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Corrosion of Carbon Steel in Acetonitrile Water Mixture

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Abstract

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The aim of this thesis was to gain better understanding of which parts of the butadiene unit's solvent cycle at the Borealis Porvoo plant are prone to internal corrosion and what could be the cause of it. On the basis of the results, the Borealis inspection organization could focus their inspection on the parts of the solvent cycle that are most likely to experience it. The thesis will cover different forms of corrosion encountered in refineries and NDT methods used to detect them. In addition, olefin unit's basic working principles are reviewed.

Thesis included mapping the solvent cycle based on its acetonitrile concentration, water concentration, flow rate and temperature. In addition, all of the results for internal corrosion were collected for each pipeline. Based on the internal corrosion results, three categories were created to ease the data interpretation.

The results of internal corrosion were compared to four process conditions mentioned in the mapping. The comparison revealed that internal corrosion was present throughout all process conditions. The comparison did not reveal straight correlation between internal corrosion and process conditions or with available inspection data. Instead, the cause of internal corrosion might be dissolved oxygen.

Keywords: corrosion, internal corrosion, process conditions, acetonitrile

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Insinööritöiden tarkoituksena oli saada parempi käsitys siitä missä osissa Borealisen Porvoon tuotantolaitoksen butadieeniyksikön liuotinkierrossa on sisäpuolista korroosiota ja pohtia mistä se voisi johtua. Tulosten perusteella Borealisen tarkastusorganisaatio voisi kohdentaa tarkastukset niihin osiin liuotinkiertoa, joissa sisäpuolinen korroosio on todennäköisempää. Työssä perehdytään jalostamoilla tavattiin eri korroosion muotoihin, kahteen eri NDT menetelmään ja siihen miten sisäpuolista korroosiota voidaan NDT menetelmillä havaita. Lisäksi käydään läpi olefiinisyksikön perustoimintaperiaate.

Työssä kartoitettiin liuotinkiertoa tarkastelemalla asetonitriliipitoisuutta, vesipitoisuutta, virtausnopeutta ja lämpötilaa. Lisäksi kaikki sisäpuolisen korroosio tulokset kerättiin linjakohtaisesti. Tehtiin kolme kategorialla sisäpuolisen korroosion tulosten perusteella tulosten käsittelyn helpottamiseksi.

Sisäpuolisen korroosion tuloksia vertailtiin kaikkiin kartoituksessa huomioituihin olosuhteisiin. Tulosten vertailu paljasti, että sisäpuolista korroosiota löytyi kaikissa prosessiolosuhteissa. Tuloksien vertailussa ei löydetty kuitenkaan suoraa korrelaatiota sisäpuolisen korroosion ja prosessiolosuhteiden tai saatavilla olevan tarkastusdatan kanssa. Sisäpuoleisen korroosion aiheuttaja voi kuitenkin mahdollisesti olla happi.

Avainsanat: korroosio, sisäpuolinen korroosio, prosessiolosuhteet, asetonitrili

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Appendix 1: Corrosion results in the solvent cycle

List of Abbreviations

ACN: Acetonitrile simplest nitrile that is commonly used in many industries due to its low volatility and high solvency.

CUI: Corrosion under insulation is a form of corrosion that occurs underneath the insulation with the presence of water. It is commonly found in refineries.

DRT: Digital radiographic works with the same principle as RT but utilizes digital computers to generate image.

DT: Destructive testing refers to material testing by damaging it making it unsuitable for future use.

EDX: Energy-dispersive X-ray is used to determine the elemental composition of a sample.

E–C: Erosion-corrosion is a mixture of both chemical corrosion and mechanical erosion. It is commonly found in pipelines.

HAZ: Heat affected zone refers to part of material that is exposed to heat during welding.

HIC: Hydrogen induced cracking is material degradation caused by hydrogen diffusion into steel leading to cracks.

NDT: Nondestructive testing refers to material testing without any sort of damage to it, which enables its use after inspection.

PFD: Process flow diagram is used to illustrate general flow path of process. It is widely used in process and chemical engineering.

PPM: Parts per million is used to show very low concentrations of substances in a mixture.

P&ID: Piping and instrumentation diagram shows piping and related process equipment. It is widely used in engineering field.

RT: Radiographic testing is widely known NDT method that generates radiographs with the use of X-rays or gamma rays. It can be used to find defects and thickness measurement.

SCC: Stress cracking corrosion is a form of corrosion that occurs in the presence of tensile stress and corrosive environment.

SEM: Scanning electron microscope is used to scan the surface of sample with focused beam of electrons. It is used in scientific research.

SOHIC: Stress oriented hydrogen induced cracking is same as HIC but it is stress driven.

TLE: Transfer line exchanger quenches the gas coming from olefin cracking furnace.

UDC: Under deposit corrosion is a form of corrosion happening under deposit making the solution inside more concentrated.

UT: Ultrasonic testing widely used NDT method utilizing ultrasound to scan material for defects and thickness measurement.

1 Introduction

Corrosion poses a major challenge to the petrochemical and refining industry causing damage to all types of refinery equipment, for example, pipes, columns and heat exchangers. Corrosion can pose a major risk to the refineries due to sudden failures of the refinery equipment. These failures cause severe risk to employees on site and loss of revenue. In United states alone, corrosion related costs at refineries are estimated to be up to 3.7 billion dollars annually [1]. In addition, the environment can also be harmed due to corrosion related issues in the refinery equipment.

Better knowledge of problems caused by corrosion is essential to ensure sound and safe operation of petrochemical and other refinery plants. It is crucial to remember that corrosion cannot be stopped, but it can be lessened or minimized by a well implemented corrosion control program. That is why it is important to study and understand different corrosion related problems and take them into account in plant maintenance.

The purpose of this thesis was to gain better understanding of internal corrosion in the butadiene unit's solvent cycle at the Borealis Porvoo plant. Previous inspections have indicated that some refinery equipment have suffered internal corrosion and even a few minor leaks have occurred over time. This thesis focused on finding which parts of the solvent cycle have suffered internal corrosion and what process conditions might be causing it. On the basis of the findings Borealis inspection organization can improve their inspection strategy and prioritize inspections to the parts of the solvent cycle that are prone to internal corrosion.

2 Butadiene production

Most of the butadiene is produced as a co-product of ethylene production by steam cracking hydrocarbons. This method of steam cracking process accounts

for up to 95 % of the global butadiene production. The steam cracking process is an essential petrochemical process which produces olefins such as ethene, propene and butadiene. It aims to break saturated hydrocarbons into often smaller unsaturated ones. The remaining 5 % of the global butadiene production is performed by catalytic hydrogenation production, oxidative hydrogenation production and ethanol-based production. [2, s. 49; 3.]

2.1 Olefine production

The olefin production unit can be separated into three main sections which are the steam cracking furnace, hot distillation section and cold distillation section. This whole process is illustrated in Figure 1. The steam cracking furnace breaks down hydrocarbon feedstocks that can be liquid or gaseous such as naphtha, gasoil, propane and ethane. The used feedstock influences the butadiene yield, for example heavier feed such as naphtha produces C4 whereas light feeds such as ethane and propane do not. These feedstocks are diluted with steam and then fed to the steam cracking furnace where cracking takes place in approximately one second. In the furnace the feedstock is heated approximately 850 °C and with the absence of oxygen the carbon-hydrogen and carbon-carbon bonds start to crack. This reaction breaks the saturated hydrocarbons smaller and desirable the yield of unsaturated hydrocarbons is as high as possible. Right after the cracking furnace the gas must be quenched as fast as possible to stop the pyrolysis reaction and to preserve the current composition of the gas. Transfer line exchanger (TLE) is used to cool the gas quickly to approximately 325 °C. After the TLE gas is quenched further by oil or water depending on the used feedstock, usually naphtha feedstock uses quenching oil and in some cases water tower as well. After cooling the cracked gas is compressed by compressors in several stages during which acid gas purification is done and the gas can be sent to a dryer to absorb the moisture from the gas. [3; 4; 5.]

The cold and hot distillation sections perform the product fractionation, which aims to separate and purify the stream containing mixed hydrocarbons to

desired ones such as ethylene, propylene and butadiene. The fractionating process is similar for all feed stocks but with heavier feeds the process becomes larger and more complex because more products must be separated and by larger quantity. At first the stream is separated into several fractions based on their carbon chain length. These processes are done by demethanizer, de-ethanizer, depropanizer and debutanizer distillation columns which can be seen in Figure 1. [6.]

- Demethanizer separates methane and hydrogen from heavier C_2+ stream (compounds with two or more carbon atoms). Methane and hydrogen are vented out from the top of the column and are usually used as fuel at the furnace. From the bottom of column C_2+ stream is sent to de-ethanizer. [6.]
- De-ethanizer separates C_2 stream from heavier C_3+ stream. C_2 stream is vented out from the top of the column and led to C_2 splitter and from the bottom of column C_3+ stream to depropanizer. [6.]
- depropanizer separates C_3 stream from heavier C_4+ stream. C_3 stream is vented out from the top of the column and led to C_3 splitter and from the bottom of column C_4+ stream is sent to debutanizer. [6.]
- debutanizer separates C_4 stream from heavier streams. C_4 stream is vented out from the top of the column and led to C_4 splitter and heavier stream from the bottom of column is further split to produce fuel oil. [6.]

The fractionated C_2 , C_3 and C_4 streams obtained from the distillation process contain various hydrocarbon molecules beyond the desired components such as ethylene, propylene and butadiene. For example, the C_2 stream typically includes ethane, ethylene, and acetylene, necessitating further purification to isolate ethylene. [6.]

than the feed components. Extractive distillation requires at least two columns, although the number varies based on the complexity of the recovery process. There are a few methods to refine C₄ fraction into 1,3-butadiene and those methods are extractive and conventional distillation process using aqueous n-methyl-2-pyrrolidone, dimethylformamide solvent extraction process (nonaqueous) and aqueous separation and acetonitrile (ACN) extraction.[7, s. 12–13; 8; 9.]

Example of butadiene unit which utilizes aqueous separation and acetonitrile extraction method can be seen in Figure 2. As mentioned before at least two extractive distillation columns have to be used to mix the C₄ fraction coming from the debutanizer and ACN. Afterwards when ACN has dissolved the C₄ fraction, the formed solution heads to the solvent stripper in which the 1,3-butadiene is separated from the ACN and sent to further purification while ACN is recovered. After the recovery ACN is further purified, and it can be sent back to extractive distillation columns to be used again. [7; 8.]

