessment, inspection, corrosion loop

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Tässä insinöörityössä oli tarkoitus osallistua riskiperusteisen tarkastuksen (RBI) soveltamiseen ja toteuttamiseen Borealiksen olefiinituotannossa, Porvoon tuotantopaikkakunnalla. Tarkasteltavana olevat painelaitteet ja putkistot sijaitsevat olefiinituotannon eteeniyksikön kuumatislausprosessissa.

Insinöörityön päämääränä oli osallistua laitteiden ja putkistojen kriittisyysluokitteluun, jossa arvioidaan yksittäisen laitteen ja putkiston muodostama riski liittyen turvallisuuteen, terveyteen, ympäristöön, liiketoimintaan ja yhtiön maineeseen. Insinöörityössä oli myös tavoitteena selvittää menetelmiä, miten parantaa riskinhallintaa tarkastustoiminnalla sekä tutkia vauriomekanismeja, joita on tunnistettu olevan läsnä tai joita voisi esiintyä tarkasteltavana olevissa laitteissa ja putkistoissa.

Ulkopuolisen toimijan teettämässä korroosiotutkimuksessa kuumatislausprosessin laitteet ja putkistot on jaettu korroosioryhmiin mekaaniseen eheyteen vaikuttavien tekijöiden perusteella.

Korroosiotutkimustulokset katselmoitiin ja painelaitteista sekä putkistoista koostuvat ryhmät validoitiin ja määritettiin tarkastustietokantaan. Riskiperusteisen tarkastuksen soveltamis- ja toteutusprosessin aikana sovellettiin Borealiksen spesifikaatioita ja ohjeita. Laitteiden ja putkistojen kriittisyysluokitteluprosessia hallinnoitiin IMS-tarkastustietokannan avulla, hyödyntäen tietokantaan integroitua PEI-moduulia. Kriittisyysluokittelun aikana tutkittiin tarkasteltavana olevien laitteiden ja putkistojen nykyistä kuntoa sekä tarkastus- ja käyttöhistoriaa. Riskiperusteisen tarkastuksen soveltamisesta ja toteuttamisesta saatiin arvokasta kokemusta Porvoon tuotantopaikkakunnalla. Semi-kvantitatiivisesta riskiperusteisen tarkastuksen toteuttamisesta kerättiin olennaisia havaintoja ja tietoa siitä, kuinka kriittisyysluokittelun tarkkuutta, korroosiotutkimuksen toteutusta ja tietokannan PEI-moduulin soveltamista voitaisiin kehittää. Tehdyn työn perusteella on riskinhallintaa mahdollista optimoida olefiinituotannossa soveltamalla ja toteuttamalla riskiperusteista tarkastusta tarkasteltavana olleisiin laitteisiin ja putkistoon. Insinöörityössä kerätyn tiedon avulla luotiin lisäksi taulukko, johon kerättiin olennaisia tietoja liittyen riskinhallinnan kehittämiseen tarkastustoiminnan avulla.

Avainsanat: prosessiteollisuus, omaisuuden eheydenhallinta, riskiperusteinen tarkastus, riskinarviointi

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List of Abbreviations

ACFM: *Alternative Current Flow Measurement.* Non-destructive examination (NDE) method, which uses electromagnetic fields to identify and size cracks in materials of construction.

AET: *Acoustic Emission Testing*. NDE method, which uses ultrasonic waves to identify defects in materials of construction.

API: *The American Petroleum Institute*. National trade association that represents all aspects of U.S of America's oil and natural gas industry.

AUT: *Automated Ultrasonic Testing.* Generic term associated with computerized collection of ultrasonic data. AUT is associated with NDE, which comprises several different ultrasonic testing (UT) techniques.

BFD: *Block Flow Diagram*. Drawing of a chemical manufacturing process, which is used to illustrate, understand, and simplify the basic elements of a process in a sequential order.

CEN: *Comité Européen de Normalisation.* The European Committee for Standardization, an organization, which is responsible for determining and developing standards at European level.

CML: *Condition Monitor Location*. Determined locations on equipment where presence and rate of degradation are monitored.

CMMS: *Computerized Maintenance Management System.* Software and database used to manage information and data of maintenance operations and facilitate management of processes associated to maintenance operations.

CoF:	*Consequence of Failure.* The outcome of a pressure equipment failure.
CSCC:	*Chloride Stress Corrosion Cracking.* Degradation mechanism in austenitic stainless steels, which initiates due tensile stress, oxygenated environment, high temperature and chloride ions.
CUI:	*Corrosion Under Insulation.* Type of corrosion occuring in process equipment and piping which are externally insulated.
ECT:	*Eddy Current Testing.* NDE method, which uses the electromagnetism to detect flaws in conductive materials of construction.
EEMUA:	*The Engineering Equipment and Materials Users Association.* European non-profit membership organization that develops and provides standards and guidelines for various industrial sectors.
EN:	*European Norm.* Technical standards developed and maintained by CEN.
EU:	*European Union.* Economic and political union between 27 European countries.
FCC:	*Fluid Catalytic Cracking.* Conversion process applied in the petrochemical industry to convert high-molecular weight hydrocarbon fractions (of oil and gas refinery products) into gasoline, olefinic gases, and other petroleum products.
H_2S:	*Hydrogen sulfide.* Chemical compound, which is a toxic, flammable, and colorless gas.
HAZ:	*Heat Affected Zone.* Non-melted area of the base metal where metallurgical changes occur due to exposure of high temperatures

and rapid temperature changes during welding, heat cutting, laser cutting etc.

HDPE: *High density polyethylene.* Thermoplastic polymer made from petroleum.

HIC: *Hydrogen Induced Cracking.* Degradation mechanism, which manifests as cracking in carbon steels and occurs due to hydrogen absorption.

IMS: *Integrity Management System.* A database for managing the integrity of various types of pressure and civil equipment used in the process and other industry sectors. Developed by Cenosco in collaboration with Shell Global Solutions.

IOW: *Integrity Operating Window.* Established thresholds values for process parameters, the exceedance of which may significantly affect the mechanical integrity of the process equipment and piping.

LDPE: *Low density polyethylene.* Thermoplastic polymer made from petroleum.

MFL: *Magnetic Flux Leakage.* Electromagnetic NDE method used to detect corrosion, pitting and wall loss in steel structure applications.

MT: *Magnetic Particle Testing.* NDE method used for detection of linear surface breaking flaws in ferromagnetic materials.

NDE: *Non-Destructive Examination.* Also known as Non-destructive testing (NDT). Analysis and testing technique used in the industry to examine properties of materials, structures and components or to examine defects in weldments or discontinuities in materials without causing any mechanical damage to the object being examined.

PAUT: *Phased Array Ultrasonic Testing.* Advanced UT method that utilizes during examination a set of UT probes, which are pulsed individually by applying computer-calculated timing.

PED: *Pressure Equipment Directive.* The European Pressure Equipment directive provides mandatory guidance for the design, fabrication, and conformity assessment of pressure equipment with a maximum allowable pressure above 0.5 bar. Compliance with this Directive is required during the operation of pressure equipment and pressurized piping as well as required for designers and manufacturers looking to sell their equipment in the region of EU.

PEI: *Pressure Equipment Integrity.* Module in the IMS for managing integrity of multiple types of pressure equipment.

PFD: *Process Flow Diagram.* Technical drawing which illustrates the essential equipment and parameters of a process.

PoF: *Probability of Failure.* The probability that a failure of an equipment or component will occur during a certain period of time.

PSK: *Prosessiteollisuuden Standardoimiskeskus.* Finnish standards and development association, which supports business activities of companies in various industry sectors by standardization and training.

PSV: *Pressure Safety Valve.* Type of valve used to limit or control the pressure in a system and protect the system during an overpressure event.

PWHT: *Post Weld Heat Treatment.* Method applied after a welding process to eliminate unfavorable metallurgical changes of the weld and base material.

P&ID:	*Piping and Instrumentation Diagram*. Detailed technical drawing used to display equipment, pipelines, components, instrumentation, and control devices, which pertain in a process.
RBI:	*Risk-Based Inspection.* Risk assessment and management process that is focused on loss of containment of pressurized equipment and piping in the process industry. A decision-making method for development of inspection plans which are based on the assessed risk.
RT:	*Radiographic Testing.* NDE method that uses gamma rays or x-rays to identify internal flaws and defects as well as discontinuities in materials of construction.
S-RBI:	*Shell-Risk Based Inspection.* Methodology for optimizing inspection and monitoring activities. S-RBI is used to manage mechanical integrity of pressure equipment, pressurized piping, storage tanks and related components as well as PSVs. S-RBI is part of the risk and reliability management (RRM) system, which is developed by Shell Global Solutions.
SCC:	*Stress Corrosion Cracking.* Degradation mechanism, which initiates from the combined influence of a corrosive environment and tensile stress.
SOHIC:	*Stress-Oriented Hydrogen Induced Cracking.* Type of HIC, the initiation of which is influenced by stress and propagate perpendicular towards material surfaces.
SSC:	*Sulphide Stress Cracking.* Type of HIC, which appears in welds and HAZs of carbon steels and high-strength steel alloys.
StF:	*Susceptibility to failure.* The probability an environment initiates degradation, which causes an equipment or component to fail.

SWUT: *Shear Wave Ultrasonic Testing.* Advanced UT inspection technique, which is primarily used for inspection of welds. Also known as angle beam inspection.

TOFD: *Time-of-Flight Diffraction.* Advanced UT inspection technique used for inspection of flaws in welds. A pair of ultrasonic probes are applied on opposite sides of the weld-joint or area of interest to size and detect flaws.

Tukes: *Turvallisuus- ja kemikaalivirasto.* The Finnish Safety and Chemicals Agency. A supervisory authority that promotes safety and reliability of products, services, and industrial activities.

UT: *Ultrasonic Testing.* NDE method that uses high frequency sound energy to conduct examinations and make measurements in materials of construction.

VT: *Visual Testing.* The most common NDE method. VT encompasses examination of surface defects, discontinuities, and other types of deterioration with the naked eye in materials of construction of equipment and components.

VNa: *Valtioneuvoston asetus.* Finnish government degree. An act specifying or supplementing Finnish law, which is applied based on a legislative mandate.

WFMT: *Wet Fluorescent Magnetic Particle Testing.* NDE method that provides detection of linear surface breaking flaws in ferromagnetic materials by using ultraviolet light in a darkened environment.

1 Introduction

Risk-based inspection (RBI) is intended to be applied and implemented into critical pressure containing equipment and piping, which are installed in the production plants at the Borealis Porvoo site. The main purpose of the application and implementation of RBI in the production plants is to improve and optimize risk management of the mechanical asset. The main objective of this thesis was to participate in the RBI implementation process of the pressure equipment, which are operated at the olefin production plant in the hot end distillation process of the ethylene unit. The main element of the implementation of RBI is the equipment criticality classification (risk assessment). The application of RBI and the RBI process at the Porvoo site is in the development stage. The objective of this thesis is to make observations and conclusions about improvements how to apply RBI reasonably at the Borealis Porvoo site. Implementation of the RBI was primarily managed in the Integrity Management system (IMS) and conducted by applying the Pressure Equipment Integrity (PEI) module.

1.1 Objective

The objective of this thesis was to provide essential information that would support and improve the accuracy of the equipment criticality classification. It was also aimed to act as an aid in practical matters considering the equipment criticality classification. The baseline of this thesis was to review the outcome of a corrosion study that was recently carried out on the equipment that are operated in the hot end distillation part of the ethylene unit. The objective of the thesis also included to study the RBI process, the criticality classification assessment and the corrosion study as well as bring out matters worthy of attention, which could be used in the development of the RBI process. The aim of the thesis was also to study the relevant degradation mechanisms of the pressure equipment which are being criticality classified and to provide essential information how to improve the inspection effectiveness of considered pressure equipment. Particularly, the objective included providing applicable Non-Destructive Examination (NDE) methods and techniques to inspect the considered degradation mechanisms in the considered pressure equipment.

1.2 Scope, content

RBI is to be applied and implemented during this thesis on two predefined corrosion loops, which constitute the pressure equipment that operates in the hot end distillation process of the ethylene unit. The theoretical section of this thesis comprises RBI in general and in brief about elements included in an RBI assessment. The theory section focuses on the essential factors, which should be considered in an RBI risk assessment (criticality classification) and risk management of the pressure equipment. The theory of risk management is focused on the inspection activities. The theory of RBI is primarily based on American Petroleum Institute (API) guidelines and recommended practises about implementation of RBI, which are globally accepted and are referred to in various RBI methodologies developed by other institutes. The theoretical section comprises also the degradation mechanisms, which are relevant in the corrosion loops that were selected to be examined in this thesis.

1.3 Borealis, Borealis Polymers Oy Porvoo

Borealis is a worldwide chemical company focused on supplying polyolefin solutions and polyolefin circular economy solutions. Borealis is a market leader in Europe in producing and supplying basic petrochemicals and fertilizers as well as being mechanically recycling plastics. Borealis have business in over 120 countries and employs over 6900 people. The company headquarters is located in Vienna, Austria. (About Borealis 2021.)

Borealis Polymers Oy produces basic petrochemicals and polyolefins in Porvoo, Finland. Kilpilahti area in Porvoo is the biggest oil refinery and chemical industry centralization in the Northern Europe. Two petrochemical and four polyolefin production plants are operating at the Porvoo site. The petrochemical plants comprise one olefin production plant and one phenol and aromatics production plant. The olefin production plant consists of an ethylene unit, a propylene unit, and a butadiene unit. The phenol and aromatics production plant consists of a benzene unit, a cumene unit and a phenol unit. The polyolefin production plants comprise two different types of polyethylene production plants, a polypropylene production plant and a mixed production plant. In addition, at the Porvoo site there are an innovative center and a pilot plant. At the Porvoo site, the produced polymer compounds are mainly raw material for numerous piping applications, steel pipe coatings, package material and cable applications. Figure 1 shows a photo of the Porvoo site petrochemical plants. (Borealis Porvoo tuotanto 2021; Borealis Porvoo 2021.)

Figure 1. The petrochemical plants of Porvoo site. The olefin production plant is at the farther distance and the phenol and aromatics production plant is nearer. (Itäväylä. 2021)

The operation of the ethylene unit in Porvoo started at the end of the year 1971 by the Finnish oil refinery company Neste. At the same time, the high-pressure polyethylene (LDPE) production was initiated. For further processing of the ethylene unit by-products, other production plants and units as well as regeneration units were constructed and commissioned in stages over the years as following; Butadiene extractive distillation unit (1973), propylene distillation unit (1977), benzene unit (1978), phenol unit (1981), polypropylene production plant (1988) and a low-pressure polyethylene (HDPE production) production plant (1994). Since year the 1994, Borealis Polymers Oy has been responsible of the operation considering every unit and plant mentioned above. (Riistama etc. 2003.)

