Pertanika J. Sci. & Technol. 32 (4): 1665 - 1685 (2024)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Review Article

Processing Plants Damage Mechanisms and On-stream Inspection Using Phased Array Corrosion Mapping—A Systematic Review

Jan Lean Tai[1], Mohamed Thariq Hameed Sultan[1, 2, 3]* and Farah Syazwani Shahar[1]

[1]*Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[2]*Laboratory of Biocomposite Technology, Institute of Tropical Forest and Forest Product (INTROP), University Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia*
[3]*Aerospace Malaysia Innovation Centre, Prime Minister's Department, MIGHT Partnership Hub, 63600 Cyberjaya, Selangor, Malaysia*

ABSTRACT

This review aims to study the process plant damage mechanisms published by previous research, such as general corrosion, localised corrosion, and stress corrosion cracking. This review was conducted by analysing the current application of the common inspection method and technique and focusing on the phased array ultrasonic testing application. In order to further the current study, the review seeks direction on evaluating phased array corrosion mapping techniques to detect corrosion and metal loss during plant operation and minimise the plant's need for maintenance. This systematic literature review provides a better understanding of the current damage mechanisms and shows the possibility of an extended future study.

Keywords: General corrosion, localised corrosion, non-destructive testing (NDT), phased array ultrasonic testing (PAUT), pitting, stress corrosion cracking (SCC)

ARTICLE INFO

Article history:
Received: 16 August 2023
Accepted: 02 January 2024
Published: 25 July 2024

DOI: https://doi.org/10.47836/pjst.32.4.12

E-mail addresses:
taijanlean2008@hotmail.com (Jan Lean Tai)
thariq@upm.edu.my (Mohamed Thariq Hameed Sultan)
farahsyazwani@upm.edu.my (Farah Syazwani Shahar)
* Corresponding author

INTRODUCTION

The in-line inspection activities of the petrochemical process plant are performed to carry out routine planned inspections of the plant's equipment to ensure that the entire system is in good working condition and avoid unexpected failure without the plant's shutdown.

Non-destructive testing (NDT) techniques have been widely utilised in

ISSN: 0128-7680
e-ISSN: 2231-8526

the petrochemical industry. Conventional NDT methods, such as visual inspection (VT), magnetic particle testing (MT), penetrant testing (PT), and eddy current testing (ECT), are commonly used to detect surface defects. Ultrasonic testing (UT) and radiography testing (RT) are typically employed for internal flaws. The phased array corrosion mapping technique is a UT technique that provides image-based results and requires less testing time.

This systematic literature review aims to investigate the application of the phased array corrosion mapping technique for detecting corrosion and metal loss in high-temperature environments without shutting down the plant operation and minimising the plant's downtime for turnaround maintenance.

To better understand the subject matter, the first research question aims to identify the current plant damage mechanisms, in-service defects, and material distortions in equipment or piping systems studied by other researchers. The second research question sought to determine the materials involved in these damage mechanisms.

The third research question focuses on the current application stage of phased array ultrasonic testing and phased array corrosion mapping. The aim is to understand the advanced UT technique's capabilities and its application by other researchers. Finally, this review seeks to determine the feasibility of using phased array corrosion mapping in a plant's operating conditions.

LITERATURE REVIEW

The search strategy employed in this literature review utilised the keyword "corrosion," encompassing various forms of corrosion such as general and localised corrosion, erosion corrosion, microorganism-induced corrosion, galvanic corrosion, and stress corrosion cracking. A total of 40 articles were selected based on these keywords, and articles that pertained to non-metal and non-process plants were excluded to address research questions one and two.

The second focus pertains to current inspection methods used in high-temperature plant operations. Specifically, the application of phased array ultrasonic testing (PAUT) is of interest, including its utilisation for corrosion mapping, weld inspection, application on non-metallic materials, and other phased array ultrasonic applications.

The Process Plants Damage Mechanism

The cause of equipment deterioration or disintegration is known as the damage mechanism. Selecting the type of damage mechanism is done by screening the composition of the plant's equipment material, the fluid that is processed or stored in the equipment, the surrounding processing environment, and other conditions that affect the screening of the damage criteria (Siswantoro et al., 2021).