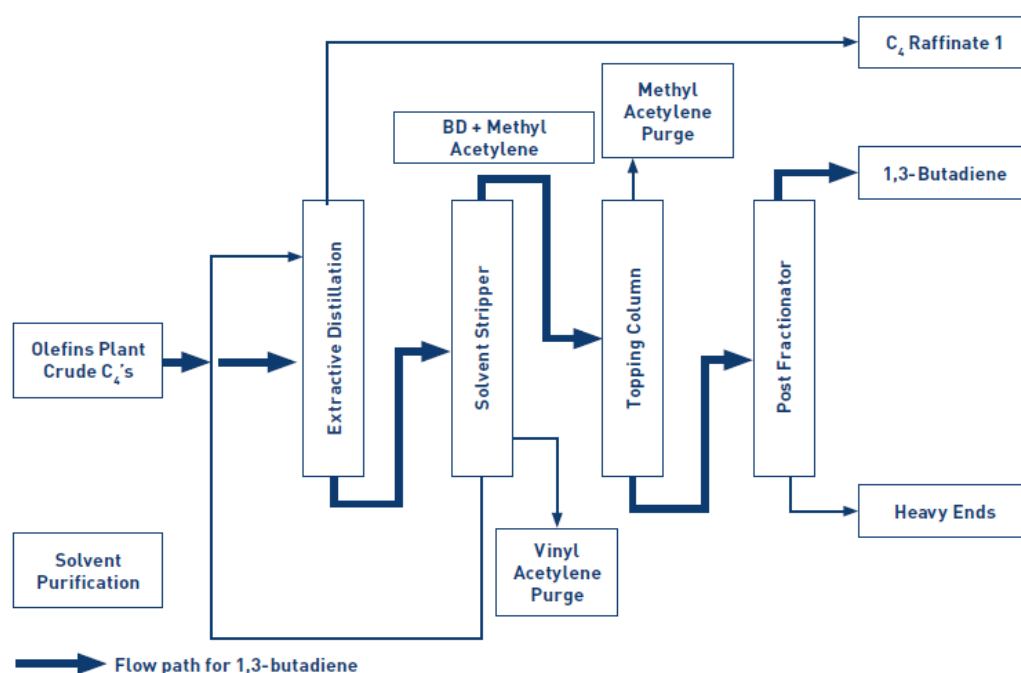


Figure 2. Simplified process of butadiene purification process by aqueous separation and acetonitrile extraction method. [7.]

2.2.1 Acetonitrile

Acetonitrile is the simplest organic nitrile with the molecular compound of CH_3CN . Nitrile is a class of organic compounds which contains a carbon atom triple-bonded to a nitrogen atom ($-\text{C}\equiv\text{N}$) [9]. Acetonitrile is a clear, colorless liquid with a sweet ethereal odor, also known as methyl cyanide, cyanomethane or ethanenitrile. [10.]

Most of the chemical reactions of acetonitrile mainly involve the nitrile, or $-\text{CN}$ group. Acetonitrile is primarily used as solvent in industrial field. Acetonitrile is an excellent polar aprotic solvent with high dipole moment (3.44 D) and dielectric constant (36.0). Acetonitrile is fully miscible with water and many other unsaturated hydrocarbons but immiscible with most saturated hydrocarbons. Its high dipole moment and dielectric constant make it a good solvent for many inorganic and organic compounds. Acetonitrile can dissolve most of the polar organic materials. When acetonitrile is combined with one or more organic compounds or with water it can form azeotropes, which means constantly boiling mixtures. These factors make acetonitrile well suited for extractive purification and chemical analysis. [10; 11.]

3 Corrosion in refining industry

Corrosion is known to cause damage to refineries and their equipment and has effects that are the loss of revenue and safety hazards to plant personnel and other bystanders. Refinery corrosion can be generally divided to two main categories which are low-temperature corrosion which occurs in the presence of water and below 260°C and high-temperature corrosion which occurs in the absence of water and above 260°C . These two main categories include many types of corrosion mechanisms that occur in various environments/operating conditions and materials. [12, s. 1-3, 13-1; 13.]

There are several factors that have a significant effect on the rate and severity of corrosion in the refining industry. To lessen the effect of these factors,

changes in process conditions would have to be made. Nevertheless changes to the process conditions are often impossible to make, or they cannot be made sufficiently to alter corrosion rates. Acids have a major role in corrosion depending on the type and the amount of acid present in water. A large amount of acid present in water mixture equals more hydrogen ions and therefore more severe corrosion. Temperature can have positive or negative effects on the rate of corrosion. Low temperature is known to reduce corrosion by slowing down the chemical reaction and high temperature is known to increase corrosion rate, unless the high temperature prevents the formation of liquid water. Pressure primarily affects the concentration of gases, such as hydrogen sulfide and carbon dioxide, in water and hydrocarbons. Higher pressures enhance the solubility of gases in the water, leading to a reduction of pH in some cases depending on the solubilized gases and thereby increasing corrosion in the water mixture. Turbulent flow of the fluid also has an impact on the corrosion. It has been observed that turbulent flow has a tendency to remove protective corrosion product from the surface of the metal revealing bare material and thereby increasing the corrosion rate. In addition, the selection of proper material has a major impact on the corrosion rate of equipment. Some alloys are more resistant to strong acids, others to strong bases and so on. By selecting the correct alloy the effects of corrosion can be kept in control. [12, s.13-5–7]

3.1 Low-temperature corrosion

In the refining industry low-temperature corrosion is often referred to as wet corrosion, aqueous corrosion or electrochemical corrosion. Low-temperature corrosion requires the presence of aqueous solution, even a very small amount of water is adequate to start the reaction, or act as an electrolyte in a hydrocarbon stream. Corrosion can also occur in process streams containing vapor, and it is often found where water condenses. There are several forms of corrosion that can be found in a low-temperature environment. [12, s. 1–4]

3.1.1 Uniform corrosion

Uniform corrosion is the most common type of corrosion which can be characterized as a corrosive attack to the whole metal surface. This leads to thinning of the metal and as a result reduction in mechanical strength and in the long run rendering it unusable. Visual signs make it quite easy to detect because the whole surface of the metal is corroded. Then protective measures such as protective coating can be applied in some cases. [14.]

3.1.2 Galvanic corrosion

In galvanic corrosion at least two dissimilar materials are in contact with each other and have a common electrolyte. As a result, in the less resistant metal corrosion rate increases and its surface becomes anodic. At the same time the more corrosion resistant, also known as nobler metal, surface becomes cathodic and corrosion rate decreases. Galvanic corrosion rate is influenced by the area, distance and geometric effects. The ratio of the surface area between the two metals has an impact on corrosion. When the more noble metal has more surface area compared to a more active metal, the galvanic couple is under cathodic control. Under cathodic control the anodic current density on the more active metal is vastly increased accelerating the corrosion rate on more active metal. The opposite ratio of the surface areas of more active and noble metal lead to only slight acceleration of corrosion. The distance between two dissimilar metals also affects the corrosion rate, usually if they are close together it results in more corrosion. This effect of distance is driven by conductivity of the solution as the main factor considered is the path of current flow. The geometry of a circuit influences corrosion because the current encounters resistance when flowing around the corners. The effects of geometry are thereby caused by current flow which follows the path of least resistance always taking the route with least resistance. [12, s. 1-20–21; 14, s. 19–20.]

The propensity of the metal to corrode in galvanic cell is determined by galvanic series which can be seen in Figure 4. It describes if the metal is anodic or cathodic and further the two metals are apart from each other in the list more galvanic corrosion can occur. Less noble metals are most likely to experience galvanic corrosion and they are called active or anodic metals such as mild steel. More noble metals are less likely to experience galvanic corrosion and are referred to as cathodic metals such as stainless steel. Stainless steels have both solid and hollow bars on the list. Solid bar indicates that the stainless steel is in passive state meaning it has a passive film on the surface protecting the metal. Hollow bars indicate that the stainless steel's passive layer has been broken and it is under active corrosion thus having a different potential than stainless steel that is in passive state. [12, s. 1-22–23; 15.]

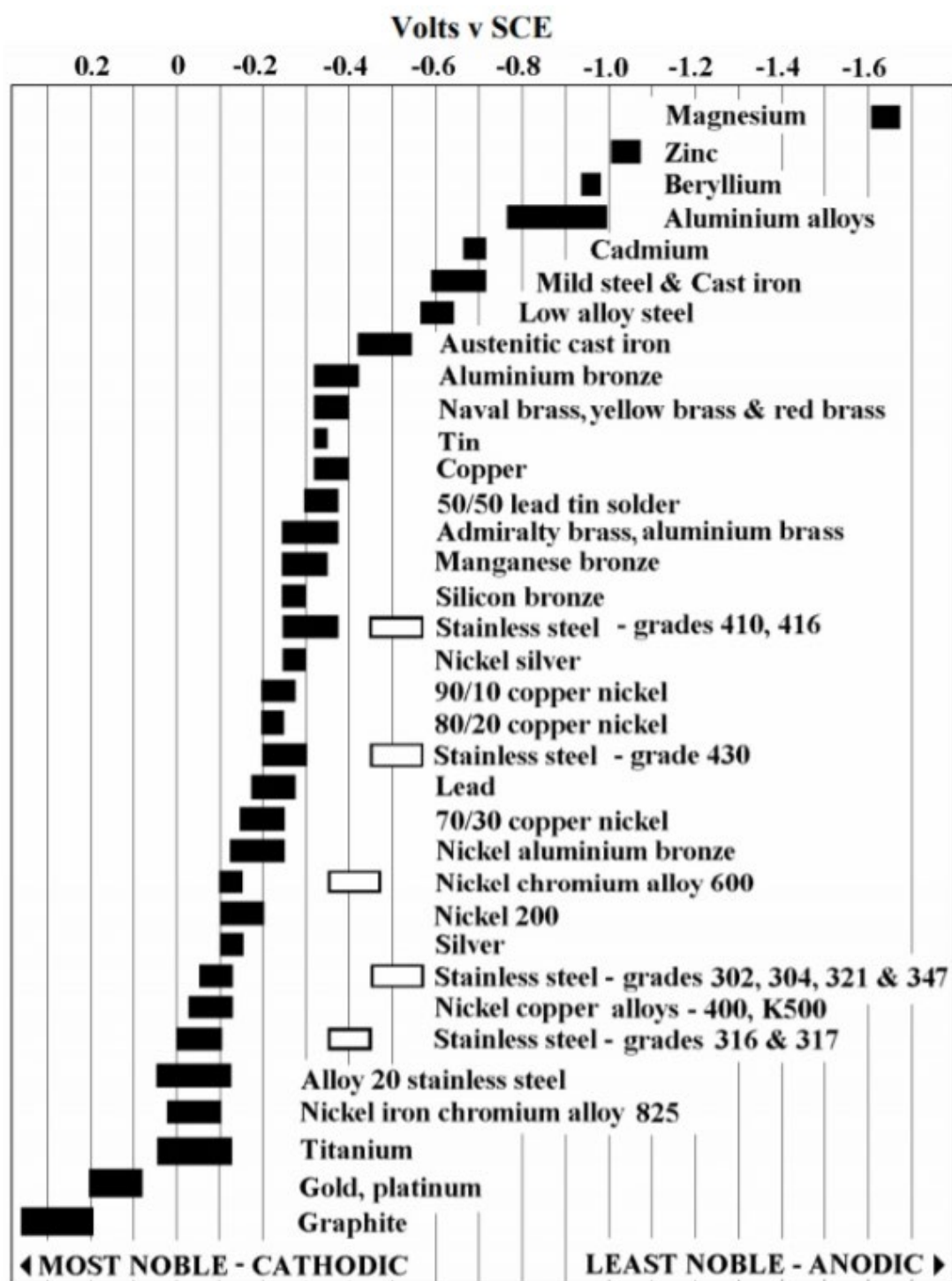


Figure 4. Galvanic series / Table of metals or alloys measured in flowing sea water at ambient temperature. [15.]