1.3.1 The olefin production plant and the ethylene unit

The Porvoo site olefin unit produces downstream products such as ethylene, propylene, and butadiene for further processing. The ethylene unit is flexible considering processing different types of feedstocks by utilizing liquid and gaseous feeds. The ethylene unit feedstocks are primarily by-products from external suppliers (e.g., oil refinery companies) but consist also of process regeneration feeds from the petrochemical production plant units. Liquid feedstocks consist of naphtha, n-butane, n-pentane, and n-hexane as well as gaseous feedstocks consisting of propane, mixed gases, n-butane (evaporated), ethane and FCC-gas. These feedstocks are fed to the steam cracking unit where they are mixed with super-heated dilution steam, after which they are led to the cracking furnaces. In the furnaces, in a temperature between 790...850 °C, the hydrocarbons in the feeds are cracked (“splitted”) into more light and simple hydrocarbon molecules. During the first distillation phase, (hot end distillation) pyrolysis fuel oil and pyrolysis gasoline are separated from light hydrocarbons. The pyrolysis gasoline is led to the benzene unit and the pyrolysis fuel oil is led to storage and further use. Water is removed from the separated light hydrocarbons in the low- and high-pressure sides of the charge gas compression unit, and acidic substances are washed from the light hydrocarbons in the caustic and water wash tower. Forward from this, light hydrocarbons are separated, cooled down as well as distilled in several stages to different types of downstream products. For instance, fractionated ethylene and propylene are downstream products from the ethane and propane fractionation. Ethylene and propylene are sent further from the olefin production plant to the polyolefin production plants for downstream operation. Figure 2 illustrates ethylene production by steam cracking of ethane. (Riistama etc. 2003; Ethylene production via cracking of ethane-propane. 2015.)

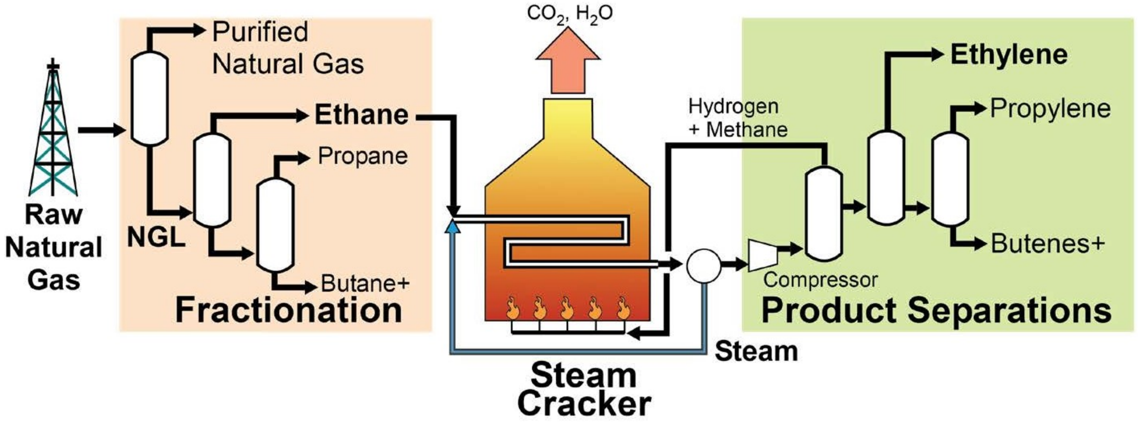


Figure 2. Illustration of ethylene production by steam cracking of ethane. (Birth of the petrochemical industry. 2021)

1.3.2 The ethylene unit, hot end distillation process

The hot end distillation process begins from the cracking furnace outlet. Based on the type of feedstock, the cracking furnace heater effluent is first quenched by oil or water, which afterwards is led to the gasoline fractionator, where pyrolysis fuel oil is separated. The pyrolysis fuel oil is led to the fuel oil stripper for further processing. Steam and the pyrolysis gasoline, which consists of lighter hydrocarbons, are lead from the gasoline fractionator to the quench tower. Pyrolysis gasoline is fractionated in the quench tower for further processing. The quenched charge gas (consisting of cooled hydrocarbons and steam) is led from the top of the quench tower to the low-pressure side of the charge gas compressor unit. The quenched charge gas is compressed by a turbine driven centrifugal compressor. Water is separated from the charge gas during compression in four to six stages with cooling in between before it is sent for acid gas removal to a caustic and water wash tower. The purified hydrocarbon charge gas is led forward from the caustic and water wash tower to the high-pressure side of the charge gas compressor unit, where water and moisture are stripped furthermore. (Riistama etc. 2003; Francisco José Orantos Borralho. 2013.)

2 Asset Mechanical Integrity Management at the Porvoo Site

The asset mechanical integrity at the Borealis Porvoo production site is managed by the Plant Availability & Turnaround organization, which consist of several departments related to maintenance, inspection, and reliability. The main responsibility of the organization is to ensure safe and reliable operation as well as to ensure high availability of the production plants and units. The inspection department participates in several activities to maintain the mechanical integrity in mechanical structures and static (fixed) equipment of the production plants. The main responsibility of the inspection department is to maintain high availability and safe operation of the pressure equipment installed at the production plants. One of the main tasks of the inspection department is to coordinate and implement inspection activities in order to manage risks in pressure equipment. In general, the inspection department examines and monitors the mechanical condition of the operating pressure equipment to ensure that degradation is detected and corrected before a failure occurs. (Painelaitteiden kunnonvalvonta (yhtiöohje) 2017.)

At the Porvoo site, the inspection activities are managed with the help of an integrity management system (IMS) and a computerized maintenance management system (CMMS) SAP. Associated to maintaining the mechanical integrity and safe operation of the pressure equipment, the inspection department is responsible for ensuring compliance with legal regulations, codes, standards, and specifications. The compliance with legal regulations, codes, standards, and specifications is based on provisions of the Finnish law, guidelines of the Finnish safety and chemicals agency (Tukes), international and national standards and Borealis Group guidelines. The following Finnish legislation is primarily applied at the Borealis Porvoo site by the inspection department; The Finnish Pressure Equipment Act (1144/2016), The Finnish Government Decrees on Pressure Equipment (VNa 1548, 1549 and 1550/2016) and the Chemicals Act (744/1989 and its decrees 675/1993, 59/1999 and 856/2012). The Finnish Pressure Equipment act (1144/2016) is based on the European Union Pressure Equipment Directive (2014/68/EU PED). (Painelaitteiden kunnonvalvonta (yhtiöohje) 2017.)

2.1 Integrity Management System (IMS)

IMS is a web-based asset integrity management database that is used to manage the integrity of the mechanical asset of production plants in the process industry. The database is used by the Borealis inspection department to manage inspection and risk mitigation activities at production plants considering active pressure equipment, pressurized piping, and pressure safety valves (PSV) and above ground storage tanks during their life cycle. The inspection activities are coordinated, inspection schedules (intervals) are determined and calculated in IMS, as well as associated documents and data related to the inspection activities are managed in IMS. Determination of the inspection schedules and the scope of inspections in IMS are carried out considering factors associated to repairs and modifications of the pressure equipment, law provisions, events (e.g., turn arounds or shutdowns), a risk-based Inspection (RBI) program or active corrosion circuits (corrosion calculations). Corrosion loops are used as a tool to facilitate degradation management, RBI assessments and management as well as the coordination of inspection activities. A risk-based inspection module is integrated to the database. The module is used to implement and manage assessments and operations associated to RBI and overall risk management. The inspection department is responsible for maintaining the IMS. (RBI Software – Qualitative and Quantitative and everything in between. 2019; Integrity Management with S-RBI. 2020.)

2.2 Corrosion loop

A corrosion loop is a group of clustered pressure equipment and components related to the pressure equipment, which are susceptible to identical degradation. Typically, all the pressure equipment and the components, which pertain to the same corrosion loop, are constructed of the same type of materials and are exposed to identical process conditions. Several different types of pressure equipment, such as steam drums, heat exchangers, pipelines etc., or other components related to the equipment previously mentioned may be included in one corrosion loop. A corrosion loop may be clustered based on identical factors, which affect the equipment mechanical integrity, such as the process chemistry, process conditions, mechanical environment, material metallurgy, pressure equipment in-service history etc. Associated to risk management (e.g., degradation management), the purpose of a corrosion loop is to provide comprehensively data and information associated to the mechanical integrity of the pertaining pressure equipment. A corrosion loop optimizes the management of inspections and maintenance activities in the operating pressure equipment. The inspection data from one object in a corrosion loop may indicate the level of the mechanical condition of other objects pertaining to the same corrosion loop. Corrosion loops are commonly visualized and determined at block flow diagram (BFD) and process flow diagram (PFD) level. In Figure 3, there is an illustration of corrosion loops determined by color in a process. (API RP 580 Risk-based Inspection third edition. 2016; Overview of Corrosion loop. 2021)

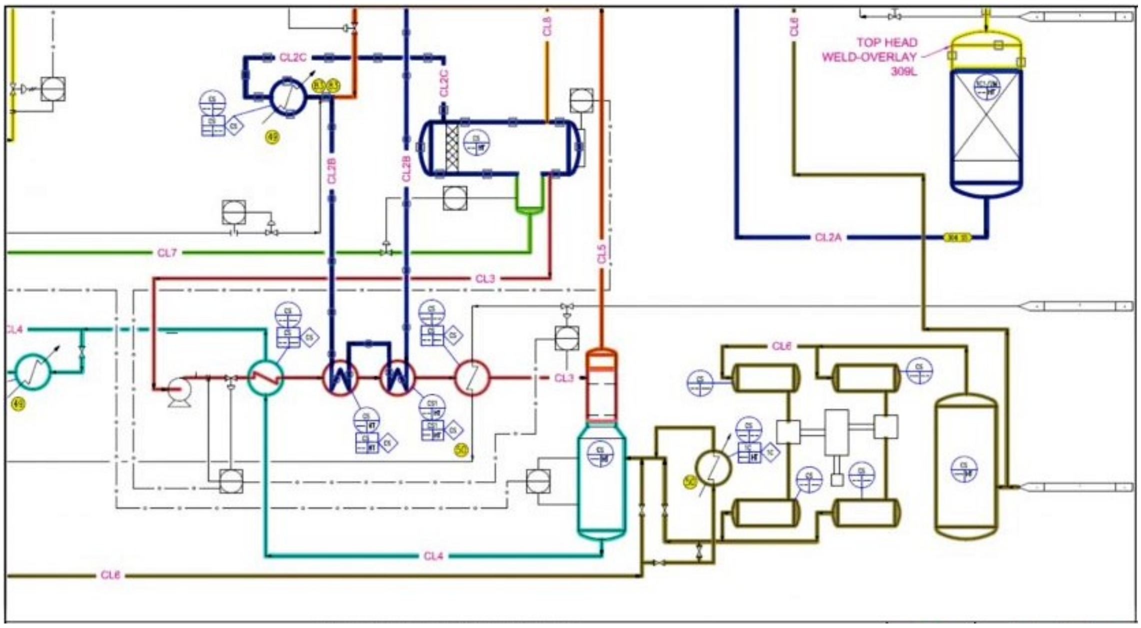


Figure 3. Corrosion loops determined by colour in a PFD of a hydrodesulfurization unit. (Damage Mechanism Reviews. 2019.)

3 Risk-Based Inspection

Risk-based Inspection (RBI) is a risk assessment methodology and a risk management process that is applied in the process industry to maintain safe and reliable operation of production plants. RBI is a methodology used to understand and identify the risk factors that affect the mechanical integrity of the assets at the production plants. Commonly, RBI is a methodology used as a tool to identify and understand the life cycle stages of in-service pressure equipment. The outcome of an assessment, which is performed based on the RBI methodology is a criticality classification for an equipment. The criticality classification is based on the risk that the equipment represents at the production plant or production unit. In the RBI ideology, a risk at production plants is commonly a combination of a potential pressure equipment failure due to degradation and a potential discharge of hazardous content or stored energy due to loss of containment (failure) of the pressure equipment. (API RP 580 Risk-based Inspection third edition. 2016; What is Risk-based inspection (RBI) 2021.)

Material degradation (mechanisms) represents the initial risk in the RBI methodology. A completed RBI assessment (RBI program) provides risk mitigation actions to manage material degradation and provides an effective and reliable inspection plan to monitor material degradation. An applicable inspection plan developed from the RBI assessment uses methods, which provide certainty in a sufficient and reliable way in order to understand the present mechanical condition of the object being examined. (API RP 580 Risk-based Inspection third edition. 2016.)

A common and conservative approach to implement pressure equipment inspections at production plants is periodical and it can be applied on a wide range of objects. The RBI assessment addresses inspection activities or other risk mitigation actions for the object being assessed based on the criticality classification, in other words, based on the risk it represents. The economical benefits that can be achieved by applying RBI consist of increasing utilization rates of the production plants and optimized cost-efficient risk management. The

RBI methodology is most widely applied in the energy and petrochemical industry but could also be applied and adapted in various other branches of industries. The RBI approach may not be exclusively an adequate approach to ensure safety in all industrial sectors, such as in the nuclear power industry, where the consequences of an event may be very serious and extent. (API RP 580 Risk-based Inspection third edition. 2016; What is Risk-based inspection (RBI) 2021.)

There are several codes, standards and recommended practices that provide guidelines associated to requirements, methods, or implementation of RBI and equipment criticality classifications (risk assessments), such as:

- CEN EN 16991 Risk-Based inspection framework (RBIF)
- ASME PCC-3 Inspection Planning Using Risk-Based Methods
- EEMUA Publication 206 Risk Based Inspection
- PSK 6800 Criticality Classification of Equipment in Industry
- API RP 580 Risk-Based Inspection
- API RP 581 Risk-Based Inspection Methodology
- DNVGL G101 Risk-based inspection of offshore topsides static mechanical equipment

"One objective of RBI is to determine what incident could occur (consequence) in the event of an equipment failure, and how likely (probability) it is that the incident could happen" (API RP 580 Risk-based Inspection third edition. 2016.)

One of the main elements of an RBI assessment is the risk assessment. In a risk assessment, a risk should be identified and determined based on how critical (significant) it is, and whether the risk is acceptable. According to API 580, main elements of a risk assessment are:

- Determination of the probability of an equipment failure (the PoF assessment)
- Determination of the consequences, which may potentially result from the equipment failure (CoF assessment)
- Identifying every scenario, which may lead to a specific consequence (scenario which initiate from an equipment failure) and determination of the probability of every identified scenario

- Determination of the final risk (risk calculation)

The probability of a scenario initiated by a pressure equipment failure (loss of containment) in a certain timeframe combined with the consequence associated with this specific scenario is the eventual risk in the RBI methodology. The resultant probability is the product of the probability of failure (PoF) and the probability of a scenario which is initiated by the failure. In mathematical terms, in the API RBI methodology, the risk is calculated by using the formula number 1.

$$risk = probability\ x\ consequence \tag{1}$$

In the RBI methodology, a logical continuum after completion of a risk assessment is development of an inspection plan or updating it and development of risk mitigation actions. (API RP 580 Risk-based Inspection third edition. 2016.)