Crude oil is a mixture of dissolved gases, water, and salts in the form of liquid hydrocarbons. It is an emulsion of water droplets dispersed throughout the continuous hydrocarbon phase. Natural gas is a gaseous mixture of hydrocarbons, nitrogen, carbon dioxide, sulphur dioxide, water, and trace amounts of mercury, organic acids, and inert gases. CO_2, H_2S, H_2O, mercury, and organic acids can cause metal corrosion in natural gas production, separation, processing, transportation, handling, and storage (Groysman, 2017).

Carbon dioxide causes corrosion called sweet corrosion. Sour corrosion occurs when H2S is the cause of corrosion. The corrosion caused by O_2 is called oxygen corrosion. Oxygen corrosion has a pitting appearance. Carbon steel, low alloy steels, copper, and its alloys are corroded by oxygen. However, oxygen is essential to maintain protective oxide layers on stainless steel, titanium, and aluminium.

Corrosion is responsible for 80% of total petrochemical plant failures. The corrosion rate increases 1–3 times for every 10°C increase in temperature, and pressure increases the solubility of corrosive gases, accelerating corrosion. Stainless steel (SS) is resistant to ordinary corrosion. However, pitting corrosion is still problematic (Wan & Yang, 2021).

Corrosion is generally classified into two primary categories, general corrosion and localised corrosion, which are determined by the appearance of corrosion. Stress corrosion cracking (SCC) is a notable damage mechanism that has garnered significant attention from researchers because of its detrimental effects. As depicted in Figure 1, this classification scheme highlights the crucial dissimilarities between various forms of corrosion.

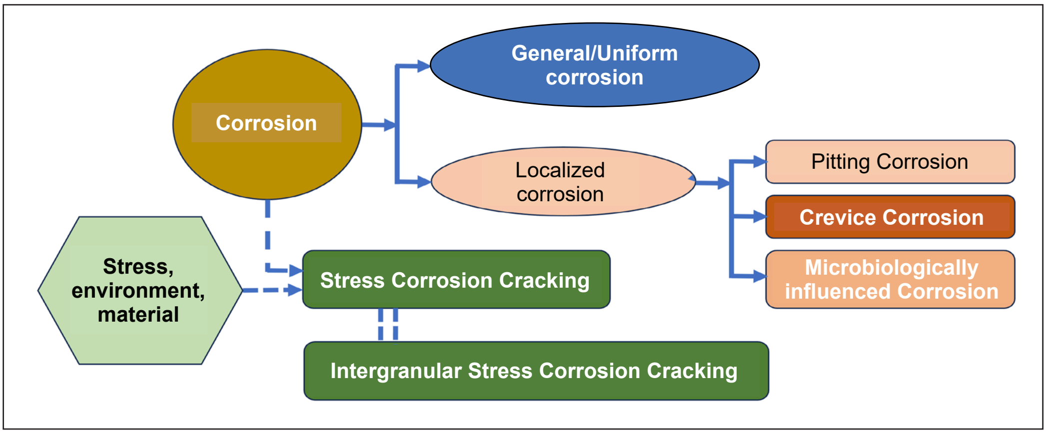

Figure 1. Classification of corrosion

General Corrosion

Mazumder (2020) described corrosion as a localised electrochemical oxidation and reduction reaction occurring on the metal surface. An anode, cathode, and aqueous solution, or electrolyte, with positively and negatively charged ions with some conductivities, are used in the electrochemical corrosion process. When metals dissolve, electrons are moved to another location on the surface, causing slow degradation and eventual failure of the host metal (Fajobi et al., 2019).

Internal corrosion is linked to the gases or liquids that are stored or transferred. Continuous exposure to fluids causes corrosion under both anaerobic and aerobic conditions. Chemical reactions primarily cause internal piping corrosion, whereas electrochemical reactions cause material loss. Therefore, the corrosion type, depth and width, average corrosion rate, and vertical deviation are common indicators of corrosion damage (Shafeek et al., 2021).

Du et al. (2020) indicated that corrosion is the most common problem in atmospheric and vacuum distillation units, especially in low-temperature components because crude oil includes a lot of corrosive chemicals such as water, salt, sulphide, and acid. Therefore, the primary failure mechanisms of the atmospheric and vacuum distillation units can be regarded as internal corrosion thinning, including uniform and localised corrosion thinning wet hydrogen sulphide damage and exterior corrosion.