3.1.3 Pitting corrosion

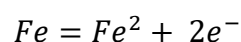
Pitting corrosion is known to be a highly localized type of corrosion in which the metal surface is under intense attack. Pitting corrosion takes place when the protective layer on the metal surface is broken down locally.

In order to pitting corrosion to happen, the alloy must have a protective passive oxide layer such as stainless steels. Pitting occurs when the protective surface of the metal breaks down locally. It usually occurs in stagnant flow conditions and when bromine, sulphate or chloride ions are present in the electrolyte solution. Chloride ions can penetrate protective films due to their relatively small size. Stainless steels, form an oxide layer on the metal surface which acts as a protective layer against corrosion. However, this protective oxide layer is weakened by insertion of chloride into the metal's oxide layer. This formed metal chloride complex cannot withstand the harsh aqueous environments and exposes the bare metal surface to the aggressive aqueous environments leading to pitting corrosion. [12, s. 1-24; 17, s. 215 & 216.]

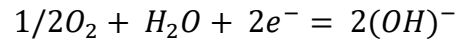
In pitting corrosion material undergoes oxidation inside the pit, and at the same time, the cathodic reaction occurs on the surface. This leads to an excess of positive ions within the pit, prompting chloride ions to move towards them for electrical balance. The subsequent hydrolysis decreases the pH in the pit solution, hastening the oxidation of the metal. [12, s. 1-24.]

When chloride ions are present pits grow by autocatalytic mechanism illustrated in Figure 3 [17.]. Reactions in the pit are the following:

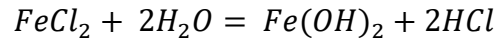
Anodic reaction in the pit (also known as dissolution of iron) [17].



As anode releases electrons to flow to the cathode (the passive film) they are discharged in cathodic reaction. This results the electrolyte in the pit gaining a positive charge and the electrolyte outside pit a negative charge. [17.]



Now the pit that is positively charged starts to attract negative chloride ions Cl^- , thereby increasing the acidity of the electrolyte inside the pit [17].



Inside the pit the pH of the electrolyte decreases from 6 to 2-3 accelerating corrosion. In addition, a large ratio between the anode and cathode is known to increase the corrosion rate, which is further accelerated by the corrosion product $Fe(OH)_3$ forming around the pit. [17].

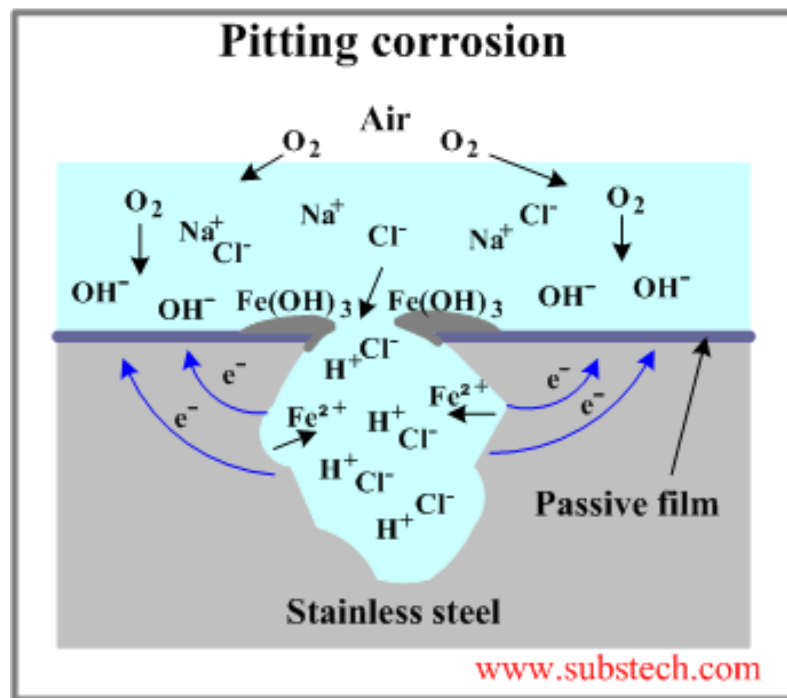


Figure 3. Autocatalytic pitting corrosion mechanism for stainless steel. [17.]

3.1.4 Erosion-corrosion

Erosion-corrosion (E-C) is a combination of mechanical erosion and chemical corrosion commonly found in piping and heat exchangers. Mechanical erosion causes mechanical wear and abrasion, leading to a loss of metal. It is mainly accelerated by higher fluid (liquid or gas) flow velocity and turbulent flow

especially coupled with solid particles. This mechanical wear can be observed as damage in the form of linear grooves, valleys, elongated holes, and gullies along the metal surface. Corrosion, on the other hand, is an electrochemical process which leads to metal loss. [12, s. 1-26–27; 18.]

When combined mechanical wear and chemical corrosion create ideal circumstances to accelerate material degradation. This is because mechanical erosion continuously exposes new material and carries away corrosion products and at the same time chemical corrosion accelerates the overall corrosion rate. [18.]

3.1.5 Stress corrosion cracking

Stress corrosion cracking (SCC) refers to cracking caused by a combination of corrosive environment, metallurgical conditions and tensile stress. As SCC occurs majority of the metal or alloys surface remain unattacked, with fine cracks advancing through the material seen in Figure 5. Consequences of this cracking phenomena are serious because it can happen under stresses much lower than design stresses of the material. This can lead to spontaneous failure as the normally ductile metal cracks. [19.]

The reason for this sudden failure can be often found in the metal's simultaneously exposure to a seemingly mild chemical. While the surface indicates only few signs of corrosion, fine cracks penetrate deeply into the metal. [12, s. 1-46.]

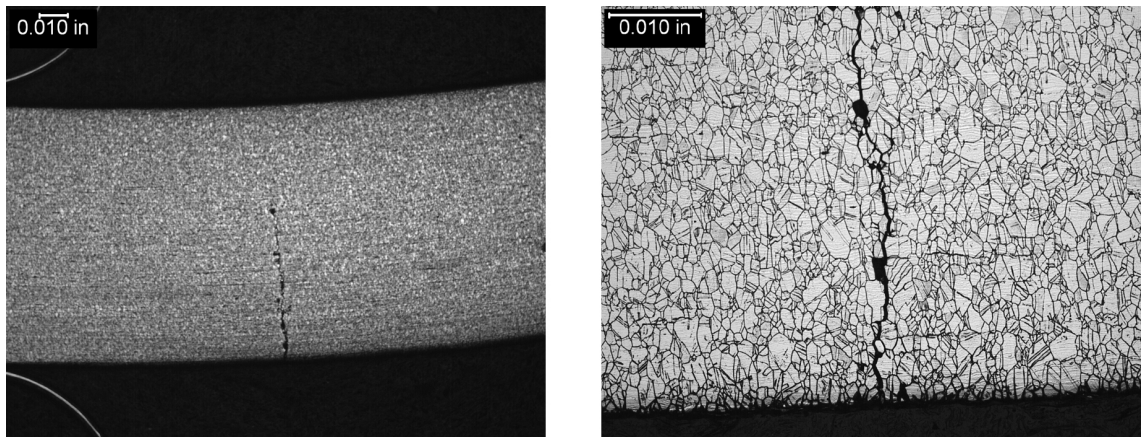


Figure 5. SCC crack development under microscopy.

3.1.6 Hydrogen induced cracking

Hydrogen induced cracking (HIC) is a known form of wet H_2S damage, and it possibly occurs due to hydrogen's ability to diffuse into steel. HIC can be observed as a through wall crack which is formed by parallel hydrogen flaws that link together without any applied stress. HIC is known to be caused by internal stresses resulting from the accumulation of hydrogen within blisters or voids. Cleanliness of the steel plays a big role in HIC and it goes all the way back to the methods of steel manufacturing. HIC-resistance can be provided by controlling the manufacturing variables and limiting trace elements such as sulfur. Since HIC is not stress-driven, post weld heat treatment does not offer much value. [12, s. 1-57.]

HIC is prone to occur in weldments, more precisely in the heat affected zone (HAZ) although it can occur in the weld itself. As mentioned before hydrogen has the ability to diffuse into steel, when temperature is increased, for instance, in the liquid weld pool it becomes more mobile and some of it is diffused into the atmosphere. Once the weld is cooled down hydrogen has more trouble to escape and it tends to collect in the HAZ and grain boundaries. Over time hydrogen is drawn to these areas increasing the up stress that can cause HIC. [20.]

When HIC is stress-driven, it is called stress-oriented hydrogen induced cracking (SOHIC). SOHIC is similar to HIC except that the crack forms perpendicular to the primary stress direction and is frequently encountered in heat-affected zone of welds where it originates from other cracks or defects. Since stress is included, post weld heat treatment can reduce the likelihood of SOHIC. [12, s. 1-57–58.]

3.2 Under deposit corrosion

Under deposit corrosion (UDC) is very aggressive and localized form of corrosion which develops under or around the formed deposits on the metal surface, especially affecting pipelines and other refinery equipment. UDC cases differ from each other since different alloys, corrosive species and types of deposits may be involved and there is not a single mechanism to describe the UDC. However there are three potential scenarios that have been commonly assumed to take place in the formation of UDC. [22.]