The risk management principles of the API 580 Risk-based Inspection are universally applicable but emphasize maintaining the mechanical integrity in pressure boundary equipment that are particularly used in the hydrocarbon, and chemical process industry. The practices of the API 580 aim to minimize or eliminate the risks associated to loss of containment (release of hazardous content) of an active pressure equipment. In the RBI methodology, loss of containment is commonly the result of a failure in a pressure equipment. A pressure equipment failure occurs typically due to material degradation. In an RBI assessment, by using discretion, also other types of failures could be included (which is recommended), in addition to loss of containment. For instance, the loss of function of a pressure equipment due to a mechanical failure in a related component or structure could also lead to serious consequences. The loss of function in the following equipment or components could also be critical: heat exchanger tube bundles, other mounted components or structures in a pressure equipment, PSVs, or rotating equipment. Commonly, functional failures are considered in reliability centered maintenance (RCM) programs, which is the reason why they are not considered in detail in the API 580. (API RP 580 Risk-based Inspection third edition. 2016.)

There are different types of approaches to carry out an RBI assessment. The approach may be either qualitative or quantitative, or both approaches may be applied in different stages of the RBI assessment. If so, an RBI assessment approach may also be of a semi-quantitative type. The more detailed an RBI assessment is, the more quantitative the assessment is. The fundamental difference between these approaches is the level of accuracy and the extent of the data and the information required to carry out the sub-assessments, calculations, and configurations, which are included in an RBI assessment. The accuracy of the qualitative assessment outcome depends typically on the technical expertise, decision making ability and experience-based knowledge of the individuals performing the RBI assessment. Nevertheless, the qualitative approach may be effective when screening low-risk objects. It is possible to reach sufficient accuracy and to achieve equally identical benefits as with quantitative approach. The quantitative approach uses numerical models to calculate risks. The input data required for executing a quantitative RBI assessment is more detailed and based on numerical values. The methods used in the quantitative approach are more systematic, consistent, and documented than the methods of a qualitative approach. Software programs are often used as a database and to calculate risks during a quantitative RBI assessment. The accurate input data and development of numerical models of the objects being assessed makes the quantitative approach very intensive considering data management. (API RP 580 Risk-based Inspection third edition. 2016.)

Companies have usually determined the criteria related to risk acceptance (limits). These risk thresholds are usually applied during decision making in an RBI assessment. The risk acceptance is usually considered from the aspects of safety, environment and economy. A resultant risk from an RBI risk assessment is commonly presented and illustrated in a risk matrix or in a risk plot (risk graph). Commonly, a risk matrix is used during risk presentation without numerical models, although numerical values may be used to facilitate the illustration. Figure 4 shows an example of a risk matrix that could be used to present the results from an RBI assessment which is more of a qualitative type. (API RP 580 Risk-based Inspection third edition. 2016.)

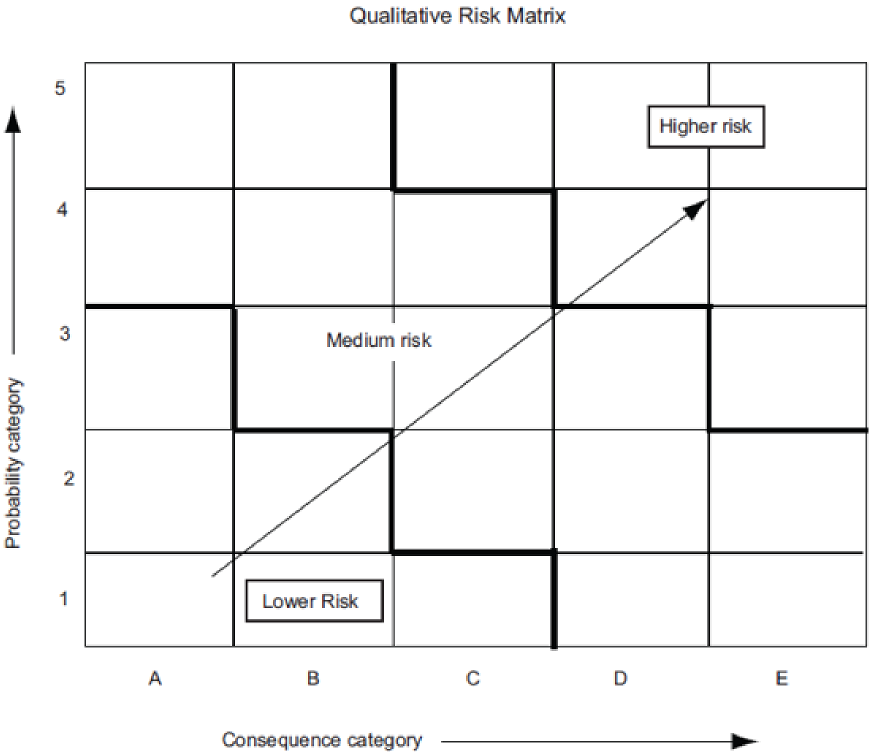


Figure 4. Example of a risk matrix that could be used to illustrate the resultant risk of an RBI risk assessment. (API RP 580 Risk-based Inspection third edition. 2016.)

When an RBI assessment is more of a quantitative type and the numerical values are more relevant, risk plots are used. In a risk plot, a logarithmic scale and a risk acceptance limit (ISO-risk line) are commonly used. The ISO-risk line is the determined risk acceptance limit (risk threshold). Figure 5 shows a risk plot presenting an illustration of resultant risk values of ten assessed equipment, and a determined ISO-risk threshold. In this illustration, the resultant risk values of the assessed equipment 1. 2. and 3. are not acceptable. The resultant risk should be reduced by applicable methods, so that the resultant risk values would place below the determined risk acceptance threshold (ISO-risk line), which is illustrated in Figure 5. (API RP 580 Risk-based Inspection third edition. 2016.)

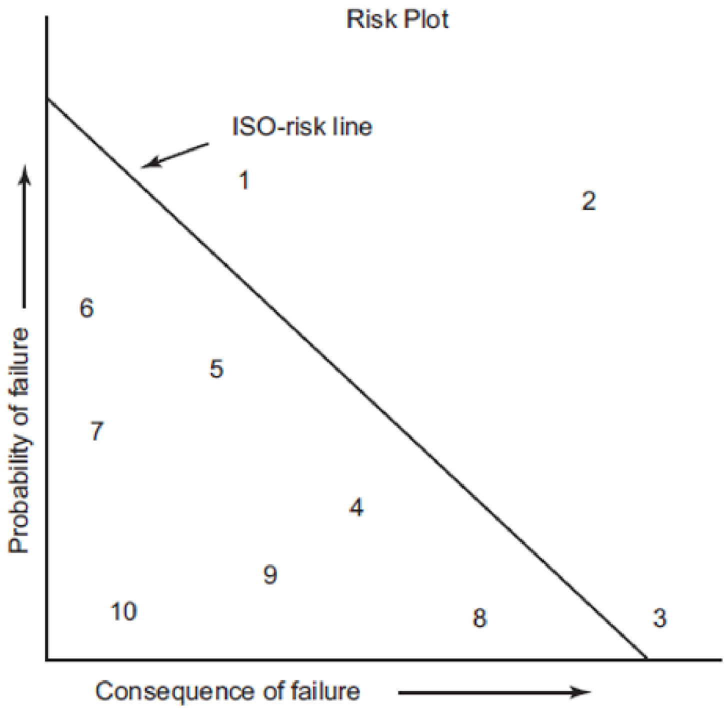


Figure 5. Example of a risk plot (risk graph) which could be used to illustrate the resultant risk value of an RBI assessment.

The asset data and information collection is an essential part of an RBI assessment. The quality of the collected data and information may have a significant influence on the accuracy of the RBI assessment outcome. The function of the collected data is to provide necessary and essential information to implement a convincing and reliable RBI assessment. The primary purpose of the collected data and information is to provide aid to identify potential degradation mechanisms, facilitate implementation of the PoF and CoF assessments, as well as to provide information for developing inspection plans or other risk mitigation actions. (API RP 580 Risk-based Inspection third edition. 2016.)

A fundamental element of an RBI assessment is to identify the potential degradation mechanisms, which affect the mechanical integrity of the pressure equipment operating at the production plants. Essential matters associated to the identified degradation mechanisms such as the morphology of the degradation mechanism (degradation mode), failure modes, degradation rate and degradation susceptibility should be determined in an RBI assessment. In general, the types of material degradation are the following; cracking, corrosion, mechanical damage and metallurgical degradation. The comprehension of the process conditions, surrounding and mechanical environment (e.g., prevalent static or dynamic loads in considered pressure equipment) are key factors when identifying potential degradation mechanisms in the pressure equipment being assessed. The comprehension and knowledge of the potential and the prevailing degradation mechanisms complete the required competence to perform a PoF assessment. It also facilitates ability to develop applicable, reliable, and optimal inspection plans. Understanding the identified degradation mechanisms also provides aid in decision-making related to the implementation of the required risk mitigation actions. The PoF of a pressure equipment may significantly be reduced by risk mitigation actions, such as process changes, process fluid composition changes, material selection or implementing condition monitoring. (API RP 580 Risk-based Inspection third edition. 2016.)

A completed RBI program is a dynamic tool, which is used to manage current and future risks in production plants. As time goes by, changes and deviations are inevitable considering the pressure equipment, which operate at production plants, which potentially can lead to changes in the present risk. Therefore, it is important to maintain and update an RBI program to assure that the latest data and information is processed adequately to identify factors, which may trigger the necessity for an RBI re-assessment in considered objects. (API RP 580 Risk-based Inspection third edition. 2016.)

The primary outcome of an RBI assessment is an active program, which manages identified risks at an individual level in assessed in-service pressure equipment. Based on the criticality classifications of an RBI assessment, optimized cost-efficient inspection plans and risk mitigation actions are developed in order to manage the identified risk factors in the assessed pressure equipment. (API RP 580 Risk-based Inspection third edition. 2016.)

3.1 Probability of failure assessment

In a PoF assessment, the probability of a pressure equipment failure during operation is determined. A pressure equipment failure initiates commonly due to material degradation (degradation mechanism). Before a PoF assessment is conducted, the pressure equipment and related components in the scope of the RBI assessment, that are susceptible to degradation should be identified. In particular, the relevant degradation mechanism(s) should be identified. In a quantitative type of a RBI assessment, the probability is determined as a numerical value. Commonly, the PoF is determined as failures per run length (between turnarounds) or per year (e.g., 0.01 failures per year). In a qualitative PoF assessment, probability is determined commonly in simple categories such as high, medium, and low. (API RP 580 Risk-based Inspection third edition. 2016.)

In a PoF assessment, the potential failure modes of every identified degradation mechanism should be determined. The failure mode is a characteristic of a degradation mechanism, representing the physical manifestation how the equipment can fail. Considering a pressure equipment failure, there can be various types of failure modes, depending on the type of the degradation mechanism. The failure mode is an essential factor associated to the severity of a consequence, which result in a pressure equipment failure. A specific consequence result from a scenario, which is initiated by a specific failure mode. The failure mode determines the “hole” size from which the content discharges during loss of containment. For instance, consequences resulting from a pinhole type of leak (failure mode) due to pitting corrosion in a pressure equipment differ significantly from consequences resulting from a rupture (failure mode) due to material brittleness in a pressure equipment. Usually, several failure modes are determined per potential degradation mechanism. (API RP 580 Risk-based Inspection third edition. 2016.)

A degradation mechanism may not always be the root cause for a pressure equipment failure. In a PoF assessment, following factors may be considered alternatively, which may cause a pressure equipment to fail, such as seismic activity, extreme weather phenomenons, process malfunctions, design flaws in structures or even sabotage. Most of the above-mentioned factors are usually ignored in a PoF assessment. (API RP 580 Risk-based Inspection third edition. 2016.)

According to API 580, the primary factors, which influence the probability of a pressure equipment failure should be considered in a PoF assessment. The primary factors are potential degradation mechanisms and degradation rates as well as the effectiveness of the mechanical integrity management of the considered production plant / unit. Regardless the chosen type of the RBI assessment (qualitative, quantitative, or semi-quantitative), these above-mentioned factors should be considered in a PoF assessment. (API RP 580 Risk-based Inspection third edition. 2016.)

For every credible internal and external degradation mechanism, which may initiate in the assessed object due to process conditions, surrounding and mechanical environment should be considered in a PoF assessment. Considering age-related degradation mechanisms, the degradation rates should be determined and considering the non-age-related degradation mechanisms, the susceptibility should be determined in a PoF assessment. In addition to normal operation conditions, various process conditions that may influence degradation rates and susceptibilities may have a significant influence on the PoF. Process conditions during malfunctions, process startup, process shutdown and other process deviations should be considered in a PoF assessment. In addition, factors related to equipment fabrication that may contribute and affect degradation rates and susceptibilities must be also considered. Considering the pressure equipment being assessed, the probability of each potential failure mode should be determined in a PoF assessment. (API RP 580 Risk-based Inspection third edition. 2016.)

Associated to mechanical integrity management, the inspection plan effectiveness, maintenance performance as well as process monitoring effectiveness may significantly influence the probability of a pressure equipment failure, which is the reason why they should be considered in a PoF assessment. One significant factor affecting the probability of a pressure equipment failure is the effectiveness of the inspection plan. Adequate effectiveness of an inspection plan reduces uncertainty of the degradation state (damage state) in the pressure equipment and improves the predictability of potential failures. Considering pressure equipment, the predictability of a potential failure or the predictability of the end of the service life decreases the probability, that a failure will occur during operation of the pressure equipment. In other words, adequate inspections lower the risk and the criticality classification of the pressure equipment. The PoF assessment should examine the effectiveness of the inspection plans (what are being used and new developed ones) to detect, identify and monitor the identified degradation mechanisms. The performance of the production plant maintenance comprehends of the ability to execute repairs and renewals before a failure occurs in an operating pressure equipment, this is a factor that may influence the PoF. The effectiveness of process monitoring may also significantly influence the PoF. Process parameter monitoring measures and analyzes relevant factors related to process conditions such as contaminants and parameters which may indicate potential degradation initiations in operating pressure equipment. For instance, pressure fluctuations or H_2S concentrations may initiate degradation in operating pressure equipment. Factors such as, the current mechanical condition, the remnant service life as well as the damage tolerance of the pressure equipment being assessed are also essential factors that may influence the probability of a pressure equipment failure. (API RP 580 Risk-based Inspection third edition. 2016.)

A PoF assessment should be consistently reproducible and assumptions as well as the outcome of the assessment should be documented. (API RP 580 Risk-based Inspection third edition. 2016.)

3.2 Consequence of failure assessment

The consequences of a potential pressure equipment failure are determined in a CoF assessment. The consequences, which result from a pressure equipment failure, determine the severity of the potential incident. The main objective of a CoF assessment is to screen pressure equipment by the significance of the consequences, which may result due to a failure. In a CoF assessment, it should be estimated what may potentially occur due to loss of containment (or loss of function) of the assessed pressure equipment. A CoF assessment should be a convincing assessment of what can be expected to occur as a result of a scenario initiating from a pressure equipment failure. In the RBI methodology, a consequence, which is a result of a pressure equipment failure, initiates due to discharge (release) of hazardous content into the surrounding environment. The CoF assessment examines all potential consequences that are likely to result from every potential failure mode. (API RP 580 Risk-based Inspection third edition. 2016.)