Colombo et al. (2018) studied the elements to determine why closed water-cooling systems fail at 270°C. The primary material for the cooling water system is a zinc-coated galvanised steel pipe. However, it still has corrosion issues, especially with high chloride and sulphate concentrations, temperature, and low pH.

Electrolytic corrosion and galvanic corrosion are two mechanisms that cause corrosion to occur. Due to its high mechanical properties, availability, and low cost, carbon steel has become the standard material for pipeline transportation (Ameh et al., 2018).

However, Kansara et al. (2018) believe uniform corrosion is defined as corrosion that occurs consistently across the exposed metal surface. It is generally easy to assess and anticipate, making catastrophic failures uncommon.

Localised Corrosion

Wang et al. (2021) introduced pitting corrosion, also known as localised corrosion or pinhole corrosion, as a kind of corrosion with a small diameter and considerable depth. Pitting pits form on the microscopic scale and cause metals and alloys to fail through perforation and stress corrosion cracking, among other failure modes.

Shekari et al. (2017) described pitting as a localised metal loss where the pitting diameter is on the order of the thickness of the plate or less, and the depth of pitting is less than the thickness of the plate. If not enough attention is paid to the enlarged pit, the damaged device can leak once the pit turns into a hole and penetrates the device housing.

Pitting is a corrosion mechanism in various pipeline steel grades used in the petroleum industry. Localised pits are produced by the differential cell, which expands by an autocatalytic mechanism known as self-stimulating and self-propagating (Subramanian, 2018).

Shekari et al. (2016) also introduced a fitness-for-service assessment method to determine plant equipment suffering from pitting corrosion. Pitting is a local corrosion type that could penetrate the equipment wall and cause serious incidents. Salt in crude oil promotes pitting corrosion of metal structures in crude distillation overhead systems. It is also caused by hydrochloric acid in crude distillation overhead systems, particularly at temperatures of approximately 338°C (Fajobi et al., 2019).

Piri et al. (2021) indicated that failure and corrosion of carbon steel fire water pipes, predominantly localised corrosion, can cause pipeline leakage and rupture, resulting in costly repairs or replacement or even uncontrollable conditions during a plant's emergency. When the pressure of the fluid is lower than its vapour pressure, vapour pockets and bubbles can form on the pipe's inner surface, resulting in cavitation damage (Vanaei et al., 2017).

Khouzani et al. (2019) reported that microorganism-induced corrosion (MIC) is affected by microorganisms, including microalgae, bacteria, archaea, and fungi. MIC can occur in the absence of other corrosion or in combination with other corrosion failures.

MIC is an electrochemical phenomenon caused by microorganisms that can alter corrosion processes and increase localised corrosion. Bacteria, fungi, and microalgae are all microorganisms, but bacteria are the primary source of corrosion. MIC may arise during system operation or construction.

According to the results of many chemical and microbiological experiments from Chidambaram et al. (2018) study, they defined the fire water supply pipeline as ruptured by sulphide-reducing bacteria. Sulphide-reducing bacteria cause the MIC of fire-fighting water supply pipes.

Crevice corrosion is localised corrosion that occurs internally in the piping in either metal-to-metal or metal-to-non-metal grooves. Crevice corrosion is often used to describe the damage to passivating metals, but it can also refer to the failure of non-passivating metals caused by oxygen concentration cells (Cheshideh et al., 2021).

Austenitic stainless steels (ASS) are prone to pitting corrosion under chloride conditions. The critical pitting temperatures for 304 and 316 SS are approximately 30°C and 55°C, respectively (Martins et al., 2014).

Based on this review, the authors have identified four critical factors that influence corrosion: the pH and chemical composition of the product, the materials used in fabrication, temperature, and environmental conditions. In addition, the API Recommended Practice 571: Damage Mechanisms Affecting Fixed Equipment In The Refining Industry (2011), which is structured around both the environment and the product to classify corrosion mechanisms into various categories such as atmospheric corrosion, cooling water corrosion, and boiler water condensate corrosion (API, 2011).

Table 1 provides a selective overview of the critical damage mechanisms, highlighting the crucial factors and affected materials to understand better the four key factors influencing corrosion. Owing to space limitations, detailed information and explanations of all damage mechanisms have not been included (API, 2011).