- In the first scenario, metal beneath the deposit is anodically coupled to uncovered areas that are cathodic. The driving force for galvanic corrosion is considered to be the electrical potential drop, which leads to different environment for the outside and inside of the deposits. [22.]
- In the second scenario, both cathode and anode exist beneath the deposit without external cathode. The irregularities of the deposit create differences in the local chemistry that is well suitable for pitting corrosion, and it leads to galvanic corrosion. [22.]
- In the third scenario, there is not local separation of cathode and anode, which can lead uniform corrosion beneath the deposit. For instance salts and clays with higher absorbability have been noticed to cause UDC under operating conditions which bare steel would not experience corrosion damage. [22.]

In the oil and gas industry deposits can be generally divided into two groups organic deposits and inorganic deposits. Organic deposits can be either living organisms formed by microbiological activity or non-living substances precipitated from the crude oil. In refining and petrochemical industry, non-living substances are mostly present in the form of high molecular weight

hydrocarbons, such as, naphthenates, coal and tar. Inorganic deposits are formed in the system due to corrosion such as corrosion products such as iron sulfides and oxides. Another way is that water precipitates and forms scaling species such as barium sulfate, calcium carbonate and Sulphur deposits or is transported from the formation. [22.]

3.3 Corrosion effects of organic solvents

The effects of acetonitrile water mixture on corrosion are not very well known and studies about it are scarce. One study concludes that even a small amount of water in organic solvents such as acetonitrile will alter the passivation and corrosion behavior of iron. A study for dissolution and passivation of iron in acetonitrile-water mixtures was done under potentiodynamic (cyclic voltametric) conditions. High-performance liquid chromatography grade acetonitrile with water content of 0.02 % and anhydrous LiClO_4 as supporting electrolyte were used in the study. Water and chloride were added to the electrolyte based on the calculation of yearly leakage. Iron wire with 0.5 mm diameter with 99 % purity was used as a electrode. Distilled water was used when neutral acetonitrile-water mixtures were prepared. The study indicates that water content between 0.5–2 % initiated active dissolution to corrosion damaged and fresh surfaces. If the water content is increased to 6 % dissolution of iron becomes highly significant. Only when water content in the mixture was negligible below 0.02 % the iron surface electrochemically stable at low potentials below 0.5 V. [22.]

A study of corrosion in process containing organic solvent in petrochemical plant also indicates that even a very small amount of water can cause corrosion in the refinery equipment. Although the organic solvent used in the study is not known it is likely that it has at least some similarities with acetonitrile that have the same effect on corrosion. The study claims that water in organic solvent is known to precipitate onto metal surfaces when it flows through equipment, thus creating water film on the surface of the vessel. The solution had water content of 200 weight ppm, and it had ethylene dichloride and dissolved chloride that

could not be removed. The created water film on the surface therefore absorbs chlorides from the organic solution increasing the rate of corrosion. [23, s. 3, 7]

If corrosion is able to occur in organic solvents containing even a small amount of water, it can be assumed that different forms of low temperature or wet corrosion can occur in the refining equipment under those conditions.

3.4 Corrosion inhibition

Corrosion inhibitors play an important role in corrosion mitigation in the processing industries and oil extraction sites. Corrosion inhibitors are used to lessen the rate of corrosion by the use of chemicals. Most knowledge of corrosion inhibitors is acquired from trial and error in the field and laboratories. Corrosion inhibitors are chemical substances that, when added in small amounts into solutions, reduce the corrosion rate. In general, the higher concentration of inhibitor, the more effective it is. [25, s. 833.]

Corrosion inhibitors work by reacting with the metallic surface or the solution protecting the metallic surface. A protective film is created on the surface of the metal by the inhibitor by adsorbing itself to the metal. [25, s. 834.] Inhibitors alter the corrosion rate by doing the following:

- Increasing the electrical resistance of the metal surface
- Increasing the cathodic or anodic polarization behavior
- Reducing the movement or diffusion of ions to the metallic surface

One example of anodic corrosion inhibitor is sodium nitrite NaNO_2 , which is widely used in aqueous closed systems such as oil / gas production and cooling water systems. It forms a protective film on the metal surface by the reaction of sodium nitrite and dissolved oxygen. This newly formed protective film can be kept intact by sodium nitrite alone. It offers great protection for ferrous metals against corrosion and performs best at the pH range of 9.5–10.5. [25; 27]

A study for effects that pH has on sodium nitrite as corrosion inhibitor was done at a high concentration of 800 ppm of NaNO_2 with varying pH and temperature. The test was done to mild carbon steel. At pH 4.0 or below the protective layer dissolved revealing a bare metal surface leading to severe corrosion attack. Reduction of dissolved oxygen accelerated corrosion rate. When pH was increased above 4, deposits were formed from iron oxides precipitated from solution. Uniform corrosion was gradually reduced, but an under-deposit attack began by the formation of Fe_2O_3 in the surface. The best corrosion inhibition was achieved at the pH of 9. At a near-neutral range of pH 4–10, corrosion depends on oxygen diffusion. The efficiency of the inhibitor was observed to decrease as the temperature increased due to increased oxygen diffusion to the metal surface. [25.]

When exposed to oxygen, sodium nitrite converts to sodium nitrate and thus it is not recommended that sodium nitrite be used in open systems that are exposed to air. Sodium nitrite is also prone to microbiological attacks which can lead to UDC. [25.]

3.5 Corrosion in the Porvoo site ACN circulation

The corrosion product found in the solvent cycle containing mixture of ACN and water had uniform corrosion, heavy deposits (fouling) and pits both isolated and uniform in both piping and heat exchanger tubes. It was observed that in some pipes the fouling product covered approximately 180 degrees of the pipe. In these cases pipes are most likely installed in horizontal position and pipe being only half way full causing only half of it to have the fouling product.

4 Nondestructive testing

Nondestructive testing (NDT) refers to techniques that are used to evaluate the condition of materials without conducting any sort of damage to the material. NDT methods gather useful data of the lifespan of the material. Use of NDT techniques leads to better understanding of material behavior and increases the

reliability of the components. For detecting internal corrosion in piping, a radiographic method or an ultrasonic method can be used.

For thickness measurement and internal corrosion detection, two NDT methods are widely used which are ultrasonic testing (UT) and Radiographic testing (RT) which both have advantages and disadvantages illustrated in Table 1.

Ultrasonic testing	
advantages	disadvantages
<ul style="list-style-type: none"> -Gives results immediately. -Fairly easy and simple to use in some applications. -Can be used by single person. -Quick and cheap. 	<ul style="list-style-type: none"> -Insulation must be removed. -Surface needs to be cleaned and flat. -Internal corrosion cannot always be measured accurately.
Radiographic testing	
advantages	disadvantages
<ul style="list-style-type: none"> -Needs minimal preparations. -DRT gives results almost immediately. -Good at detecting corrosion and other defects. 	<ul style="list-style-type: none"> -Gives information only at chosen point of the pipeline -Emits hazardous radiation -Require certification and experience. -Expensive and requires multiple persons.

Table 1. Advantages and disadvantages of ultrasonic testing and radiographic testing methods for wall thickness measurement.

4.1 Radiographic testing

Radiography (RT) is an NDT method which enables objects to be viewed internally. Radiography utilizes gamma or X-rays to project onto the specimen under examination, capturing the intensity of radiation transmitted through the object using a photosensitive film known as industrial X-ray film. The film is

chemically processed after exposure thus obtaining the radiograph which can be viewed against an illuminator and examined. Instead of using conventional film to obtain the radiograph, digital radiographic testing (DRT) can be used instead. It converts radiation straight into a digital signal utilizing digital imaging board. The digital signal is then processed and amplified accordingly by a computer to obtain the image. [26, s. 7.]

X-rays are generated by specially designed vacuum tubes called X-ray tubes also called hollow-cathode tubes. These tubes emit penetrating electromagnetic radiation called X-rays when electrically operated. Intensity and penetration of the X-rays is generated by high voltage kV and current mA and they are usually adjustable. Gamma rays are emitted by radioactive isotopes such as iridium-192 and cobalt-60. Gamma rays are also electromagnetic radiation just like X-rays and these two differ by the way they are produced, gamma radiation having shorter wavelength and higher energy. [27, s. 7.]

Digital radiography and radiography in general can be used to determine the wall thickness of the pipe. Reduction of wall thickness indicates that pipe has endured either internal or external corrosion, which can be determined from the radiograph. Two methods can be used to measure the pipe's wall thickness tangential and double wall measurement. In both cases the data is converted into numeric measurements. [27, s. 10.]

When studying the radiograph of a pipeline, either internal or external corrosion or deposit can be interpreted on the basis of the sharpness of the edge of the pipe and lighter or darker spots or area in the radiograph. If the internal edge of the pipe is uneven and blurry, it indicates internal corrosion, and if it is the outer edge of the pipe it is external corrosion. Light spots or area in the radiograph also indicates corrosion, and they can be classified to internal or external corrosion based on the edge and darker spots or area can be interpreted as deposits. Figure 6 illustrates what corrosion looks like in the radiograph. While vertical pipe is intact, the horizontal pipe has suffered external corrosion, more specifically, corrosion under insulation (CUI) indicated by the uneven edge and

light spots. The gray tube with darker edges which can be seen over pipe is insulation.