The consequences of a pressure equipment failure may potentially have an impact on a wide scale of different matters. In the CoF assessment, different aspects are considered when determining the potential negative impacts (consequences) of a pressure equipment failure. The consequences due to loss of containment of the pressure equipment are typically considered from the aspects of health, safety, environment, and economics. Considering the production plant personnel, in an event of a pressure equipment failure, consequences from the aspects of health and safety could be determined by the necessity of first aid or medical treatment or the resulting injuries, potential disabilities or even fatalities. In a quantitative type of a CoF assessment, monetary values are used to determine the health and safety consequences. Monetary values are also used to determine the environmental and economic consequences. From the environment and economic point of view, the affected area is also considered in which monetary units are specified. (API RP 580 Risk-based Inspection third edition. 2016.)

The key elements of a CoF assessment are to determine and assess the probable consequences, identify the probable scenarios which lead to the specific consequence and determine the level of discharge (volume of fluid released) during the pressure equipment failure (during loss of containment). (API RP 580 Risk-based Inspection third edition. 2016.)

In a CoF assessment, the following factors should be considered when estimating the volume of fluid that will potentially be released into the surrounding environment during the potential pressure equipment failure: (API RP 580 Risk-based Inspection third edition. 2016.)

- The maximum volume of fluid that may discharge from the pressure equipment
- The determined failure modes (leak magnitude, “hole size”)
- Rate of the discharge (leak rate (fluid flow rate))
- Time of detection and practices to stop the leakage

During a pressure equipment failure, the maximum volume of fluid what will discharge is typically considered as the maximum volume of fluid the pressure equipment and connected piping contain during operation. Sections are considered before shut-off valves in the connected piping (shut-off valves may be closed manually or by automation in an event of a pressure equipment failure). Commonly, the maximum volume of fluid that would be released into the surrounding environment during loss of containment is the same as the maximum volume of fluid contained in the pressure equipment and the connected piping during operation. In order to reduce or isolate discharges (leaks) during a pressure equipment failure, safeguards (safety systems) and emergency practices are usually implemented. Safeguards and emergency practices should be also considered when determining the volume of discharge (volume of fluid) during a pressure equipment failure. (API RP 580 Risk-based Inspection third edition. 2016.)

During a pressure equipment failure, the discharge of energy or hazardous content in the surrounding environment is the reason why consequences result, which impact in a negative way different kind of matters associated to safety, health, environment, production plant operation and business. It is important to consider and to assure that essential factors related to the potential hazards are taken into account in the CoF assessment. According to API 580, regardless the type of the RBI assessment (qualitative, quantitative, or semi-quantitative), the following factors should be considered, while determination of potential consequences of a pressure equipment failure: (API RP 580 Risk-based Inspection third edition. 2016.)

- Flammable events (fire and explosions)
- Discharge of toxic fluid/substance
- Discharge of other hazardous fluid/substance
- Effects on the environment
- Effects on the production and business
- Repair and rebuilding costs

The flammable events (fire and explosions) originate from the combination of the discharge (leak) and an ignition. The ignition of a leaking substance may result from an event or an ignition without an event is also possible (auto ignition). A fire may cause damage due to heat radiation and explosions may cause damage due to overpressure. Most damage due to heat radiation is generated over a short distance, but overpressure from an explosion may cause damage from a greater distance. (API RP 580 Risk-based Inspection third edition. 2016.)

The toxic releases should be considered in the CoF assessment while having an impact on personnel (at the production site and the surrounding environment). Discharges of toxic substances may cause consequences from a longer distance than a fire, for instance. The consequence resulting from a toxic release, does not need an additional event to cause it, as a fire needs ignition. (API RP 580 Risk-based Inspection third edition. 2016.)

The release of other hazardous substances should also be considered when potential consequences might potentially affect personnel. Other hazardous contents are substances, which may potentially cause injuries or disablement due to contamination. The discharge of other hazardous substances such as caustics, acids, hot water, and steam may cause significant consequences that should be considered in the CoF assessment. (API RP 580 Risk-based Inspection third edition. 2016.)

The consequences, which have a negative impact on the environment, are important elements when determining the overall risk at a production plant. The CoF assessment should be focused on consequences, which are acute and immediate on the environment. Liquid substances may contaminate soil, groundwater, or other aquatic ecosystems due to loss of containment of the pressure equipment. The gaseous discharges are more challenging to estimate. The consequences during gaseous discharges are often related to legislative restrictions and fines for exceeding defined thresholds. (API RP 580 Risk-based Inspection third edition. 2016.)

The economic consequences of a pressure equipment failure are typically related to business interruptions or production losses. Commonly, the most severe economic consequence during a pressure equipment failure is the value of the production shutdown related to time (days). (API RP 580 Risk-based Inspection third edition. 2016.)

The repair and rebuilding costs comprise resources required for repair, reconstruction or renewal of equipment and structures of the production plant. (API RP 580 Risk-based Inspection third edition. 2016.)

During a pressure equipment failure, the loss of containment is only the first event of a scenario, which leads to a consequence. The probability of a specific consequence is affected significantly by the series of the potential events, which make up the scenario. For instance, the initiation of safety systems (safeguards) which indicate or provide alerts of process malfunctions, deviations, or equipment failures, may have a huge impact on the magnitude of the consequences. The emergency procedures, which isolate, bypass, or interrupt a process, may also significantly affect the extent of the consequences resulting from the pressure equipment failure. The failures of safety guards or emergency procedures should also be considered in an RBI assessment. When all probable scenarios, which initiate from a pressure equipment failure, are identified, also the probability of every scenario should be estimated. (API RP 580 Risk-based Inspection third edition. 2016.)

In summary, according to API 580, in order to assess the potential consequences during loss of containment of the pressure equipment, the following factors should be taken into account: (API RP 580 Risk-based Inspection third edition. 2016.)

- The volume of discharge (release rate)
- The total amount of the discharge in the surrounding environment (volume of fluid released)
- The dispersion of the discharge (instantaneous or continuous)
- The phase of the fluid during discharge into the surrounding environment
- The functional principles of safeguard systems and emergency procedures during an event of a pressure equipment failure

3.3 Relation between inspection activities and risk management

At production plants, one of the primary purpose of inspection activities is to improve awareness and knowledge of the degradation state and the degradation tolerance of the mechanical asset. Associated to degradation of a pressure equipment, inspection activities provide information, which creates ability to predict when a critical point is achieved related to safe operation of the pressure equipment. The ability to identify and characterize degradation mechanisms and the ability to estimate and monitor degradation rates is provided by applicable inspection methods and techniques (inspection effectiveness). (API RP 580 Risk-based Inspection third edition. 2016.)

A risk is not directly reduced by inspection activities, meaning that a pressure equipment failure is not prevented by inspection activities. However, a risk is managed by reducing the uncertainty related to it. A significant factor affecting the probability of a pressure equipment failure (PoF) is the uncertainty related to the degradation state of the equipment. The uncertainty is managed and reduced by providing critical awareness with inspection activities. If uncertainty is not reduced enough by inspection activities, other risk mitigation measures need to be implemented. By providing awareness, inspection activities also allow corrective actions such as implementation of risk mitigation measures (if necessary) to prevent equipment failures. Implementation of risk mitigation measures, such as process changes, structure material changes, equipment repair or renewals may significantly reduce the risk of a pressure equipment failure. (API RP 580 Risk-based Inspection third edition. 2016.)

Regarding the pressure equipment operating at production plants and units, the prevailing risks are commonly managed by an inspection plan or strategy. Thus, effectiveness of an inspection plan is essential. The inspection effectiveness influences the probability of a pressure equipment failure. The effectiveness of the inspection process is based on the ability of the used inspection methods in detecting, identifying, characterizing, and measuring degradation mechanisms in pressure equipment. The coverage of performed inspections on areas that are susceptible to degradation comprise also inspection effectiveness. In a PoF assessment, it should be considered that the inspection methods and techniques may significantly differ in the following aspects; ability to detect and identify various types of degradation mechanisms, ability to estimate the extent of damage, accuracy and ability to determine degradation rates and propagation. Factors, such as complexity of inspected structures, accessibility to perform inspections, inspected surface preparation and competence of inspectors should also be considered while determining the inspection effectiveness of an inspection plan/method. The inspection frequencies may also significantly influence the PoF by affecting the ability to characterize a degradation mechanism. During an RBI assessment, the ability of the current and developed inspection plans to reduce the PoF should be assessed. When assessing the risks of the operating pressure equipment, the effectiveness of the current inspection plan is an essential factor. (API RP 580 Risk-based Inspection third edition. 2016.)

Associated to pressure equipment failures, the inspection activities do not always allow reduction of the risk. Certain degradation mechanisms can be impossible to detect by inspection methods. For instance, a brittle fracture due to metallurgical degradation of a material, stress corrosion cracking (SCC) or fatigue could be challenging to detect and identify by any inspection method. A degradation mechanism could develop and propagate within a short period of time due to a consequence of an event, or due to rapid and significant changes in the process conditions. These previously mentioned influential factors, which are related to process conditions, cannot be prevented or managed by inspection activities. Regardless of whether an inspection plan is time, risk or condition based, according to API 580, a comprehensive integrity operating window (IOW) program should be commissioned to inform the inspection department personnel of deviations associated to process conditions which may influence the mechanical integrity of the operating pressure equipment. (API RP 580 Risk-based Inspection third edition. 2016.)

One objective of an RBI assessment is to optimise risk management to be more cost sufficient. The RBI methodology aims to optimize resources of inspection activities. The resources of inspection activities are meant to be focused on identified high-risk objects and reduced in identified low risk objects. Potentially, there are objects where inspection activities may not have any value in risk management. These objects should be also identified in an RBI assessment to achieve optimization of resources. Another way to optimise inspection resources is to identify effective inspection methods and techniques, which are applied and implemented during operation of the pressure equipment. There is a huge potential to optimise resources of inspection activities if the pressure equipment can be confidently and comprehensively inspected during operation. The external inspections during operation by applicable methods may potentially be a sufficient way to provide information and data of the potential degradation state of the pressure equipment. Adequate external inspections performed during operation of the pressure equipment may eliminate the need to blind piping and nozzles, dissemble, purify, and clean the pressure equipment. Most importantly, external inspections during operation eliminate the need to shut down and interrupt operation of the considered production plant/unit. Adequate external inspections during operation of a pressure equipment may affect the up time of a production plant/unit significantly. Internal inspections are often greatly sufficient, but in order to arrange an internal inspection, the pressure equipment must be disconnected from the process, which in many cases mean that the production plant/unit must be shut down. Interruption of the production is a huge disadvantage considering internal inspections of the pressure equipment, which is not cost-efficient due to production losses. The internal inspections of pressure equipment may also trigger degradation, which may potentially affect the probability of the pressure equipment failure. For example, moisture, damaged internal coatings, damaged material passive films or human errors during start-up and shutdown may initiate degradation in the pressure equipment. In an RBI assessment, cost efficiency should also be considered when selecting sufficient inspection methods for the external and internal inspections. (API RP 580 Risk-based Inspection third edition. 2016.)

A RBI assessment shall identify which is the dominant factor affecting the overall risk in the assessed object, if it is the PoF or the CoF. Based on the identified dominant risk, actions are implemented to manage or reduce the risk. Commonly, if the dominant risk factor is related to the PoF, there is potential to manage and reduce the risk by inspection activities. (API RP 580 Risk-based Inspection third edition. 2016.)

4 Risk-Based Inspection at Borealis

At the Borealis Porvoo site, RBI is applied to manage risks and to obtain safe as well as reliable operation of the production plants. At the Porvoo site, the application of RBI is primarily based on the IMS PEI module and guidelines of the Borealis Group. Regarding the application and implementation of RBI, Borealis Group guidelines apply largely API recommended practices and guidelines, which are also studied in this thesis. From a practical point of view, everything related to the implementation of RBI is managed in the IMS. Statutory requirements related to pressure equipment impose limits on applying RBI at the Porvoo site and extensive application of RBI requires cooperation with the authorities.

At Borealis, RBI is currently not applied to the pressure relieving equipment such as safety valves. Regarding the pressure relieving equipment, risks and the mechanical integrity are managed by applying specific Group guidelines. The equipment associated to end product handling, instrumentation air and water lines are also excluded from the RBI scope unless the fluids in the considered equipment are hazardous or toxic to the personnel at the production site, as well as if the production is significantly affected due to a failure of the considered equipment.

At the Borealis Porvoo site, a specific RBI program is maintained in order to manage the risks related to corrosion under insulation (CUI) in the pressure equipment and piping. In this RBI program, the criticality of every insulated pressure equipment and piping is classified based on the risk they represent. The criticality classification is based on the susceptibility that the process conditions and the surrounding environment constitute to initiate CUI, and the severity of consequences that would result from a pressure equipment failure due to CUI. At the Group level, an inspection strategy has been developed to manage risks related to CUI. The inspection strategy describes sufficient inspection plans that can be applied depending on the criticality of an equipment. Based on the outcome of the CUI criticality classification assessment, these inspection plans are implemented to manage risks in the considered pressure equipment. The implementation and coordination of the inspection plans are managed in the IMS. The CUI criticality classification assessment is conducted by the PEI module.

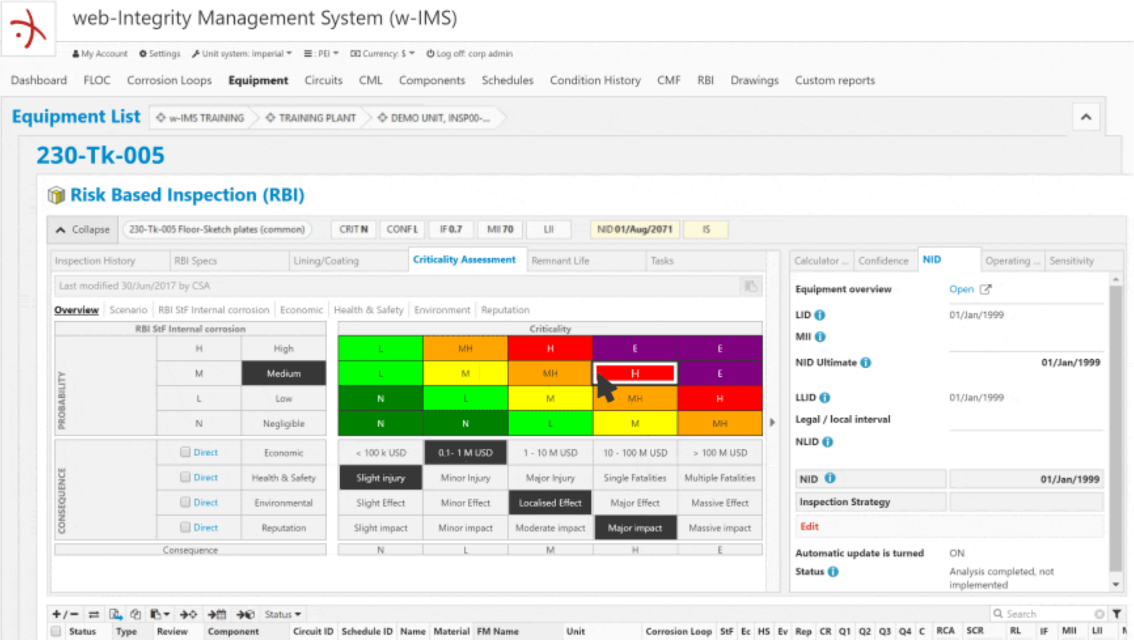
The aim at the Porvoo site is to further develop the application of RBI on pressure equipment and piping with the help of the IMS PEI module. The criticality classification assessments of the considered pressure equipment and piping are going to be based on the susceptibility that the process conditions, the surrounding and the mechanical environment constitute to initiate degradation which may cause a failure, and the severity of the consequences that could take place due the failure in the considered pressure equipment. Every relevant degradation mechanism that may cause a failure in the pressure equipment being assessed are to be considered in the criticality classification assessments.