Table 1
Critical factors of damage mechanism

Damage Mechanism	Description Damage	Critical Factors	Affected Materials
Atmospheric Corrosion	Corrosion due to moisture in atmospheric conditions is a common phenomenon, particularly affecting marine environments and humid, polluted industrial areas. The dry rural environments, on the other hand, experience minimal corrosion. This corrosion can occur in the form of general deterioration or localised damage.	Factors impacting corrosion include environmental settings, humidity levels, temperature fluctuations, and the presence of salts, sulphur compounds, and dirt. Corrosion rates increase with rising temperatures, peaking at 121°C, beyond which surfaces become too dry for corrosion.	Carbon steel, low alloy steels and copper alloyed aluminium.
Cooling Water Corrosion	Corrosion, whether general or localised, can have a detrimental impact on carbon steels and other metals due to the presence of dissolved salts, gases, organic compounds, or microbiological activity. Cooling water corrosion can result in various damage, including general and pitting corrosion, MIC, stress corrosion cracking, and fouling.	Cooling water corrosion and fouling are related issues that require consideration of factors such as temperature, water type, cooling system type, oxygen content, and fluid velocities. Higher process side temperatures and cooling water inlet temperatures increase the likelihood of scaling, which can occur if the water outlet temperature exceeds 46°C in brackish or saltwater.	Carbon steel, stainless steel, copper, aluminium, titanium and nickel base alloys.
Boiler Water Condensate Corrosion	The boiler system and condensate return piping are prone to general and localised pitting corrosion.	Dissolved gases like oxygen and carbon dioxide caused oxygen pitting and carbonic acid corrosion in boiler systems. Important factors like concentration, pH, temperature, feedwater quality, and treatment systems affect corrosion likelihood. Addressing these factors is crucial for prevention and mitigation.	Carbon steel, low alloy steel, 300 Series SS and copper-based alloys.
CO_2 Corrosion	Carbon dioxide corrosion occurs when carbon dioxide dissolves in water, forming carbonic acid. This acid can lower the pH, leading to general or pitting corrosion in carbon steel, resulting in localised thinning.	Elevated CO_2 partial pressures lower pH and accelerate corrosion, especially in liquid form. Higher temperatures increase corrosion rates until CO_2 vaporises. However, even with higher chromium levels in steels, improved corrosion resistance is not guaranteed until a minimum of 12% chromium is reached.	Carbon steel and low alloy steels.
Microbiologically Induced Corrosion (MIC)	MIC is corrosion caused by living organisms like bacteria, algae, or fungi. It often occurs with tubercles or organic substances, and the corrosion's characteristic feature is localised pitting beneath deposits or tubercles, where the organisms hide.	Microorganisms in aquatic environments often face stagnant or low-flow conditions that promote growth. They can thrive in harsh conditions, such as an oxygen deficit, exposure to light or darkness, high salt levels, a pH range from 0 to 12, and temperatures from -17°C to 113°C.	Carbon and low alloy steels, 300 and 400 Series SS, aluminium, copper and nickel base alloys.

Erosion Corrosion

Khan et al. (2019) introduced pipelines as one of the essential structural elements of refineries and petrochemical facilities. The pipe elbows with a rough surface will increase erosion-corrosion significantly.

Erosion corrosion is another possible result of the deterioration of metals caused by corrosion processes that occur directly or indirectly from the metabolic activities of MIC. Although pipeline corrosion is inevitable, it can be detected, assessed, controlled, and managed (Vanaei et al., 2017).

Galvanic Corrosion

Bimetallic corrosion is another name for galvanic corrosion. Galvanic corrosion occurs when one material comes into electrical contact with another in the presence of an electrolyte. The electrolyte contained two dissimilar materials, one serving as the anode and the other as the cathode. The electrical potential difference between the electrode reactions drives an accelerated attack on the anode metal, which dissolves into the electrolyte. As a result, the metal at the anode corrodes faster than otherwise, and the corrosion at the cathode is slowed (Kansara et al., 2018).

Stress Corrosion Cracking

SCC is a crack propagation process caused by the interaction of mechanical force with the environment. It occurs in various metallic materials and conditions and is often aided by pitting corrosion. The role of mechanical action is to accelerate and regulate the pit-to-crack transition in SS (Cui et al., 2021).

The SCC remains the leading cause of service failure in the chemical industry, affecting steam generator tubes, booster instrumentation penetrations, heater sleeves, nozzles, heat exchangers, and other components. For stress corrosion to occur, three essential components must be present: tensile stress, environment, and sensitive material. Changing these factors can often eliminate or reduce SCC susceptibility (Spisák & Szávai, 2019).