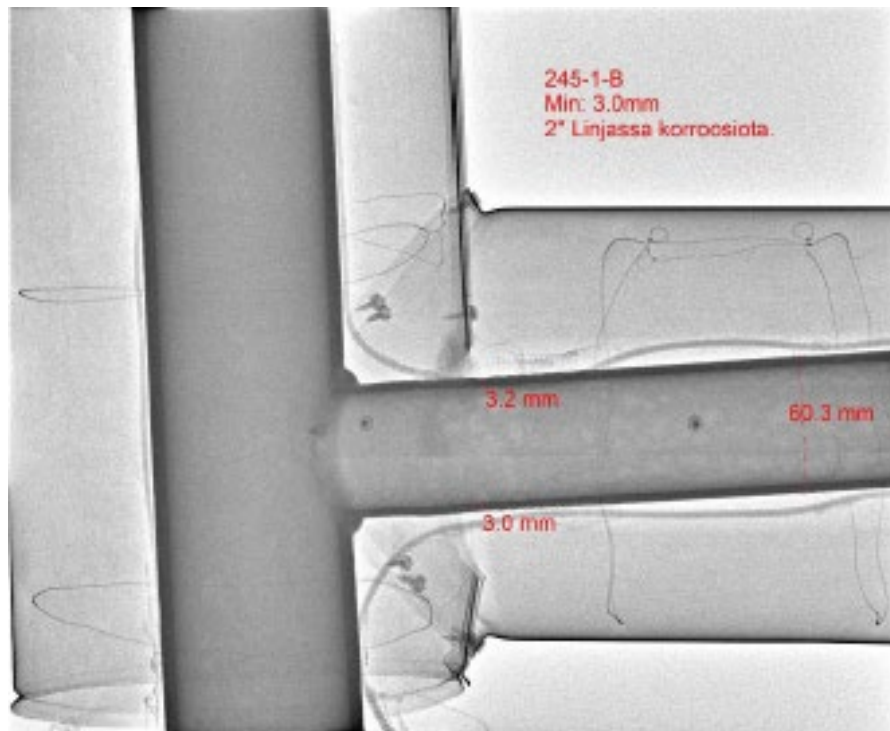


Figure 6. Radiograph of pipe with external corrosion.

4.2 Ultrasonic testing

Ultrasonic inspection (UT) is a widely recognized NDT method for identifying defects in materials by utilizing high-frequency sound waves. Using UT metal can be scanned for metal loss, cracks, and other discontinuities at different depths inside the metal. UT works by emitting ultrasonic waves that travel through the metal and reflect from surfaces. By examining the reflected sound wave's locations all irregularities can be identified and localized and thickness of the material can be measured. [29.]

Conventional UT method utilizes probe to emit sound waves to metal using pulse-echo method. Frequencies between 0.2 MHz and 100MHz are used and the pulse duration is usually a few microseconds. UT requires a coupling agent to fill the gap between the surface of the metal and probe in order to sound

waves to transfer from the probe to the surface of the metal. The emitted sound waves propagate in the metal at the characteristic sound velocity of the metal. Locations where the propagation speed of the sound wave changes produce the sound waves reflection. This reflection of the sound wave is called an echo. Echoes occur at cavities, cracks and pores and are referred to as flaw echoes or backwall echoes. The depth of the material or the flaw can be determined by the time between the emitted sound and the registration of the echo. For this the speed of sound in the metal needs to be known. [29; 30.]

UT utilizes different kinds of probes for several kinds of use cases. Normal probe is the simplest kind of probe. It has one piezoelectric element (transducer), which acts both as the transmitter and receiver alternately. First it emits the ultrasonic pulse and after the pulse has been emitted it can switch to receiving mode. There is a short period in which the signal cannot be received because the probe has not switched to receiving mode yet. This period is referred to as dead time. Imperfection near the surface and thin metals cannot be noticed by this probe, and this area near the surface of the metal is called the dead zone. To tackle this problem, probes can use delay lines to sift the dead zone so that the whole metal can be covered. Another type of probe is a transmitter-receiver (TR) probe which is well suited for corrosion detection. TR probes have both the transmitter and receiver, they are separated from each other by a sound barrier. The benefit of this configuration is that the probe can act simultaneously as a transmitter and receiver enabling near-surface flaw detection and thin metal measurement. TR probe's transmitter and receiver are slightly tilted towards each other to flaw echo to be detected. The more they are tilted the smaller the dead zone at the surface becomes, but sensitivity at deeper depth becomes less accurate. [30.]

Internal corrosion or erosion can be detected by the UT method as a noticeable wall thickness reduction and as varying results at local area of the pipe. Ut readings for pipes give similar results for both external and internal corrosion. This is illustrated in Figure 7 as both internal and external corrosion reduce in thickness [29]. However with uneven surface thickness, measurement becomes

challenging because not all ultrasound reflect straight back. While external corrosion can be seen visually internal corrosion cannot. When the surface of the pipe is in good condition and UT gives vastly varying results for pipe thickness, the pipe is most likely corroded from the inside. If the internal corrosion has caused majorly uneven surface, measuring the exact thickness can be challenging. This is because the sound waves are reflected somewhat aimlessly to the receiver by internal corrosion.

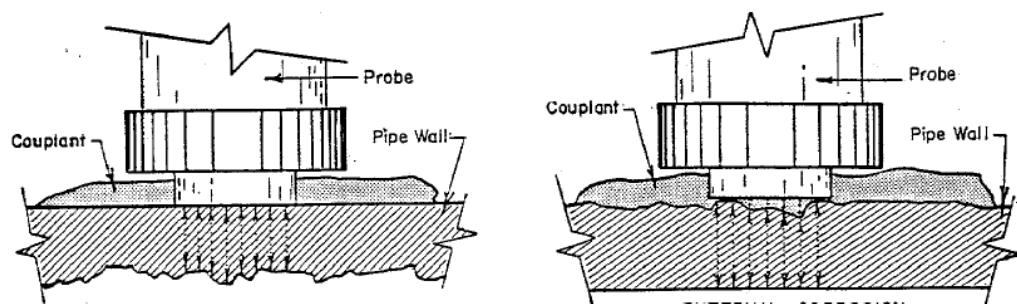


Figure 7. UT method measuring wall thickness for corroded pipe. [25]

5 Destructive testing

Destructive testing (DT) refers to testing methods which are conducted to find the exact point of failure of components, materials or machines. DT conducts tests that eventually will deform or destroy the material rendering it unusable for its original use purposes. DT is often used to find the specific characters of the material and common test methods for it are corrosion testing, tensile testing, torsion testing, stress testing and aggressive environment testing. DT is widely used in quality assurance and failure analysis across various industries. DT has crucial role in understanding material behavior by analysis, whereas NDT is used to ensure sound operation of components by inspections. [32; 33.]

5.1 DT results from solvent circulation

Two samples from the Borealis' Porvoo site butadiene unit solvent circulation were taken in order to find what have caused the internal corrosion in the solvent circulation. One sample was taken from 2" pipe and other one was a sample tube from heat exchangers. Both of them were examined thoroughly. They were cut in half to examine the corrosion product inside the pipe by scanning electron microscopy (SEM) with the energy dispersive X-ray analysis (EDX) testing technique. SEM-EDX is a method that can be used to do advanced surface analysis and is used for failure analysis and contamination identification. Traditional microscopy utilizes light to create an optical signal while SEM uses electrons, and EDX is then utilized for detecting and analyzing elements [34].

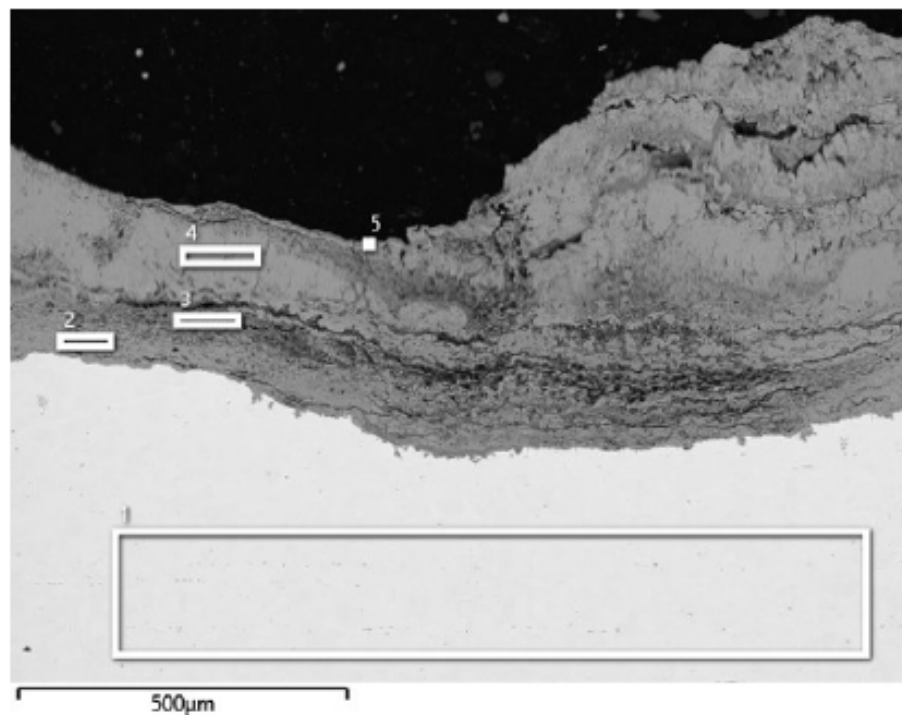


Figure 8. SEM-EDX analysis points of corrosion product.

Figure 8 shows the corrosion product of the pipe with five measurement points. The lighter specimen area labeled as 1 is pure carbon steel without any

corrosion product. The grey area above carbon steel is the corrosion product that has accumulated to the surface of the carbon steel. Table 2 shows results for the each area of Figure 8. Specimen Area 1 which is carbon steel is composed of 97.6 % iron, 1.43 % carbon, 0.62 % magnesium and 0.07 % of chromium. All of the specimen areas 2–4 which comprise the corrosion product show major increase in oxygen content. SEM-EDX analysis indicated that the corrosion product was mainly iron oxide with a traces of aluminum and Calcium. Those results indicate that the driving factor for corrosion in the circulation is dissolved oxygen.

Spec.	C	O	Na	Mg	Al	Si	P	S	Ca	Cr	Mn	Fe	Cu	Zn
1	1,43					0,28				0,07	0,62	97,60		
2	2,62	26,29			0,09	0,47			0,17	0,23	0,68	69,46		
3	13,23	25,03			0,07	0,78			0,59	0,49	0,62	59,18		
4	2,62	26,29				0,25				0,03	0,11	70,70		
5	3,39	32,36			0,12	0,33					1,78	62,02		

Table 2. Result of five measurement points from SEM-EDX analysis.

6 Data collection

Data collection from pipelines of the butadiene unit was done to gain better understanding of process conditions and how they affect internal corrosion of the solvent circulation. The solvent circulation contains a mixture of ACN, water and other hydrocarbons with varying concentration. Pipelines with even a very little amount of ACN and water were selected to be examined. Process conditions such as temperature, ACN concentration, water concentration and flow rate were recorded for each pipeline along with other information which could be found in Appendix 1.

In addition, previous inspection history for pipelines were studied to obtain the knowledge of which pipes have endured internal corrosion, more precisely how severe it is and where it is located. Old inspection reports on the pipelines provided insight into the internal corrosion in the pipelines by UT and RT inspections and indicated which parts of piping had been replaced due to internal corrosion.