4.1 IMS PEI module and S-RBI

The Shell-Risk Based Inspection (S-RBI) is a Shell Global Solutions-developed risk-based approach and methodology that is compliant to API 580, API 581 and to API 571 degradation mechanisms. S-RBI approach is utilized in the integrated PEI module in the IMS, which is developed to facilitate the implementation of qualitative, semi-quantitative or quantitative RBI assessments as well as the management of RBI. S-RBI provides different types of methodologies to implement RBI assessments considering the pressure equipment and piping or other equipment such as storage tanks and PSVs. The results of RBI assessment can be integrated with inspection results, wall thickness measurements and calculations, and schedules. The results of RBI assessment can thus be used to define the next inspection dates, which can interface with the site's CMMS. In S-RBI methodology, the following matters listed below are some of the main elements in the equipment criticality classification assessment (the risk assessment) and to define the next inspection date for an assessed equipment: (RBI Software – Qualitative and Quantitative and everything in between. 2019.)

- Corrosion loop
- Criticality assessment
- Confidence assessment
- Inspection monitoring and planning

Based on the configuration of the system, the user is allowed to swap between qualitative, semi-quantitative and quantitative methodologies. The default is a semi-quantitative approach, but with some customization the module using S-RBI approach can be setup to comply fully with API 581. The factors related to mechanical integrity management (inspection effectiveness, process monitoring effectiveness etc.) are considered in a confidence assessment, which does not directly affect the criticality assessment, but has a significant impact on the maximum inspection interval recommended by the PEI module. The outcome of the IMS RBI criticality assessment is the product of the Susceptibility to failure (StF) and the CoF. The StF could be described as the probability a degradation mechanism initiates and may result in a failure of the assessed object due to the prevailing process conditions, the surrounding and mechanical environment. (Integrity Management with S-RBI. 2020.) Figure 6 shows an overview of the IMS and the integrated PEI module).



CRIT **N** | CONF **L** | IF **0.7** | MII **70** | LII | NID **01/Aug/2071** | IS

Last modified 30/Jun/2017 by CSA

RBI StF Internal corrosion			Criticality				
PROBABILITY	H	High	L	MH	H	E	E
	M	Medium	L	M	MH	H	E
	L	Low	N	L	M	MH	H
	N	Negligible	N	N	L	M	MH
CONSEQUENCE	☐ Direct	Economic	< 100 k USD	0.1- 1 M USD	1 - 10 M USD	10 - 100 M USD	> 100 M USD
	☐ Direct	Health & Safety	Slight injury	Minor Injury	Major Injury	Single Fatalities	Multiple Fatalities
	☐ Direct	Environmental	Slight Effect	Minor Effect	Localised Effect	Major Effect	Massive Effect
	☐ Direct	Reputation	Slight impact	Minor impact	Moderate impact	Major impact	Massive impact
Consequence			N	L	M	H	E

Equipment overview Open
LID 01/Jan/1999
MII
NID Ultimate **01/Jan/1999**
LLID 01/Jan/1999
Legal / local interval
NLID
NID **01/Jan/1999**
Inspection Strategy
Edit
Automatic update is turned ON
Status Analysis completed, not implemented

Figure 6. An overview of the IMS and the integrated PEI module (risk matrix). (Integrity Management Software. 2022.)

The corrosion loops are used as a tool in the IMS to manage degradation and risk mitigation. For instance, IOWs are managed on the corrosion loop level in the IMS. In the IMS, the Degradation Management Framework is part of the corrosion loops, providing “barriers” (risk mitigation actions) to be used. The barriers, such as IOWs, coating, corrosion allowance, material resistance etc. mitigate degradation and provide degradation management. Status of the barriers are automatically updated from the inspection results. During the criticality assessment, all failure scenarios are considered and the StF as well as the CoF are determined to every degradation mechanism that the assessed component (equipment) is susceptible to. Considering age-related and non-age-related degradation mechanisms, StF is determined differently in the IMS PEI module. For instance, the StF associated to a corrosion mechanism is greatly influenced by the expected corrosion rate (or actual corrosion rate) and the design corrosion rate of the assessed object. Considering degradation such as creep and fatigue, remnant life calculation models are provided by the PEI module to determine the StF level. Associated to creep and fatigue, the remnant life calculations are based on the use and operation of the assessed object.

Considering non-age-related degradation mechanisms, the StF is determined by modelled decision trees, graphs, tables, or questionnaires provided by the PEI module. In the PEI module, the mentioned models, graphs, tables, questionnaires etc., are determined based on critical factors associated to process conditions, mechanical and surrounding environments, maintenance, equipment fabrication etc., which potentially affect the initiation of the specific type of degradation. In the PEI module, the consequences of a failure (CoF) are determined from the aspects of the asset, people, environment and the reputation. In addition, the severity of the consequences is determined by five different categories. Considering the CoF assessment, the PEI module provides tools such as release rate calculators of liquids and of some gaseous substances. The overall criticality (risk) of the assessed object is the combination of the most severe consequence and the StF level. In the PEI module, the criticality assessment is followed by the confidence assessment. In the confidence assessment, it is determined if risk management is provided by inspection activities (inspection effectiveness), by relevant process parameter monitoring or by other risk mitigation activities. The inspection personnel´s awareness of the degradation propagation is also considered in the confidence assessment. (RBI Software – Qualitative and Quantitative and everything in between. 2019; Integrity Management with S-RBI. 2020.)

Considering age-related degradation mechanisms, both the criticality assessment and confidence assessment have an impact on the recommended inspection interval. For some non-age related degradation mechanisms, separate inspection strategies may need to be followed, instead of a recommended inspection interval provided by the PEI module. (Integrity Management with S-RBI. 2020.)

5 Corrosion Study

The main purpose of a corrosion study is to identify at a theoretical level the contributing factors, which influence the mechanical integrity of the pressure equipment and piping that are installed in the process of a production unit that is being studied. The main element of the corrosion study is the identified degradation mechanisms.

An important outcome of the corrosion study is clustered corrosion loops of the pressure equipment, which operate at the hot end distillation process. Aggregation of the corrosion loops is based on the potential and active degradation mechanisms associated to the materials of structure of the pressure equipment. In the corrosion study, also degradation rates are assessed at corrosion loop level and at equipment (or component) level (alternatively). The degradation rates are given in corrosion rates (mm/a) or susceptibility levels (low, medium or high). The degradation susceptibility is based on the potential of the process environment to expose the equipment to specific degradation mechanisms and the probability that a material will fail before the considered degradation is detected. The susceptibility estimations were also affected by current condition of the considered equipment, based on the inspection history. The morphology of the considered degradation mechanisms is also determined in the corrosion study. The corrosion study is an essential part of the criticality classification assessment of the equipment at the ethylene unit hot end distillation process. As a summary, the objective of the commissioned corrosion study was to provide the required information and data to perform a comprehensive RBI assessment on the pressure equipment in the hot end distillation process.

In the corrosion study, the potential internal and external degradation mechanisms of the considered pressure equipment are studied. The areas of structures that are exposed to specific degradation in the pressure equipment are identified in the corrosion study as well, which can divide the pressure equipment into several corrosion loops. The degradation mechanisms, which initiate due to a mechanical load or stress such as ductile fracture, fatigue or thermal fatigue, were excluded from the corrosion study. Related to the following atmospheric degradation mechanisms, the degradation rates and susceptibilities were not assessed in the corrosion study: CUI, chloride SCC (related to CUI) and chemical degradation. If the probability of corrosion to occur was estimated to be low, a reasonably low default corrosion rates was set. The default corrosion rate is an important indication for inspection planning, stating that corrosion may occur in all equipment and piping that are part of the corrosion loop in question. (Corrosion Study Porvoo (Borealis) – Cracker Hot Distillation Unit. 2021.)

The corrosion study of the hot end distillation process at the Borealis Porvoo site´s ethylene unit was carried out by a Belgian company METALogic, which is a subsidiary of the *TÜV* Austria Group. The corrosion study was commissioned by the inspection department of the Porvoo site. As a result of the corrosion study, 17 corrosion loops were defined for the hot end distillation part of the ethylene unit. It was decided during the study that utility process equipment will be left out of the scope, as the utility corrosion loops should be defined for the whole production unit.

The corrosion loops were determined in the corrosion study at PFD level. Two corrosion loops were selected to be examined and to be criticality classified during this thesis. The selected corrosion loops were “Pyrolysis fuel oil” and “Condensed water”. The potential degradation mechanisms identified in the Pyrolysis fuel oil corrosion loop are sour water corrosion and wet H_2S damages. The degradation mechanisms associated to wet H_2S damages are hydrogen blistering, Hydrogen Induced Cracking (HIC), Stress-Oriented Hydrogen Induced Cracking (SOHIC) and Sulphide Stress Cracking (SSC). In addition to the two degradation mechanisms mentioned above, oxygenated process water corrosion was identified as a third relevant degradation mechanism for the Condensed water corrosion loop. The material of construction of the equipment and piping in the corrosion loops is carbon steel. (Corrosion Study Porvoo (Borealis) – Cracker Hot Distillation Unit. 2021.)

5.1 Corrosion loop Pyrolysis fuel oil

The corrosion loop Pyrolysis fuel oil includes all pressure equipment, piping and associated components that are internally or externally in contact with an environment that consists of pyrolysis fuel oil. The corrosion loop is part of the hot end distillation process where fractionated products from the gasoline fractionation are led to the fuel oil stripper column, where pyrolysis fuel oil is stripped from the fractionated products. Stripped pyrolysis fuel oil is led from the fuel oil stripper via heat exchangers to a storage tank located outside the process area. Pyrolysis fuel oil contains heavy hydrocarbon chains, such as aromatics, paraffins and naphtha. It is stated in the corrosion study that the corrosion loop fluid does not contain any significant amount of chlorides, and the hydrogen sulfide concentration is estimated to be max. 50 ppm in the corrosion loop fluid. Water is estimated not to be significantly present, and oxygen is estimated not to be present in the corrosion loop. The temperature range of the fuel oil stripper is between 130 °C and 220 °C during operation and the temperature range of the column inlet piping is between 40 C° and 150 °C during operation. The pressure range of the inlet piping is between 0.5 and 1.5 bar(g) during operation. The temperature range of the column outlet piping is between 20° and 150 °C and the pressure range is between 0.5 and 12 bar(g) during operation. (Corrosion Study Porvoo (Borealis) – Cracker Hot Distillation Unit. 2021.)

If water were present in the corrosion loop, sour water corrosion might take place. According to the corrosion study, a fluid containing dissolved hydrogen sulfide may inhibit corrosion or accelerate corrosion in carbon steels during contamination. The pH of the corrosion loop fluid is calculated to be 4.9. Based on the pH, it is likely that a thin iron sulfide film is formed on the surfaces of the structures of the equipment which pertain in the corrosion loop. It is stated that the sulfide film may inhibit corrosion. The assessed sour water corrosion rate in the corrosion loop is set to be 0.05 mm/a resulting as general thinning. (Corrosion Study Porvoo (Borealis) – Cracker Hot Distillation Unit. 2021.)

Another identified possible degradation affecting the pressure equipment of the Pyrolysis fuel oil corrosion loop is associated to wet H_2S damages. The hydrogen sulfide concentration (50 ppm) in the corrosion loop is a threshold value below which wet H_2S damages generally do not occur. Water is required to be present in the corrosion loop for wet H_2S damages to initiate. According to the Corrosion study, hardness of the corrosion loop structure materials is below 200 HB. Based on this information, is stated in the corrosion study that the potential of SSC is eliminated. Significant corrosion is estimated not to be present in the corrosion loop and the susceptibility of wet H_2S damages is set to be low. Wet H_2S damages result as cracking or blistering in the structures of the pressure equipment pertaining in the corrosion loop. (Corrosion Study Porvoo (Borealis) – Cracker Hot Distillation Unit. 2021.)

5.2 Corrosion loop Condensed water

The corrosion loop Condensed water includes all the pressure equipment and related components that are internally or externally more or less in contact with the environment that consists of condensed water. The corrosion loop fluid is water, which is separated from the quenched and compressed charge gas in the low-pressure side of the charge gas compression unit. Water is separated in several stages from the charge gas in the suction drums. The operating pressure of the corrosion loop is between 2.1 and 10.5 bar(g) and the operating temperature is between 9 °C and 37 °C. (Corrosion Study Porvoo (Borealis) – Cracker Hot Distillation Unit. 2021.)

In the corrosion loop Condensed water, oxygenated process water corrosion is a potential degradation mechanism. According to the corrosion study, the electrolyte (water), oxygen concentration and the fluid pH are the most influential factors regarding the initiation of oxygenated process water corrosion. Oxygen concentrations or other contaminants are not being analyzed from the corrosion loop fluid. According to the corrosion study, oxygen is not present in the corrosion loop. Based on the absence of oxygen, significant corrosion is not expected in this corrosion loop. The corrosion rate of the oxygenated process water corrosion in the corrosion loop is estimated to be 0.05 mm/a. This type of corrosion results as localized thinning in pressure equipment structures, which pertain in the corrosion loop. (Corrosion Study Porvoo (Borealis) – Cracker Hot Distillation Unit. 2021.)

Sour water corrosion is the other type of corrosion, which is seen possible in the corrosion loop Condensed water. The essential influential factor of this corrosion type is the concentration of the dissolved hydrogen sulfide in the corrosion loop fluid (170 ppm). Based on the calculated pH (4.7) of the corrosion loop fluid, is the rate of sour water corrosion estimated to be 0.03 mm/a. Based on the calculated pH of the fluid, it is possible for an iron sulfide film to form on the steel surfaces which are contaminated. This thin iron sulfide film may potentially prevent corrosion from taking place. Based on the corrosion study, significant sour water corrosion is not expected in the corrosion loop. The morphology of this type of corrosion is stated to be general thinning. (Corrosion Study Porvoo (Borealis) – Cracker Hot Distillation Unit. 2021.)