SCC is a frequent damage mechanism in ASS, and it is also the most typical mode of failure in 310S SS. The main influencing elements for the SCC of 310S SS are hydrogen and temperature. The SCC sensitivity index of 310S SS increases with temperature and peaks at 10 MPa and 160°C.

Intergranular stress corrosion cracking (IGSCC) is a corrosion attack that occurs primarily at grain boundaries. IGSCC is not apparent on the surface and must be identified by microstructural testing. Owing to the relatively high carbon concentration of the 304H base metal, the risk of IGSCC is higher than that of the lower carbon content of the 304 L grade. Sensitisation leads to IGSCC susceptibility in ASS.

Metals experienced intergranular corrosion within their interiors and at the grain boundaries. Destructive corrosion affects the metal's cross-sectional area, causing it to deteriorate (Fajobi et al., 2019).

Uchida et al. (2019) described SS IGSCC as one of plant facilities' most commonly reported material concerns. However, no significant accidents have been documented owing to meticulous inspections and maintenance, backed up by the tireless efforts of plant utilities and benders.

Table 2 shows that most metals were affected by both erosion and galvanic corrosion. Temperature and pH play crucial roles in the occurrence of erosional corrosion.

The classification of SCC damage mechanisms based on chemicals includes chloride SCC, caustic SCC, ammonia SCC, ethanol SCC, sulphate SCC, and others. However, owing to space limitations, significant information regarding these mechanisms is not provided in this discussion (API, 2011).

Table 2
Erosion corrosion and galvanic corrosion

Damage Mechanism	Description Damage	Critical Factors	Affected Materials
Erosion/ Erosion—Corrosion	Erosion-corrosion occurs when corrosion removes protective coatings, exposing metal surfaces, leading to a synergistic effect that amplifies erosion and corrosion. It can cause localised thinning of the metal surface, resulting in pits, grooves, gullies, waves, rounded holes, and valleys.	The amount of metal loss depends on factors like the velocity and hardness of the impacting medium, concentration, particle size and shape, density, and susceptibility to metal loss, which can be affected by temperature and pH.	All metals and alloys
Galvanic Corrosion	Galvanic corrosion occurs when two different metals are immersed in a suitably conductive electrolyte, such as a moist environment or soil with moisture—this form of corrosion results in crevices, grooves, or pits on the metal surface.	Galvanic corrosion requires the presence of an electrolyte, typically in a moist environment, as well as the direct contact between two different materials acting as the anode and cathode and an electrical connection between them.	Most metals are prone to corrosion, except for most noble metals.

High-temperature Damage Mechanism

High-temperature corrosion (temperatures above 220°C) is mainly caused by sulphur and acid components found in crude oil and its fractions. Sulfidation, or sulphide corrosion, is the reaction of steel and other alloys with reactive sulphur compounds such as H2S in crude oil at high temperatures.

The Sulfidation corrosion rate increases with temperature peaks around 450°C and can be observed at temperatures above around 260°C. This mechanism can affect carbon/low alloy steels and stainless steels, reducing wall thickness generally (Schempp et al., 2016). However, Baby et al. (2016) believe high-temperature sulphide corrosion is uniform when operating temperatures above 204°C with sulphur oil.

Trimborn (2016) described another most common high-temperature damage mechanism. Methane generation by interaction with carbon in steel causes High-Temperature Hydrogen Attack (HTHA) deterioration. HTHA can occur in the parent material or the weld itself and can be found in various alloys. High-temperature hydrogen corrosion is a kind of corrosion that occurs when steel is subjected to high-pressure hydrogen at a high temperature. Hydrogen atoms diffuse into the steel, combine with carbon, and generate methane gas inside the material, causing decarburisation and microcracking.

The high-temperature damage mechanism related to the material grade is also an exciting area of research. Aliprandi et al. (2020) experimented on the A335 P5 steel to determine the relationship between corrosion and temperature. They found that the remaining life of steel could be many years up to 600°C, reduce the remaining life to 700°C, and drastically reduce to a few hundred hours at 800°C.

Microstructural analyses and hardness testing findings revealed no metal matrix creep or degradation signs. This analysis eliminates the likelihood of tube failure caused solely by long-term or localised high-temperature overheating. In a nutshell, fireside corrosion is the primary cause of failure in X20CrMoV12-1 steel pipes (Almazrouee et al., 2018).