6.1 Pipeline data and process conditions

Process flow diagrams (PFD) were used for gaining information about the route of pipes and process conditions such as concentrations and flow rates. process conditions were obtained from measurement points which have data of the process conditions at the specific point in the process between different major refinery equipment. From PFD's equipment relevant process conditions were identified and, and on the basis of this information, a group of pipelines with approximately similar process condition were selected to be examined. The flow rate of the solution was calculated from the volumetric flow given in the PFD for all pipe sizes in the group of pipes. It has to be kept in mind that the results for the flow rate might not be entirely accurate because pipes divide to other branches, thereby reducing the flow rate.

For identifying each individual pipe ID piping and instrumentation diagrams (P&ID) were used. Pipe IDs were required because inspection reports and corrosion results are documented under every specific pipe ID. Where PFD gave information about the route of the piping between major equipment and process conditions, P&ID shows all pipes with pipe IDs on that route and all of the equipment. From P&ID all the relevant pipes which approximately match the group of pipes with the same process conditions were obtained from the PFD and identified as individual pipe IDs in P&ID.

Isometric drawings are made to match the real orientation of pipe and are made for each specific pipe ID. They were used to find the exact location of each measurement point which usually had the amount of corrosion written into them from previous inspections and also pipe orientation, for example if the pipe is vertical or horizontal. Orientation of the pipe is important because in some cases the whole pipe is not full of process fluid and the bottom section and top sections can have quite different results.

Pipeline groups contained a varying ACN concentration all the way from ppm range to 100 % and water concentration from 0.1 to 100 %. Laboratory results

also gave information about process conditions with ACN concentrations and pH of the solution. pH measurement was done only once, and it resulted in pH of 9.5 and 9.7 at two separate spots in the solvent circulation. Oxygen was also measured just once at 0.65 % concentration. Solvent circulation also carries other substances but mostly a mixture of ACN and water. A wide range of process conditions were selected to obtain information of internal corrosion at varying concentrations, temperatures and flowrates.

6.2 Internal corrosion data

Corrosion data was gathered from an excel sheet which had corrosion results approximately from the year 2000 and onwards. In addition, inspections reports, and isometric drawings were used to gather data of internal corrosion. The vast majority of corrosion results were obtained from the excel sheet which contains the information of pipe ID, measurement point, scheduled wall thickness (nominal thickness for each pipe size), measured wall thickness, depth of internal corrosion, used NDT method and year of the measurement. Previous inspection reports also gave information of corrosion although they were mostly external corrosion and measured with the UT method. Isometric drawings gave information of the exact point where internal corrosion is located. With this information all internal corrosion results at the specific measurement points were recorded in the Excel file under pipe IDs. Some inspection reports from pipelines also gave information of where internal corrosion was located.

The condition of the pipeline was categorized into three different categories based on how widespread and severe the internal corrosion was. Every pipe was categorized into one of the three categories, except for the pipes which had no previous inspection data for internal corrosion which did not account to any category. Category 1 has the most severe internal corrosion, category 2 has internal corrosion but its rate is not that alarming and category 3 has very mild internal corrosion or does not have it at all illustrated in Table 3.

Internal corrosion (mp=measurement point)	category
No internal corrosion.	3
Mp1: 0,3 mm curve. Mp2: 0,1 mm curve.	2
Mp3: 1,2 mm curve no changes 2002, -07, -11 ja -17. Mp5: 0,4 mm curve.	1

Table 3. Example of categorized results.

7 Corrosion found and not found

Collected data was examined to find exactly where internal corrosion is located and where it is most likely to occur and what might have caused it. To this end, different process conditions were compared to all categories of documented corrosion results. Comparison revealed roughly in which process conditions internal corrosion is present.

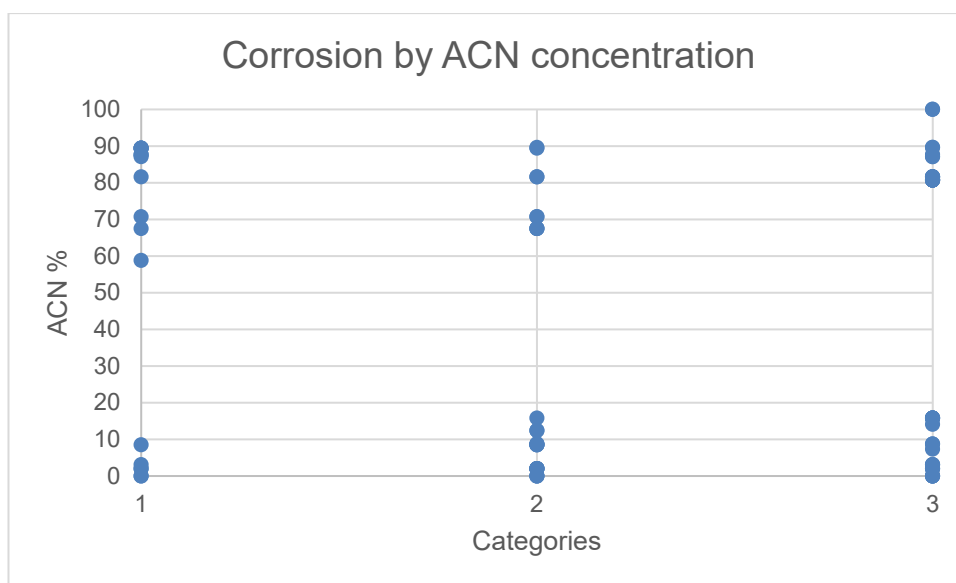


Figure 9. Corrosion results from ACN concentration for each category.

Both ACN and water exist with either high or low concentration without any sort of middle ground. This is because the solution is mainly ACN and water so if

one has a low concentration, the other must have a high concentration. On the basis of the results shown in Figure 9, the ACN concentration does not seem to have impact on internal corrosion. In addition, the severity of the internal corrosion does not seem to correlate with ACN concentration because severe corrosion was found in both low and high concentrations of ACN. The same can be said about water concentration illustrated in Figure 10. Corrosion can be found throughout all concentrations of water and all severities. ACN and water at least alone did not seem to have a straight correlation with the internal corrosion. In addition, the severity and extent of internal corrosion did not seem to be impacted by the ACN or water concentration.

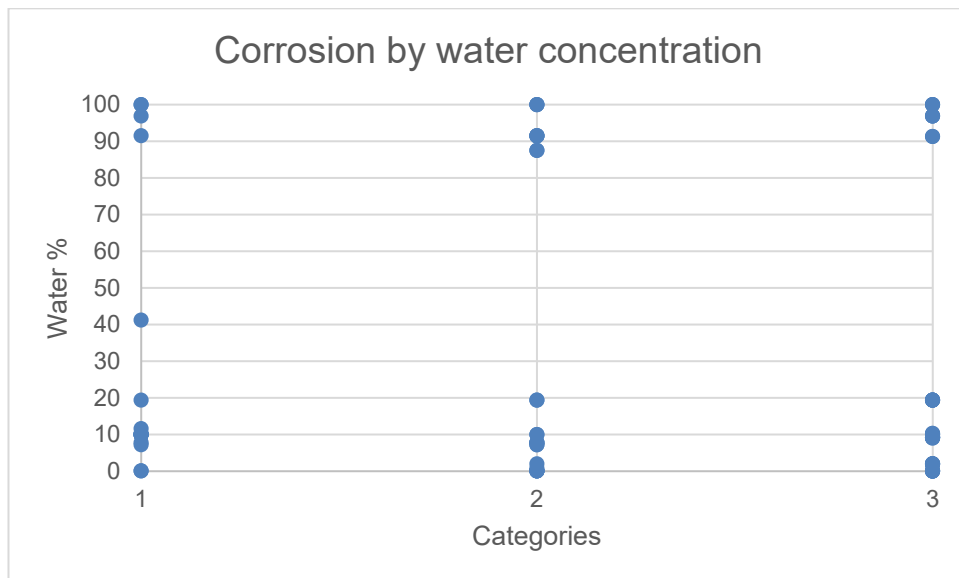


Figure 10. Corrosion results from water concentration for each category.

Flow rates for pipes showed that the majority of pipes had the flow rate of approximately 2 m/s or below as illustrated in Figure 11. Corrosion was found throughout at all flow rates. Figure 11 also indicates that at higher flow rates severe category 1 and a bit less severe category 2 corrosion is not that much present. As only a handful of the pipes had a flow rate above 5 m/s, no conclusions can be drawn. It was also noticed that in general curved sections of the piping had suffered greater amount of internal corrosion than straight pipes. It indicates that at E-C is present at least in some form.

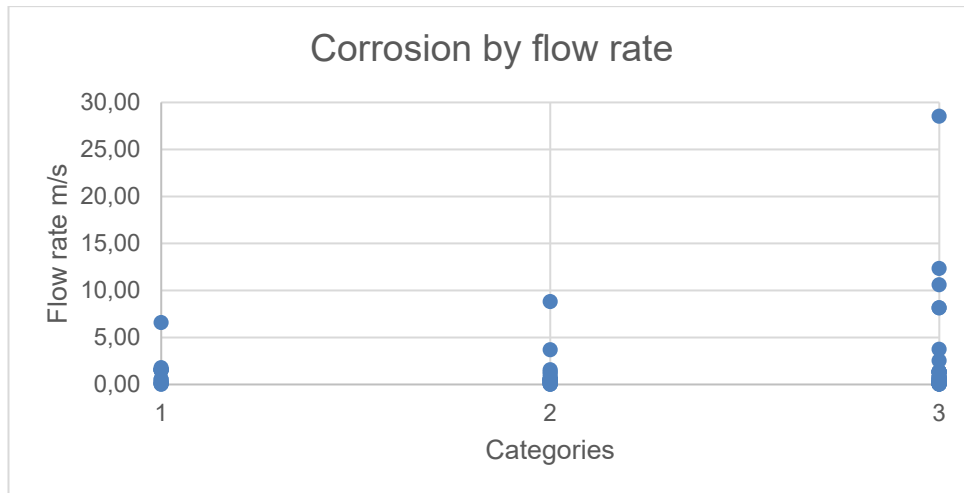


Figure 11. Corrosion results from flow rate.

Temperature range varies all the way from 20 °C to 120 °C. Some of the pipes had varying temperature due to the heat exchanger and they are excluded from Figure 12. In addition, some pipes did not have any data of the temperature. Corrosion was present throughout the temperature range. All corrosion categories are found at all of the temperatures as illustrated in Figure 12. It can be noted that category 3 seems to be more present in the low temperature range than other categories.