It has been estimated in the corrosion study that hydrogen sulfide concentration in the Condensed water corrosion loop can be up to 170 ppm. Based on the hydrogen sulfide concentration, wet H_2S damages are seen as probable degradation mechanisms in the corrosion loop. Based on the hydrogen sulfide concentration, the pH in the corrosion loop is estimated to be between 4.6 - 4.7. The corrosion loop temperature during operation is between 9 - 37 °C, which is a favorable temperature range for wet H_2S damages to occur. In the corrosion study, it is stated that the hardness of structure materials in the corrosion loop are below 200 HB. Based on the hardness value of the structure materials, the probability of SSC is eliminated (at theoretical level) in the corrosion loop. Nevertheless, the susceptibility is set to high considering other wet H_2S damages to occur in the corrosion loop. The high susceptibility level is based on the operation temperature, hydrogen sulfide concentration, pH, and the structure materials (carbon steel). The condition of the weldments in the equipment of the corrosion loop are considered to be as-welded (post-weld heat treatments are not carried out). The carbon steel used in the corrosion loop equipment are considered to have a relatively high sulphur content. Wet H_2S damage mechanisms are non-age-related type, which can appear as cracking or blistering in the corrosion loop materials of construction. (Corrosion Study Porvoo (Borealis) – Cracker Hot Distillation Unit. 2021.)

6 Identified Degradation Mechanisms

6.1 Oxygenated process water corrosion

The presence of oxygen concentrations in various industrial process water applications may cause significant corrosion activity. The combination of oxygen concentrations and low temperatures may potentially increase or even accelerate this type of corrosion in process water environments. The oxygen solubility in water increases at low temperatures. Also, the combination of high pressure and steam in process water applications increases significantly oxygen solubility in water. The oxygenated process water corrosion is typical in carbon steels and low-alloy steels. The main influential factors for this type of corrosion to occur is oxygen solubility, oxygen concentration and the temperature as well as the fluid flow type and rate in the environment. Even a modest increase of the oxygen concentration in a process water environment may increase corrosion rates significantly. Oxygen concentration levels of 20 ppb in process water applications may significantly increase the corrosion rates. The presence of oxygen in process water applications is also the main reason deposits and iron oxides form on equipment structure surfaces. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

The oxygenated process water corrosion appears mainly as extensive pitting on equipment surfaces that are in contact with process water or where condensation appear. At low temperatures, localized pitting may occur in low flow rate areas of equipment or in areas where water is stagnant like in drainage pipes. High flowrates (> 3 m/s) or a turbulent flow type may accelerate this type of corrosion in piping and components. Turbulent flow may occur downstream of piping components such as elbows, tees, valves or downstream of other internal discontinuities as weld protrusions or deposits. If the fluid is two-phased as liquid and steam in the process water application may aggressive corrosion occur on surfaces that are in contact with steam due to a higher flow rate of steam compared to the flow rate of the liquid phase. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

6.1.1 Prevention and mitigation

A sufficient way to prevent this type of corrosion in a process water system is to limit the oxygen concentration. The oxygen concentration may be analyzed from the fluid and measures to prevent this type of corrosion based on the results may be defined. According to API 571, carbon steels and low-alloy steels are recommended materials of construction in systems where oxygen concentration is below 20 ppb. Applicable corrosion inhibitors are recommended to be used to prevent this type of corrosion, but the suitability of the corrosion inhibitor should be verified by inspection and monitoring. Internal coating of equipment is also an option to prevent oxygenated process water corrosion, but it is important to select a coating suitable to the considered process conditions. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

6.1.2 Inspection and monitoring

Oxygenated process water corrosion appears typically as localized corrosion and pitting. This should be considered when selecting suitable inspection methods for the susceptible equipment. The inspections should be focused on areas where a high flow rate and a turbulent flow type is present as well as at areas with stagnant water or low-flow rates. For instance, piping inspections should be targeted at horizontal sections and downstream of components and equipment such as ejectors, control valves, throttle valves, pumps, elbows, tees, and reducers. The inspections should be also targeted at structure protrusions and discontinuities, which may affect the flow type and on structure surfaces where condensate may potentially appear. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

During internal inspections of pressure equipment, visual testing (VT) is one of the most effective methods to detect localized thinning and pitting. It is critical that the examined surfaces are cleaned for VT. During the VT inspections, a follow-up by an ultrasonic testing (UT) method is recommended. During internal inspections of carbon steel pipes, magnetic flux leakage (MFL) method may be adequate to screen localized corrosion and pitting corrosion. Indications are recommended to be followed up by an UT method. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020; API RP 581 Risk-based Inspection Methodology third edition. 2016; M.L. Berndt. 2001.)

Suitable methods to detect internal localized thinning during external inspections are grid UT, and automated ultrasonic testing (AUT), as well as radiographic testing methods (RT), for example profile RT. During external piping inspections may a long range guided wave ultrasonic testing method (GWUT) be suitable to detect localized pitting. Concerning pitting corrosion and localized thinning shall external inspections be targeted at rigorously determined condition monitoring locations (CMLs). (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020; API RP 581 Risk-based Inspection Methodology third edition. 2016; M.L. Berndt. 2001.)

6.2 Sour water corrosion

Carbon steels are subject to sour water corrosion. Stainless steels, copper alloys and nickel alloys are usually resistant to sour water corrosion. Sour water corrosion occurs due to acidic water in process applications (between pH's of 4.5 and 7). The acidity is due to dissolved H_2S in the water. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

The factors related to the process environment, which affect the formation of sour water corrosion, are the H_2S concentration, pH, temperature, flow rate and type as well as the oxygen concentration. High concentrations of dissolved H_2S typically decrease the pH in the water. Water with a pH slightly below 4.5 is considered as a weak acid. A pH below 4.5 would significantly affect the rate of sour water corrosion in process applications. Other contaminants such as hydrogen chloride (HCl) and carbon dioxide (CO_2) decrease also significantly the pH of the water that is present in the considered process environment. The oxygen concentrations may increase the sour water corrosion rate and cause pitting below sulfide deposits. According to API 571, a process application where sour water is present with a pH of 4.5, it is also possible, a thin iron sulfide film generates on structure surfaces, which inhibits corrosion. The environments that expose equipment to sour water corrosion may also potentially cause formation of thicker and porous sulfide deposits on structure surfaces, potentially leading to pitting corrosion underneath the deposits. Commonly, sour water corrosion result as general thinning. Figure 7 shows a view of the internal surface of a suction header where sour water corrosion appears. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

Figure 7. Close view of the internal surface of a suction header corroded by sour water. (Manoj Kumar etc. 2017.)

6.2.1 Prevention, inspection, and monitoring

It is possible to monitor and estimate the probability of sour water corrosion to appear in process environments by analyzing process contaminants such as H_2S, chloride, cyanide, and the oxygen content. The temperature and pH of the process fluid are also essential factors to me monitored. The recommended combination of methods to detect general thinning during internal inspections is VT and UT (thickness measurements). During internal inspections, VT is one of the most effective method for detecting general thinning, but to characterize its severity, follow up by an UT method is recommended. Localized thinning is recommended to be inspected during internal inspections by the VT method followed up by an UT method at locally thinned areas, if necessary. To detect general thinning during external inspections, thickness measurements by an UT or an RT (profile RT) method are recommended in determined CMLs. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.) (API RP 581 Risk-based Inspection Methodology third edition. 2016)

6.3 Wet H_2S damages

The degradation mechanisms described in this chapter are associated to hydrogen absorption and intrusion into steels in process environments where H_2S is present. The hydrogen atoms may potentially diffuse into steels due to a corrosion process in environments where H_2S is present. Degradation such as blistering and cracking appear particularly due to a corrosion process (sour water corrosion) which is generated by water with H_2S content. In the petrochemical industry, H_2S concentrations are mainly carried into the process by dimethyl disulfide (DMDS), which is a chemical compound what is used to prevent coke formation in coils of steam cracking furnaces. H_2S may also be carried into the process by feedstock from the oil and gas refining industry. (Corrosion Study Porvoo (Borealis) – Cracker Hot Distillation Unit. 2021; Understanding wet H_2S and where to find it. 2021; API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

The degradation mechanisms linked to wet H_2S damages are hydrogen blistering, hydrogen induced cracking (HIC), stress-oriented hydrogen induced cracking (SOHIC) and sulfide stress cracking (SSC). These degradation mechanisms may significantly reduce load resistance of pressure boundary structures, which during a failure may cause serious consequences. Carbon steels, low-alloy steels and high strength steels are commonly susceptible to wet H_2S damages. The formation of wet H_2S damages require an environment where sour water is present and in contact with the steel. The main reason for the wet

H_2S damages to occur are the process conditions (the process environment). The influential factors to formation of wet H_2S damages are the H_2S concentration, pH, various contaminants in the process fluid and the temperature. The material microstructure, material hardness and strength, material residual stress and applied loads are also factors affecting the formation of wet H_2S damages. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

In a process environment, a 50 ppm H_2S concentration in water may create adequate conditions to formation of wet H_2S damages. According to API 571, hydrogen absorption is at lowest in an environment with a pH of 7. The potential of the hydrogen absorption increases above and below this pH. Below a pH of 4, there is no need for major H_2S concentration for wet H_2S damages to initiate. In a process environment above a pH of 7, wet H_2S damages are also potential, if the environment is corrosive and if H_2S is present. Various contaminants, which decrease the pH or accelerate the corrosion, also increase the potential of hydrogen absorption. Hydrogen blistering, HIC and SOHIC are probable to occur in temperatures between ambient and 150 °C. Highest potential of SSC is at 20 °C, and the probability of SSC is commonly eliminated at temperatures above 95 °C, but an aggressive environment and a high material hardness may still initiate SSC in temperatures above this. The material defects such as inclusions and lamination commonly contribute to the formation of hydrogen blistering and HIC. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

Hydrogen blistering typically appears as bulges, commonly at the internal side of pressure equipment, shell structures, but also on the external surface of equipment, as presented in Figures 8 and 9. Hydrogen blistering occurs due to formation of hydrogen atoms on the steel surfaces as a result of a corrosion process. The sulfur in the environment prevents or delays the combining of hydrogen atoms into gas molecules (H_2). For this reason, there is a potential of hydrogen atoms to diffuse into the material and accumulate in material defects. The accumulated hydrogen atoms in the material defects combine and result as hydrogen molecules (H_2). The formed hydrogen molecules (H_2) cause a high pressure inside the material, which potentially exceeds the yield strength of the material and may result as localized deformation and internal stress in the material. Figure 8 is an illustration of how hydrogen blistering initiates inside a wall (shell) of a pressure equipment (cross sectional view). (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020; Korroosiokäsikirja. 4. painos. 2008.)

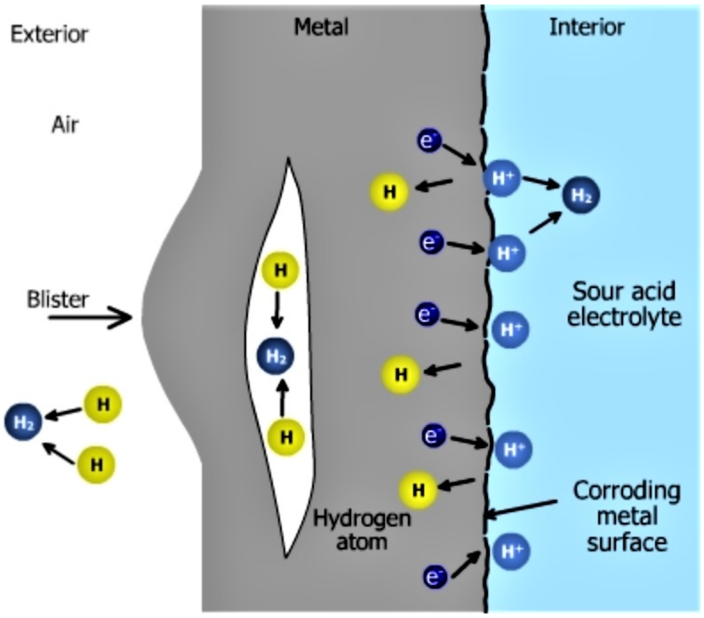


Figure 8. An illustration of hydrogen blistering inside a wall (shell) of a pressure equipment. (Hydrogen Blistering. 2004.)

Hydrogen blistering reduces strength and ductility in steels and may cause brittle fractures due to increased material internal stress. Concerning carbon steels, in environment temperatures over 220 °C, the accumulated hydrogen atoms may also potentially react with the alloyed carbon which result as methane gas (CH_4). This phenomenon may potentially damage steel alloys equally as the accumulated hydrogen gas molecules (H_2) described above. In addition to internal stresses, methane gas causes decarburization, which also reduces the strength of the carbon steels. Hydrogen blistering is potential in welded carbon steel pipes but rare in seamless carbon steel pipes. Internal hydrogen blistering in a decommissioned amine absorber column is shown in Figure 9 (API RP 571

Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020; Korroosiokäsikirja. 4. painos. 2008.)

Figure 9. Hydrogen blistering in an amine absorber column. (Gregory N. Haidemenpoulos etc. 2018.)

HIC initiates due to the same reason as the hydrogen blisters. HIC appears when hydrogen atoms diffuse into the steel due to a sour water corrosion process and accumulate into material subsurface defects. HIC appears as longitudinal cracking at different planes of the material. The cracks are parallel to the material surface. The longitudinal cracks at different planes may propagate further in the material and may potentially merge and result as a through wall crack. The through wall cracks due to HIC are commonly named as stepwise cracking (SWC). Applied or residual stresses in materials contribute initiation and propagation of HIC. HIC reduces load resistance of pressure boundary structures. HIC and SWC due to hydrogen absorption in a shell of a pressure equipment is shown in Figure 10. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

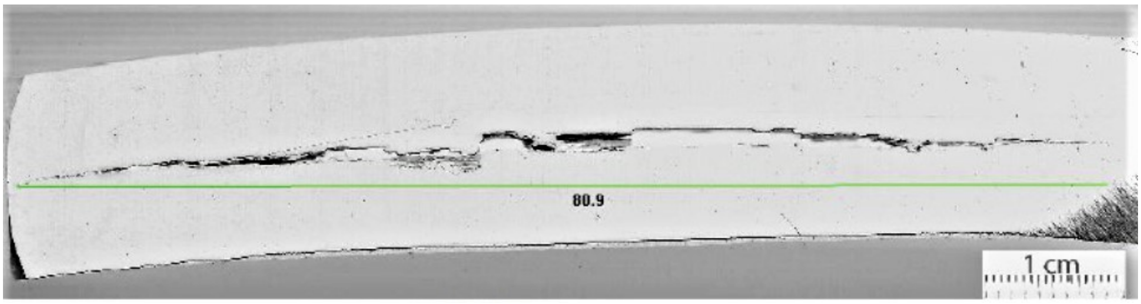


Figure 10. Cross section of a plate (shell structure) with HIC and SWC indications. (R. Molica Nardo etc. 2016.)

SOHIC is initiated by HIC. SOHIC appears as cracking which propagates perpendicular towards the steel surface causing a through wall crack. The perpendicular propagation of merged cracks occurs due to material residual internal stresses or applied mechanical loads. The hydrogen atoms, which diffuse into the steel is the main reason SOHIC initiates. SOHIC is commonly found in the heat affected zones (HAZ) of welds. The residual stresses in materials due to welded joints is the most common reason SOHIC initiates. SOHIC may also initiate merely due to SSC or material stress concentrations. SOHIC may initiate subsurface of materials and deteriorate the pressure boundary structure of a pressure equipment. Early stage SOHIC may visually be undetected as HIC and SSC. Figure 11 illustrates an indication of SOHIC in a fillet weld. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

Figure 11. SOHIC indication in a fillet weld HAZ. (Hydrogen cracking. 2022.)

SSC is another degradation mechanism that initiates due to hydrogen embrittlement. SSC appear in carbon and low-alloy steels as well as in martensitic stainless steels. Based on the background theory studied during this thesis are weldment joints of duplex steels with a high ferrite content also susceptible to SSC. SSC occurs due to the combination of applied loads or residual stress in materials and sour water corrosion. SSC initiates due to hydrogen absorption into the material. SSC appears commonly in HAZs of welds in carbon steels and high strength steels. The most significant influential factors affecting the initiation of SSC are the hardness of the weld HAZ and the residual stress of the welded area. According to API 571, if the hardness level of the HAZ and the welded area is not managed adequately by applying post weld heat treatment (PWHT) is the probability of SSC high in process environments where H_2S is present. The pH of the process environment is also a significant influential factor, which affects the initiation of SSC. Figure 12 is an illustration of SSC. (Understanding wet H_2S and where to find it. 2021; API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

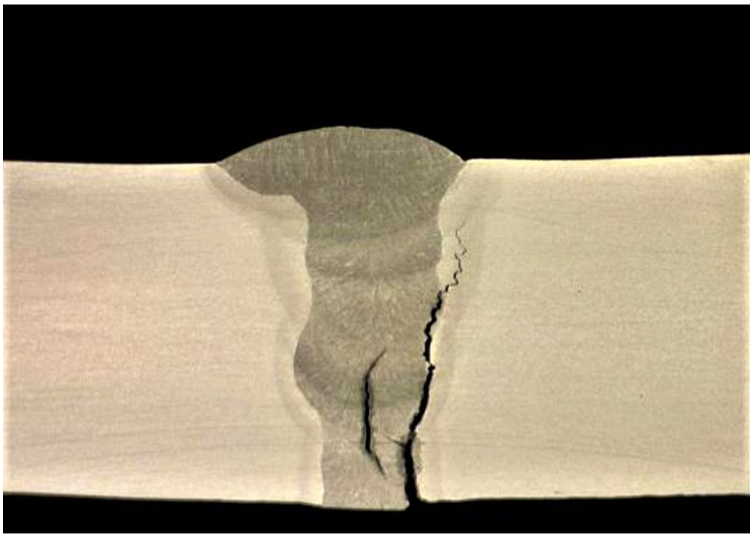


Figure 12. An illustration of SSC in a butt weld. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

According to API 571, “*wet H_2S damages typically occur in fractionator overhead drums, fractionation towers, absorbers and strippers, compressor interstage separators, knockout drums, various heat exchangers, condensers and coolers*”. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

Initiation of SOHIC and SSC is most likely in weld joints and weld HAZs as well as in high strength components such as fasteners (e.g., bolts), valves, compressor parts and pressure safety or relief valve springs. Hydrogen blistering and HIC typically appear in structures, which are fabricated from semi-finished plate type products, like pressure boundary shells. Hydrogen blistering and HIC are not associated to welds and HAZ’s but may merge towards welds what increase the probability of SOHIC initiation at the weld HAZ’s. HIC, SOHIC and SSC may appear as surface-breaking cracking or subsurface cracking in the material. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

6.3.1 Prevention and mitigation

Different kinds of cladding or coatings, which isolate steel surfaces from environments containing H_2S, may prevent hydrogen blistering, HIC and SOHIC. The management of the process environment pH by process modifications may also reduce the probability of hydrogen blistering, HIC and SOHIC to occur. In a corrosive environment measures should be done to minimize hydrogen absorption promoting contaminants such as H_2S, arsenic and cyanides. Use of corrosion resistant steels and ductile steels is also recommended to prevent wet H_2S damages. To reduce the probability of SOHIC and SSC is implementation of applicable PWHTs critical. SSC could be prevented by limiting hardness below 200 HB in carbon steel weld joints and the related HAZs. (API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020; Korroosiokäsikirja. 4. painos. 2008.)

6.3.2 Inspection and monitoring

HIC, SOHIC and SSC appear as surface-breaking cracks or subsurface cracks (at early stage) in materials of structures. Applicable inspection methods to detect and size surface-breaking cracks are wet fluorescent magnetic particle testing (WFMT) with alternating current (AC), magnetic particle testing (MT), acoustic emission testing (AET), alternating current field measurement (ACFM) and eddy current testing (ECT). Applicable inspection methods to detect or size subsurface cracks or defects are manual and automated UT methods such as the shear wave ultrasonic testing (SWUT), phased-array ultrasonic testing (PAUT) or time of flight diffraction (TOFD). The AET method is also an applicable method to detect or size subsurface cracks or defects in materials. Hydrogen blistering is commonly detected by the VT method. HIC, SOHIC and SSC are also possible to detect by the VT method, but it is not sufficient and reliable enough to be the only used inspection method. (Guidelines for Detection, Repair, and Mitigation of Cracking of Existing Petroleum Refinery Pressure Vessels in Wet H_2S Environments. 2004; API RP 571 Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. 2020.)

During external inspections of pressure equipment, an UT method that provides a C-scan presentation (e.g. PAUT) is applicable in detection of HIC and SOHIC. It is recommended to inspect equipment shells and heads (plate type semi-finished products) for potential HIC. During external inspections potential SOHIC should be examined in the base metal alongside the welds and in the weld HAZs of the pressure boundary structures and pipe nozzles by using the TOFD or the SWUT method. (API RP 581 Risk-based Inspection Methodology third edition. 2016.)

According to API 581, an applicable combination of inspection methods to detect potential HIC or SOHIC during internal inspections of pressure equipment is: (API RP 581 Risk-based Inspection Methodology third edition. 2016.)

- VT
- UT method providing A-scan or a C-scan presentation with straight beam (e.g., PAUT)
- Followed by TOFD or SWUT

Another recommended combination of inspection methods by API 581 to detect HIC or SOHIC during internal inspections of pressure equipment is: (API RP 581 Risk-based Inspection Methodology third edition. 2016.)

- VT
- WFMT or ACFM
- Follow up on indications (if necessary) by an applicable UT method

Detection of SSC in welds and HAZ’s during external inspections of pressure equipment are automated or manual ultrasonic methods applicable such as PAUT, TOFD or SWUT. The AET or RT are also applicable methods to detect SSC in the welds and HAZ’s during external inspections of pressure equipment. According to API 581 an applicable combination of inspection methods to detect potential SSC in welds and HAZ’s during internal inspections of pressure equipment are: (API RP 581 Risk-based Inspection Methodology third edition. 2016.)

- WFMT or ACFM
- Follow up on indications (if necessary) by an applicable UT method

7 Equipment Condition, Inspection, and In-Service History Study

An equipment condition, inspection and in-service history study was conducted of the pressure equipment including the corrosion loops which were examined in this thesis. The aim of the study was to provide essential data and information to improve the accuracy of the RBI assessment. One objective of the study was to constitute a summary of the current mechanical condition of the pressure equipment being assessed. The current condition of the pressure equipment and piping was studied by checking if any significant degradation or other damage had been detected during the operation history. Another objective of the study was to examine the inspection effectiveness of the current inspection plans of the considered pressure equipment. This was done by studying the pressure equipment inspection history. In the study, it was also reviewed if anything remarkable had occurred during the operation history of the pressure equipment being assessed. The degradation mechanisms identified in the corrosion loops by the corrosion study were also meant to be validated by the equipment condition, inspection- and in-service history study.

In order to form a comprehensive summary of the piping pertaining in the corrosion loops, wall thickness measurement data from the piping inspection history was collected into a separate data source and corrosion rates were calculated. The internal mechanical condition of the piping was the main concern. The short-term corrosion rate of every CML was calculated if inspection data was adequately available. The short-term corrosion rate is calculated based on the measurements taken in two subsequent inspections. The corrosion rates were simply calculated by dividing the loss of wall thickness by last inspection interval (years). The calculated corrosion rates were also compared with the estimated corrosion rates in the corrosion study, in order to evaluate how realistic, the estimated corrosion rates are. The wall thickness measurement data was also the main source for evaluating, if a corrosion circuit is required in the IMS database for all individual pipes. The necessity of the piping to pertain a corrosion circuit is based on the fact if significant internal corrosion occurs in the piping. In case significant internal corrosion has been detected, a corrosion circuit is usually necessary for storing the wall thickness measurement data and for calculating the next inspection date (in IMS). For instance, a pipe does not need to pertain a corrosion circuit, if the measurement data reliably shows that the corrosion rate is very low. Corrosion circuit is necessary for pipes with a significant corrosion rate that could lead to an unforeseen failure of the pipe. The criticality classification should be also considered while estimating the necessity of the pipe to pertain a corrosion circuit. The collected measurement data provided an overview of the current mechanical condition of the piping, and it also gave an overview of the inspection plan´s effectiveness and the current level of degradation occurring in the piping. All the matters mentioned above were essential information during the criticality classification assessment of the piping.

The relevant information and data to conduct the equipment condition, inspection and in-service history study were found from reports and log sheets associated to statutory inspections, NDEs, equipment renewals, repairs, and modifications, which have been executed during the operation history of the pressure equipment. Reports associated to process changes or deviations were also relevant information in the study. Other relevant specifics for the study were the year of deployment, internal coatings, corrosion allowance, materials of construction, insulation, mechanical structure and information related to repairs, modifications and renewals.

The information and data examined in the equipment condition, inspection and in-service history study was provided in the IMS, SAP, cloud database of the petrochemical plants and in the olefin production plant office archive.

The outcome of the equipment condition, inspection, and operation history study was reported in writing and the relevant data was gathered into a data source, which was reviewed during the RBI assessment. However, all detailed information and data associated to the pressure equipment, operation, and inspection history as well as the current mechanical condition of the pressure equipment of Borealis Porvoo production site is confidential. Therefore, the collected data sources as well as the calculated corrosion rates are not reviewed in this thesis to full extent due to confidentiality.

In addition to piping, the corrosion loop Pyrolysis fuel oil pertains a fuel oil stripper (column) and two heat exchangers. All components of the fuel oil stripper belong to the Pyrolysis fuel oil corrosion loop. The following heat exchanger structures (components) are included in the Pyrolysis fuel oil corrosion loop: shell internal side, floating head internal side, tube bundle external side and shell nozzles. These structures mentioned above are in contact with the pyrolysis fuel oil and exposed to the potential degradation mechanisms stated in the corrosion study. The fluid of the heat exchanger second space (the tube bundle internal side etc.) is quench water and belongs to another corrosion loop. The heat exchangers are horizontally mounted and coupled in series as well as equipped with a “one-pass” type of shell.

In addition to the piping, several knock-out suction drums and a condensed water drain drum are part of the Condensed water corrosion loop. The suction drums are vertical type and belong to the low-pressure side of the compressor unit. The demister structure divides the internal volume of the suction drums into two different corrosion loops. The area below the demister belongs to the corrosion loop Condensed water while the area above of the demister belongs to the corrosion loop Compression gas (low pressure). The condensed water drain drum is a horizontal vessel, and it is installed into a concrete pit below the ground level. The condensed water drain drum pertains of its entirety to the corrosion loop Condensed water.

8 Equipment Criticality Classification Assessment

The first phase of an RBI assessment is typically the data and information collection of the pressure equipment and piping within the scope of the assessment. For the hot end distillation part of the ethylene unit, this was done prior to the corrosion study, in order to allow a thorough assessment to be executed. The data and information collection was managed and conducted by the inspection department personnel. The relevant data of the equipment, process etc. were gathered in data sources. The data and information collection phase included several workshops, which were joined by the external party who conducted the corrosion study. The data and information was provided, reviewed, and validated during the workshops. The data and information collection phase were executed before this thesis.

8.1 Corrosion loop management

Considering the corrosion loops, the outcome of the corrosion study was reviewed in this thesis. The corrosion loops were validated based on the review. The validation was done in order to ensure the clustered corrosion loops and all associated matters related to the corrosion loops were correct. It was checked that the correct equipment pertain in the corrosion loop by reviewing the relevant piping and instrument diagrams (P&ID). The detected deficiencies and falsities were reviewed and discussed with the party who conducted the corrosion study and corrections were implemented. When validation of the corrosion loops was completed, the loops were determined and highlighted in the P&IDs.

To allow management of the corrosion loops, the corrosion loops were configured into the IMS database. During the configuration, the pertaining equipment was linked (at component level) to the corrosion loops. Descriptions related to the corrosion loops, process conditions and degradation mechanisms, and the colored P&IDs and PFDs of the corrosion loops were uploaded in the IMS database. To enable degradation management, all identified degradation mechanisms were determined in the corrosion loops in the IMS.

8.2 Criticality assessment

8.2.1 Determination of the susceptibility to failure

The StF of the pressure equipment and piping being assessed was determined by using the IMS PEI module. The StF is determined by four different categories which could be interpreted as different levels of the probability the equipment could fail. During determination of the StF, the outcome of the corrosion study and equipment condition, inspection, and in-service history study was applied. Associated to the corrosion mechanisms, the StF category of the assessed equipment was determined by applying theoretical models provided by the IMS PEI module. Both the estimated corrosion rates from the corrosion study and the calculated corrosion rates were used in order to determine the StF. Primarily, the calculated corrosion rates were applied, but if adequate calculations were not available, the estimated corrosion rates were applied. The design corrosion rate (CRd) used as a factor in the theoretical models was defined based on the equipment corrosion allowance and equipment design life. Associated to the wet H_2S damages, the StF was determined based on the outcome of the Corrosion study.

8.2.2 Consequence of failure assessment

In the CoF assessment, the consequence categories determined at Group (Borealis) level were applied. The consequence categories provided by the IMS PEI module were not used as is, only the risk matrix in the PEI module was applied. The current consequence categories determined in the PEI module would not provide the desired risk awareness to the Porvoo site production plants. This is due to the wide extent and severity of the determined consequence categories in the PEI module. The consequence categories used in the PEI module would not provide adequate variability between the criticality classifications (assessed risk) of the pressure equipment and piping operating at the Porvoo site.

In the CoF assessment, the severity of consequences during a failure of the assessed pressure equipment was determined by applying five different categories from the aspects of health and safety, economics, environment, and the company reputation. The consequence categories (severity level) which were applied are negligible, low, medium, high, and extreme. Verbal descriptions were applied to determine the severity of the consequences associated to the environment and the company reputation. The severity of the economic consequences was determined by monetary units and the severity of consequences associated to the health and safety were determined based on the toxicity and hazardousness of the fluid.

In the CoF assessment, such subjects and matters are discussed that require knowledge from other personnel in addition to the inspection department. To obtain more accurate estimates, broader viewpoints, and more reliable assumptions, a production engineer and a process safety expert assisted in the assessment.