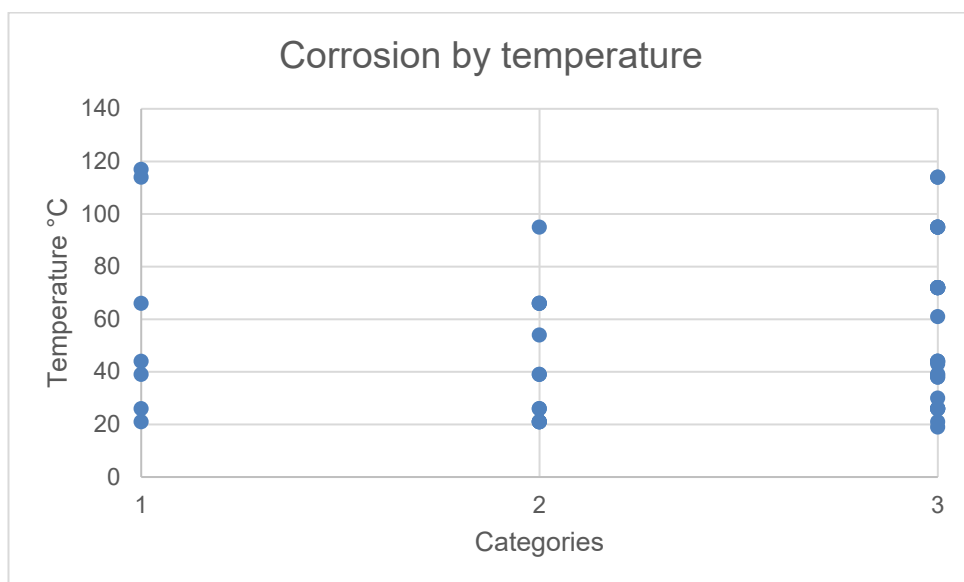


Figure 12. Corrosion results from temperature.

Most of the cases where severe internal corrosion was located were just one pipe of the whole group of pipes with approximately similar process conditions. Group 15 differs clearly from the others with the most severe and widespread internal corrosion results. It has ACN concentration of 89.4 %, water concentration of 10 %, flow rate of 1.54 m/s and varying temperature of 54 to 119 °C. At the same time other Group 9 with almost the same process condition had not suffered any sort of internal corrosion, both groups can be seen in Appendix 1.

8 Conclusions

The purpose of this thesis was to identify parts of the butadiene units' solvent cycle that have endured internal corrosion and the cause of this corrosion. The process of typical olefin plant was introduced as well as different corrosion mechanisms found in refineries. Two NDT methods for identifying internal corrosion were introduced.

Corrosion results and process conditions were determined and listed for the pipelines. Different categories were made based on the severity of internal corrosion in each pipeline. Then process condition were compared to the obtained corrosion results to find where corrosion is present. ACN concentration, water concentration, flow rate and temperature were compared to generated categories of internal corrosion.

The comparison revealed that internal corrosion occurred in almost all parts of the solvent cycle. Its occurrence seems to be random and does not seem to correlate with any of the metrics used that were mentioned before. Different parts of the solvent cycle with approximately same process conditions had vastly varying results for internal corrosion. The cause of internal corrosion cannot thereby be appointed at least straight to the used metrics. The results from both DT reports suggest that corrosion could be oxygen driven. It might be the case because oxygen measured from the solvent cycle was 0.65 % indicating that oxygen is present in the cycle, although oxygen concentration

was measured only once. More information of the oxygen concentration in the solvent cycle would be needed in terms of measurements to be able to draw conclusions.

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Corrosion results in the solvent cycle

Group	Definition	Equipment	PID	Pipeline ID	Temperature	ACN %	Water %	m/s	Internal corrosion
3	Compressor vapors to E.D.	GB-16001 -> DA-16003	EN6763-SC & EN6763-SB	12"P16045-A3, 10"P16045-1-A1 & 6"P16045-2-A1	95 °C	15,8	2	8,8 - 28,5	Local internal corrosion.
4	Solvent to E.D.	nro. 15 -> DA-16004	EN6763-SB	3"P16064-1-A3 & 4"P16064-1-A3	54 °C	89,6	10	2,3 - 3,7	Local internal corrosion.
5	E.D. bottoms	DA-16003 -> FA-16003	EN6763-SC	8"P16023-A1, 6/8"P16024-A3, 10"P16037-A3 & 10"P16039-A1	72 - 81 °C	67,5	7,8	0,6 - 1,8	Widespread and locally severe internal corrosion.
6	Crude B.B	FA-16002 -> DA-16011	EN6763-SB & EN6763-SH sh.1	6"P16028-A1, 6"P16028-1-A1, 3"P16031-A3, 3"P16031-1-A3 & 2"P16031-A3	21 °C	2	0,1	0,1 - 0,8	Widespread and locally severe internal corrosion.
7	Diluent to SDS	FA-16002 -> DA-16007	EN6763-SB & EN6763-SE	6"P16028-A1, 6"P16028-1-A1, 3"P16031-A3, 1,5/3"P16031-3-A3 & 1,5"P16082-A1	39 °C	2	0,1	0,1 - 0,2	Mostly local and mild internal corrosion, with one 1,1 mm spot.
8	E.D. bootleg	FA-16002 -> FA-16010	EN6763-SB, EN6763-SH sh.1 & EN6763-SH sh.2	1,5/2"P16034-A1	?	12,4	87,5	0,1 - 0,2	Local internal corrosion.
9	Flash liquid or LPSS feed	FA-16003 -> DA-16005	EN6763-SC & EN6763-SH sh.2	8"P16047-A1, 8"P16047-1-A1, 6"P16048-A1, 6"P16048-1-A1, 6"P16048-2-A1, 6"P16050-A3, 6"P16050-1-A3 & 6"P16050-3-A3	72 °C	80,7	9,2	0,8 - 1,3	No internal corrosion.
10	LPSS overhead	DA-16005 -> FA-16004	EN6763-SC & EN6763-SH sh.2	10"P16056-A1	43 °C	14,1	1,8	10,6	No internal corrosion.
11	Compressor vapor to HPSS	GB-16001 -> DA-16006	EN6763-SH sh.1	8/10"P16045-A3 & 8"P16045-A1	95 °C	15,8	2	4,0 - 8,1	No internal corrosion/ no data.
12	Liquid sidestream	DA-16005 -> DA-16007	EN6763-SH sh.2 & EN6763-SE	6"P16081-A1, 6"P16081-1-A1 & 4"P16081-A1	103 - 107 °C	88	9,9	0,2 - 0,4	Local internal corrosion/ no data.
13	Vapor sidesreams	DA-16005 -> DA-16007	EN6763-SC & EN6763-SE	6"P16080-A1	117 °C	87,6	11,6	6,6	Widespread and severe internal corrosion/ no data.
14	LPSS bottoms	DA-16005 -> nro. 15	EN6763-SH sh.2	6"P16000-A3, 6"P16060-1-A3 & 8"P16057-A1	?	89,7	9,9	0,8 - 1,3	Widespread and severe internal corrosion only in one pipe/ no data.
15	Circulating solvent	nro. 14 -> nro. 4	EN6763-SH sh.1, EN6763-SC & EN6763-SB	4"P16064-1-A3, 6/8"P16064-A3, 6"P16063-A3, 6"P16062-A3, 6"P16061-A3 & 6"P16060-A3	54 - 119 °C	89,4	10	1,0 - 3,1	Widespread and severe internal corrosion/no data.
16	Solvent to HPSS	nro. 17 -> DA-16006	EN6763-SH sh.1	3"P16064-A3 & 2"P16065-A1	?	89,6	10	0,3 - 1,8	Local internal corrosion/ no data.
17	Solvent bleed	Nro. 15 -> nro. 30	EN6763-SH sh.1 & EN6763-SH sh.2	1,5"P16064-3-A3	?	89,6	10	0,9	No internal corrosion.
18	HPSS bottoms	DA-16006 -> DA-16005	EN6763-SH sh.1 & EN6763-SH sh.2	4"P16054-A1, 4"P16054-1-A1NB & 3"P16055-A1	?	70,7	7,2	0,4 - 1,4	Widespread and locally severe corrosion.
19	Compressor feed	FA-16004 -> GB-16001	EN6763-SC	16"P16040-A1	61 °C	15,8	2	2,5	No internal corrosion.
22	SDS bottoms	DA-16007 -> nro. 14	EN6763-SC & EN6763-SE	4"P16087-A1, 4"P16087-1-A1, 2"P16088-A1 & 2"P16088-1-A1	114 °C	89,1	10,3	0,2 - 1,5	Local mostly slight internal corrosion/ no data.
23	SDS tops including diluent	FA-16007 -> DA-16008	EN6763-SE	3"P16089-A1	?	7,3	9	2	Local slight internal corrosion.
24	Waste gas absorber bottoms	DA-16008 -> DA16011	EN6763-SE & EN6763-SH sh.1	2"P16090-A1, 2"P16090-1-A1, 2"P16091-A3, 2"P16092-A3, 2"P16093-A3 & 2"P16093-1-A3	44 °C	3,1	96,9	0,5	Local slight internal corrosion/ no data.
25	Waste gas including diluent	DA-16008 -> BA-183510	EN6763-SE	3"P16094-A1, 2"P16094-A1, (4"P18303-A1C) & 2"WF16094-A1	30 °C	<100 ppm	0,9	0,5 - 3,7	Local slight internal corrosion/ no data.
30	BB washer feed	6 & 17 -> DA-16011	EN6763-SH sh.1	2"P16031-A3	21 °C	8,8	0,8	7	Widespread mostly slight internal corrosion.
31	BB product	DA-16011 -> variable(s)	EN6763-SH sh.1	2"P16140-A3	19 °C	<50 ppm	0,1	0,8	No internal corrosion.
32	BB washer fat water	DA-16011 -> nro. 33	EN6763-SH sh.1	2"P16124-A3, 2"P16125-A1	38 °C	8,7	91,3	0,5	Local and slight internal corrosion.
33	total fat water	nro. 32 -> FA-16010	EN6763-SH sh.1	2"P16126-A1	?	8,6	91,4	0,5	Local internal corrosion.
34	Feed to SRC	FA-16010 -> DA-16012	EN6763-SH sh.1 & EN6763-SH sh.2	3"P16127-A1, 3"P16127-1-A1, 2"P16128-A1, 2"P16128-1-A1 & 2"P16128-3-A1, 3"P16131-A1, 3"P16131-1-A1, 3"P16133-A3, 2"P16132-A3, 2"P16134-A1, 2"P16134-1-A3, 2"P16135-A3 & 2"P16136-A3	66 °C	8,5	91,5	0,3 - 0,6	Widespread internal corrosion.
36	SRC bottoms	DA-16012 -> EA-16017	EN6763-SH sh.1, EN6763-SH sh.2 & EN6763-SH sh.3	2"P16145-A1, 2"P16145-1-A1, 2"P16146-A1, 2"P16146-1-A1, 1,5"P16146-3-A1, 1,5"P16142-A3, 1,5"P16143-A3, 1,5"P16149-A3	114 - 21 °C	10 ppm	100	0,3 - 0,5	Widespread and locally severe internal corrosion.
37	Recovered solvent	FA-16011 -> ACN still(s)	EN6763-SL	2"P16240-A1, 2"P16240-1-A1	26 °C	81,6	19,4	0,1	Local internal corrosion and one pipe has severe internal corrosion.
39	Fresh solvent make up	ACN still(s) -> nro. 40	EN6763-SL	2"P16240-A1, 2"P16240-1-A1	?	100	0	?	No internal corrosion.
40	Recycle solvent to GA-16002	nro. 40 -> GB-16002	EN6763-SL & EN6763-SB	1,5"P16240-A1	?	58,8	41,2	?	Widespread and severe corrosion.