In the CoF assessment, estimations considering volumes of discharge during loss of containment were based on the failure modes, fluid volumes, flow rates, operation pressures and fluid viscosities. In this CoF assessment, there was no need to estimate gaseous discharges. Based on the morphology of the considered degradation mechanisms, the failure modes were determined. Significant concentrations of flammable or exploding substances were not present in the assessed corrosion loops.

In the CoF assessment, the most probable scenarios, which may initiate from the determined failure modes and the most probable consequences, were estimated. For the most probable consequence, a probable scenario was defined for different categories, except from the health and safety aspect. From the health and safety aspect, the severity of the consequences was determined based on the most toxic and hazard substance in the corrosion loop process fluid. Probable scenarios, which initiate from a failure and result in an actual consequence, were not considered in the health and safety consequence categories.

From the economic aspect, the severity of potential equipment failures was estimated mainly by scenarios, which could lead to production interruption and production plant shutdown. Production losses (€) per day (24 h) where mainly considered. The severity of the consequences was primarily estimated by considering the probability of production plant shutdown (production interruption) during a failure of the pressure equipment under consideration. Certain influential factors that may prevent a shutdown, such as the possibility of a temporary repair, bypass or isolation of the failed pressure equipment, were considered. The implementation of temporary repairs was considered from the safety and mechanical aspects. It was also evaluated if it is safe to carry out repairs during operation of the production plant.

The severity of the consequence from the environmental aspect due to loss of containment of the considered pressure equipment was determined based on the following factors: the extent of required clean up, effects on flora and fauna, permanence of the consequences and the effects on the production site neighbors. From the environmental aspect, the consequences due to loss of containment were estimated based on where the leaking content of the pressure equipment first ends up and where it finally ends up. Relevant factors were considered, such as if the discharge occurs at the production plant process area, where the content reaches the sewer system, or if the leak occurs outside the process area, where it can end up in the nature. Considering the severity of the environmental consequences, a relevant factor was also if the waste water treatment plant of the production site was able to safely process the volume of discharge (liquid leaks), considering toxic substances.

The impact on the company´s reputation due to loss of containment in a pressure equipment was primarily estimated based on the following factors: potential complaints from the production site´s neighborhood, negative effects on neighborhood relations, involvement of authorities and negative publicity (media).

The assessment outcome, observations, assumptions, and comments of the CoF assessment were collected in a data source, which was prepared for this assessment.

8.3 Confidence assessment

The confidence assessment was carried out by using the IMS PEI module based on the information that was provided from the corrosion study and the equipment condition, inspection, and in-service history study. Basically, factors associated to mechanical integrity management of the assessed pressure equipment were determined in the confidence assessment.

The confidence assessment includes an evaluation of several factors that may affect the probability of failure in the assessed equipment. One of the factors is the effectiveness of the current inspection plan. Other factors are the implemented risk mitigation measures and level of process monitoring related to relevant process parameters.

8.4 Outcome

The most severe StF category and the most severe assessed CoF category determined the resultant criticality classification of the assessed pressure equipment in the risk matrix of the IMS PEI module. Based on the outcome of the criticality assessment and the confidence assessment, a recommended inspection interval is defined by the PEI module. The next inspection date depends on the inspection history. If sufficient inspection methods have not been applied in the past, the system will propose immediate inspection actions for equipment with high criticality.

9 Summary and Discussion

The objective of this thesis was to participate in RBI implementation on the pressure equipment and piping in two corrosion loops. The corrosion loops are a part of the hot end distillation process at the Borealis Porvoo ethylene unit. The aim was to make observations, propose improvements and bring out matters worthy of attention related to the RBI process at the Porvoo site.

Due to the schedule of this thesis, the criticality classification assessment could not be completed for every pressure equipment and pipe, which pertain to the selected corrosion loops. However, valuable experience and information were gained about pitfalls and effective practices to continue the development of an optimal RBI assessment process at the Porvoo site. Essential experience was obtained considering the usefulness of the corrosion study, from the application of the IMS PEI module as well as from the CoF assessment.

The level of detailed data and information collected by the inspection personnel, allowed a semi-quantitative corrosion study to be conducted. During the equipment criticality classification, numerical models were used to a very limited extent in CoF assessment. Related to the outcome of the CoF assessment, experience-based expertise and knowledge played an essential part. StF was determined by applying quantitative theoretical models and tables, which required a high level of detailed data. Regarding the risk management by the IMS PEI module, the resultant inspection intervals were the product of numerical factors, which were calculated or configured in IMS based on the equipment criticality assessment outcome. Based on factors described in this paragraph, it can be summarized that mainly a semi-quantitative approach was used in the RBI assessment conducted during this thesis.

9.1 RBI process

Currently, the optimal application of the IMS PEI module at the Porvoo site is in the development stage, but an overall perception of the RBI process was obtained. The course of RBI implementation, including the main elements, was formed into a flowchart that is simplified presented in Figure 13.

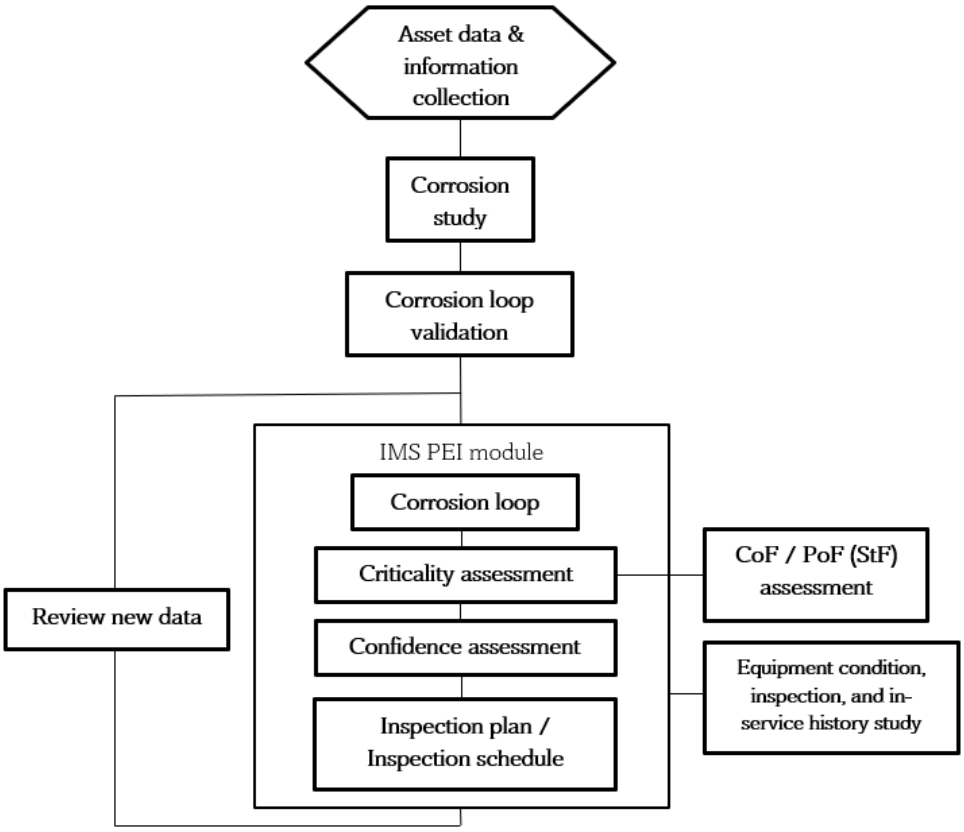


Figure 13. Simplified process of the Borealis Porvoo site RBI assessment (equipment criticality classification assessment)

In the CoF assessment, the consequence category from the health and safety aspect was determined based on the content toxicity and hazardousness. For the assessed equipment to have a low-level consequence from other aspects, the health and safety category often acted as the driving consequence category. This may lead to criticality classification, which could be considered too conservative, since a small release of toxic or hazardous chemical does not always cause a major consequence. In order to prevent an excessively conservative or inaccurate risk assessment, the consequence categories should be based on what kind of impact the chemical release may have on the production plant personnel. Typically, the health and safety consequence categories are based on the severity of injuries.

Regarding determination of the StF for the Condensed water corrosion loop, a sufficiently realistic result for wet H_2S damages was obtained by considering the operation and inspection history of the corrosion loop, and applying tables and graphs provided by the IMS PEI module, with the help of the process parameters collected in the corrosion study. By using solely the theoretical StF level that was given in the corrosion study, the outcome would have been very conservative.

The RBI program (completed assessment) is basically a constantly circulating loop. As time goes by, when new critical data and information associated to the mechanical integrity of the corrosion loops, pressure equipment or components are provided, a reassessment of the equipment criticality classification should be implemented. “Review new data” in the RBI process that is shown in Figure 13 is an essential part of the reassessment. The reassessment can lead to major changes in the criticality classification and the inspection plan of the assessed equipment.

9.2 Outcome of the RBI assessment

During the CoF assessment, it was decided to divide certain pipes into sections. This was conducted due to a great CoF difference between piping sections. The benefit of creating separate components of these sections is that the inspection activities can be prioritized on the section with a higher criticality classification. For example, piping sections that can be bypassed and repaired with reasonable effort were given a lower CoF category compared to a section where a leak could cause a plant shutdown. The pipe sections (components) were determined by color in isometric drawings of the considered piping.

Based on the criticality classification outcome of the assessed equipment, inspection efforts for the two corrosion loops can be rearranged more efficiently. The equipment and piping with a high criticality can be examined in more detail, while the inspection activities on the items with low criticality can be decreased. In the long term, this should both provide an optimization of inspection resources and improvement of risk management.

9.3 Inspection guidelines

One objective of this thesis was to examine and define applicable and reliable NDE methods for detecting and monitoring the degradation mechanisms identified in the corrosion loops. The morphology of a degradation mechanism plays an important role when selecting the inspection method. A table was compiled of the applicable NDE methods and techniques that can be used, see Appendix 1. The selection of reliable and effective NDE methods depends on several factors, for example if the inspection is internal or external, and what the susceptible areas are.

9.4 Corrosion study

The corrosion study provided essential information about the factors affecting the susceptibility of degradation. However, applying the theoretical outcome of the corrosion study exclusively in a risk assessment might lead to an inaccurate equipment criticality classification assessment. Considering the corrosion mechanisms, based on the equipment condition, inspection, and in-service history study, the objects where corrosion is present are varying in a corrosion loop even between pressure equipment in identical use. This should be considered in order to achieve accurate risk assessments. Similarly, regarding wet H_2S damages, issues related to this type of degradation have not been a concern during the plant operation history. It is recommended that, in addition to the corrosion study, information related to a thorough equipment condition, inspection, and in-service history study is applied during the RBI assessment in order to achieve more accurate assessment results.

The corrosion study is based on various process parameters in normal operation conditions. These parameters have been defined by the Porvoo site inspection and production personnel during the commissioning of the corrosion study. It is important to notice that process conditions during the start-up, shut down and process malfunctions as well as deviations, such as emergency stops are not considered in the corrosion study. The process conditions may change significantly during operation deviations, as mentioned above, affecting the probability of degradation mechanisms to occur.

Associated to the corrosion loops examined in this thesis, it is stated in the corrosion study that susceptibility to SSC is theoretically eliminated as the hardness of the equipment structure materials is low enough (< 200 HB). The corrosion study indicates that only the base material hardness is considered. Based on the theory studied in this thesis, initiation of SSC is commonly located in welds and HAZs, where hardness is typically high compared to base material. It is unknown if welding parameters have been managed properly during fabrication in order to reach low hardness level in weld material and HAZ. Due to this, SSC cannot be fully ruled out. However, according to the corrosion study, the operating temperature in the Pyrolysis fuel oil corrosion loop is usually between 130 °C - 220 °C. Based on the theory studied and the corrosion study outcome, SSC does not commonly occur in temperatures above 80 °C – 95 °C. Due to this and very low water content, eliminating the susceptibility of SSC could be discussed on certain equipment and piping in the Pyrolysis fuel oil corrosion loop.

In the corrosion study, mechanical degradation of pressure equipment and piping was left out of the scope. It is recommended that factors affecting mechanical degradation such as significant pressure or temperature fluctuations, would be monitored considering the critical objects. Unless the mentioned fluctuations take place due to design conditions, they are not usually expected, but can occur due to process deviations. The monitoring of these parameters through an IOW is recommended in the critical pressure equipment susceptible to wet H_2S damages. Based on the character and morphology of wet H_2S damages, fatigue or thermal fatigue might initiate from wet H_2S degradation due to mechanical cyclic loads or temperature fluctuations.

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Table of applicable NDE methods and techniques

Degradation mechanism	Affected material	Morphology (Damage mode)	Inspection method (Equipment internal degradation)		Susceptible areas (Pressure equipment)
Oxygenated process water corrosion	Carbon steels & Low-alloy steels	Localized thinning, extensive pitting.	Internal inspection	VT, UT (follow up) Piping: VT (Endoscope), MFL	Stagnant water, high flow rate, turbulent flow and condensate areas. Downstream of: elbows, tees, valves, reducers, weld protrusions, deposits etc.
			External inspection	Grid UT, AUT, RT Piping: Long range GWUT (Lambda waves)	
Sour water corrosion	Carbon steels & Low-alloy steels	General thinning, pitting under sulfide deposits.	Internal inspection	VT, UT (Follow up)	Stagnant water, high flow rate, turbulent areas.
			External inspection	UT , RT	
Hydrogen blistering	Carbon, Low-alloy and High strength steels	Subsurface blistering (deformations).	Internal inspection	VT	Base material, structures made of plate type semi-finished products (shells, heads etc.).
			External inspection	VT	
HIC	Carbon, Low-alloy and High strength steels	Subsurface cracking and surface breaking cracking: Longitudinal, Stepwise cracking.	Internal inspection	VT*, WFMT* (AC), MT*, ACFM*, ECT* A- or C-scan UT** (e.g PAUT**),	Base material, structures made of plate type semi-finished products (shells, heads etc.).
			External inspection	A- or C-scan UT** (e.g PAUT**), AET*,**	
SOHIC	Carbon, Low-alloy and High strength steels	Subsurface cracking and surface breaking cracking: Perpendicular cracking.	Internal inspection	VT*, WFMT* (AC), MT*, ACFM* A- or C-scan UT** (e.g., PAUT**),	Base metal alongside the weld, weld joints, HAZs, fasteners (e.g., bolts), valves, valve springs, rotating equipment parts.
			External inspection	A- or C-scan UT** (e.g., PAUT**) TOFD**, SWUT**, AET*,**	
SSC	Carbon, Low-alloy, High strength steels, Martensitic stainless steels and Duplex steels (high ferrite content)	Subsurface cracking and surface breaking cracking.	Internal inspection	VT*, WFMT* (AC), MT*, ACFM*, UT (follow up)	Weld joints, HAZs, fasteners (e.g., bolts), valves, valve springs, rotating equipment parts.
			External inspection	PAUT**, TOFD**, SWUT**, AET**, RT**	

*Applicable for surface breaking cracks
**Applicable for subsurface cracks