Group	Size	Line ID	Internal corrosion (mp=measurement point)	category	Temperature °C	ACN %	Water %	Flow rate (m/s)	Area (m2)	Volumetric flow (m3/s)
3	6"	P16045-2-A1	No internal corrosion.	3	95 °C	15,8	2	28,51	0,015	0,439
	10"	P16045-1-A1	No internal corrosion.	3						
	12"	P16045-A3	Mp1: 0,6 mm curve no changes 2008->2013.	2						
4	4"	P16064-1-A3	No data.	2	54 °C	89,9	10	2,27	0,008	0,017
	3"	P16064-A3	Mp1: 0,5 mm curve.	2						
	10"	P16023-A1	No data.	2						
5	6"	P16024-A3	Mp1: 1,2 mm curve, Mp2: 0,6 mm curve, Mp4: 0,4 mm horizontal straight, Mp7: 0,6 mm horizontal straight, Mp8: 0,2 mm curve.	1	72-81 °C	67,5	7,8	0,35	0,015	0,027
	10"	P16024-A3	Mp1: 0,7 mm curve, curve no changes 2009->2016.	2						
	8"	P16037-A3	Mp1: 0,5 mm curve no changes 2013->2017, Mp2: 0,6 mm horizontal straight.	2						
	10"	P16033-A1	Mp5: 0,3 mm vertical straight.	2						
	6"	P16028-A1	Mp1: 0,5 mm horizontal straight, Mp4: 0,4 mm horizontal straight, Mp5: 0,4 mm vertical straight.	2						
6	6"	P16028-A1	Mp1: 0,3 mm curve, Mp2: 0,4 mm curve.	2	21 °C	2	0,1	0,12	0,005	0,002
	3"	P16031-A3	Mp3: 0,3 mm curve.	2						
	3"	P16031-1-A3	No internal corrosion.	3						
	2"	P16031-A3	Mp2: 0,2 mm straight, Mp5: 0,3 mm curve, Mp6: 0,2 mm straight, Mp7: 0,1 mm straight.	2						
	6"	P16028-A1	Mp1: 0,5 mm horizontal straight, Mp4: 0,4 mm horizontal straight, Mp5: 0,4 mm vertical straight.	2						
7	6"	P16028-1-A1	Mp1: 0,3 mm curve, Mp2: 0,4 mm curve.	2	39 °C	2	0,1	0,00	0,005	0,000
	3"	P16031-A3	Mp3: 0,3 mm curve.	2						
	1,5"	P16031-3-A3	No internal corrosion.	3						
	3"	P16031-3-A3	No data.	3						
	1,5"	P16034-A1	Mp1: 0,5 mm curve, Mp4: 0,1 curve.	2						
8	2"	P16034-A1	Mp2: 0,2 mm curve, Mp3: 0,2 mm straight.	2	?	12,4	87,5	0,01	0,002	0,000
	8"	P16047-A1	No internal corrosion.	3						
	8"	P16047-1-A1	Mp2: 0,1 mm curve.	3						
	6"	P16048-A1	No internal corrosion.	3						
	6"	P16048-1-A1	No internal corrosion.	3						
9	6"	P16048-2-A1	No internal corrosion.	3	72 °C	80,7	9,2	1,32	0,015	0,020
	6"	P16050-A3	No internal corrosion.	3						
	6"	P16050-2-A3	No internal corrosion.	3						
	6"	P16050-3-A3	No internal corrosion.	3						
	10"	P16050-A1	No internal corrosion.	3						
10	8"	P16045-A3	No internal corrosion.	3	43 °C	14,1	1,8	10,59	0,090	0,228
	10"	P16045-A3	No data.	3						
	8"	P16045-A1	No internal corrosion.	3						
11	10"	P16045-A3	No data.	3	95 °C	15,8	2	4,01	0,050	0,200
	8"	P16045-A1	No internal corrosion.	3						
	6"	P16081-A1	No data.	3						
12	6"	P16081-A1	No data.	3	103-107 °C	88	9,9	0,19	0,015	0,003
	4"	P16081-A1	Mp1: 0,5 mm curve, Mp8: 0,1 mm curve.	2						
	6"	P16081-A1	No data.	3						
13	4"	P16080-A1	Mp1: 0,5 mm curve, Mp4: 0,7 mm curve, Mp5: 0,6 mm curve, Mp7: 0,2 mm curve, Mp9: 0,2 mm horizontal straight.	1	117 °C	87,6	11,6	6,57	0,017	0,113
	6"	P16060-A3	Mp1: 0,4 mm curve, Mp2: 0,3 mm curve, Mp3: 0,1 mm curve, Mp4: 0,4 mm straight, Mp5: 0,6 mm horizontal straight.	1						
	6"	P16060-1-A3	No data.	1						
14	8"	P16057-A1	No internal corrosion.	3	?	87,7	9,9	1,32	0,015	0,020
	4"	P16064-A3	No data.	3						
	6"	P16064-A3	Mp1: 0,3 mm curve, Mp2: 0,1 mm curve.	2						
15	6"	P16064-A3	No data.	2	54-119 °C	89,4	10	1,54	0,015	0,024
	8"	P16064-A3	No data.	2						
	6"	P16064-A3	Mp1: 1,2 mm curve no changes 2002, 07, 11 ja 17, Mp5: 0,4 mm curve.	1						
	6"	P16062-A3	Mp1: 0,5 mm curve, Mp2: 0,6 mm curve, Mp4: 0,5 mm curve, Mp5: 0,1 mm curve, Mp7: 0,1 mm curve.	1						
	6"	P16061-A3	Mp1: 0,1 mm straight, Mp2: 0,1 mm curve, Mp3: 0,1 mm curve, Mp5: 0,1 mm straight, Mp6: 0,4 mm curve, Mp8: 0,2 mm curve.	1						
16	6"	P16060-A3	Mp1: 0,4 mm curve, Mp2: 0,3 mm curve, Mp3: 0,1 mm curve, Mp4: 0,4 mm straight, Mp5: 0,6 mm horizontal straight.	1	?	89,6	10	0,25	0,017	0,004
	3"	P16064-A3	Mp1: 0,5 mm curve.	2						
	2"	P16065-A1	No internal corrosion.	3						
17	1,5"	P16064-3-A3	No internal corrosion.	3	?	89,6	10	0,08	0,001	0,000
	4"	P16054-A1	Mp1: 0,5 mm curve, Mp2: 0,4 mm curve, Mp3: 0,2 mm curve.	1						
	4"	P16054-1A1NB	Mp1: 0,3 mm curve, Mp4: 0,4 mm curve.	1						
18	4"	P16054-A1	Mp1: 0,3 mm curve, Mp4: 0,4 mm curve.	1	?	70,7	7,2	0,39	0,017	0,007
	3"	P16055-A1	Mp1: 0,1 mm curve, Mp15: 0,1 mm sloped straight, Mp2: 0,6 mm curve.	2						
	16"	P16040-A1	No internal corrosion.	3						
19	4"	P16087-A1	No internal corrosion.	3	61 °C	15,8	2	2,51	0,095	1,242
	4"	P16087-1-A1	No internal corrosion.	3						
	4"	P16087-A1	Mp2: 0,2 mm vertical straight.	3						
22	2"	P16088-A1	Mp1: 0,2 mm curve, Mp2: 0,2 mm curve, Mp3: 0,2 mm curve, Mp4: 0,2 mm curve, Mp5: 0,2 mm curve, Mp6: 0,2 mm curve, Mp7: 0,2 mm curve, Mp8: 0,2 mm curve, Mp9: 0,2 mm curve, Mp10: 0,2 mm curve, Mp11: 0,2 mm curve, Mp12: 0,2 mm curve, Mp13: 0,2 mm curve, Mp14: 0,2 mm curve, Mp15: 0,2 mm curve, Mp16: 0,2 mm curve, Mp17: 0,2 mm curve, Mp18: 0,2 mm curve, Mp19: 0,2 mm curve, Mp20: 0,2 mm curve, Mp21: 0,2 mm curve, Mp22: 0,2 mm curve, Mp23: 0,2 mm curve, Mp24: 0,2 mm curve, Mp25: 0,2 mm curve, Mp26: 0,2 mm curve, Mp27: 0,2 mm curve, Mp28: 0,2 mm curve, Mp29: 0,2 mm curve, Mp30: 0,2 mm curve, Mp31: 0,2 mm curve, Mp32: 0,2 mm curve, Mp33: 0,2 mm curve, Mp34: 0,2 mm curve, Mp35: 0,2 mm curve, Mp36: 0,2 mm curve, Mp37: 0,2 mm curve, Mp38: 0,2 mm curve, Mp39: 0,2 mm curve, Mp40: 0,2 mm curve, Mp41: 0,2 mm curve, Mp42: 0,2 mm curve, Mp43: 0,2 mm curve, Mp44: 0,2 mm curve, Mp45: 0,2 mm curve, Mp46: 0,2 mm curve, Mp47: 0,2 mm curve, Mp48: 0,2 mm curve, Mp49: 0,2 mm curve, Mp50: 0,2 mm 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