Jordan and Maharaj (2020) stated that five common damage mechanisms damage stainless steel in high-temperature service.

Creep embrittlement—Fracture ductility is an important mechanical property when stress concentrations and local imperfections (such as notches) are considered in the design. It is inversely proportional to creep and fracture strength, affecting the design of the propagation of cracks and, thus, the material's notch toughness.

Reheat cracking, also known as stress relaxation cracking, occurs in metals due to stress relaxation during post-weld heat treatment or in service at temperatures above 400°C and is most commonly seen in heavy-wall and coarse-grained areas of a welded heat-affected zone.

Sigma-phase embrittlement (SPE) is the most prevalent intermetallic phase in ASSaustenitic stainless steel. SPE is a typical high-temperature problem for austenitic alloys, as high-temperature service promotes the creation of this hard, brittle, nonmagnetic phase over time. When exposed to temperatures in the range of 595°C to 760°C, the formation of a sigma-phase in ASS of series 304H is unavoidable. The amount of sigma-phase formation and the rate at which the sigma-phase forms are faster and more significant in stabilised grades 321H and 347H SS than in 304H and 316H SS.

Sensitisation is the degradation of the alloy's integrity, and chromium depletion occurs near carbides precipitated at grain boundaries during welding in this situation. ASS becomes sensitised when subjected to temperatures between 400°C and 815°C.

The Process Plants Inspection Method/Technique

Many inspection methods are applied to the existing plant monitoring and inspection, aligned with the previously extracted damage mechanism information from API Recommended Practice 571: Damage Mechanisms Affect Fixed Equipment in the Refining Industry (API, 2011). The recommendations for prevention, mitigation, inspection, and monitoring of these specific damage mechanisms are detailed in Table 3 for the benefit of readers (API, 2011).

Table 3
Damage mechanism prevention, mitigation, inspection and monitoring methods

Damage Mechanism	Prevention/Mitigation	Inspection and Monitoring
Erosion/Erosion–Corrosion	Improve pipe design by altering shape, geometry, and material. Increase pipe diameter, streamline bends, thicken walls, and add replaceable baffles. Enhance erosion resistance with harder alloys, hard-facing, or surface treatments for harder substrates.	VT, UT, RT, IR and on-line electrical resistance probes.
Galvanic Corrosion	To prevent and reduce corrosion, use proper design. Avoid touching different metals in conductive areas unless they have an excellent anode/cathode ratio.	VT, UTG
Atmospheric Corrosion	Surface preparation and coatings application play a pivotal role in ensuring the longevity of materials in corrosive environments through long-term protection.	VT, UT
Cooling Water Corrosion	Prevention of cooling water corrosion and fouling requires proper design, operation, and chemical treatment of cooling water systems while maintaining process side inlet temperatures below 60°C.	ECT or IRIS Monitor pH, oxygen, temperatures, and hydrocarbon.
Boiler Water Condensate Corrosion	Implement oxygen scavenging treatments like catalysed sodium sulphite and hydrazine according to system pressure. Ensure proper operation of the mechanical deaerator, as a residual of the oxygen scavenger can carry oxygen into the steam generation system. If inadequate, consider an amine inhibitor treatment if scale control treatment does not manage carbon dioxide in the condensate return system.	MT and Water Analysis
CO2 Corrosion	Minimise corrosion in steam condensate systems with corrosion inhibitors, significantly condensing vapours with vapour phase inhibitors. Raising condensate pH above 6 reduces corrosion. The 300 Series SS has high corrosion resistance, but upgrading to stainless steel is needed for CO2 removal. CO2 corrosion causes operational issues, and the 400 and duplex SS exhibit corrosion resistance.	VT, UT, RT and water analyses
Microbiologically Induced Corrosion (MIC)	Microorganisms thrive in water-based systems, requiring biocides like chlorine, bromine, ozone, ultraviolet light, or customised compounds. While biocides hinder microorganism growth, ongoing treatment is vital. Maintain appropriate flow velocities, minimise low flow or stagnant zones, and keep non-water containment systems clean and dry.	visual appearance, monitor fouling

The literature review on process plant inspection focuses on high-temperature applications that could be inspected during plant operation. PAUT is another focus area that includes corrosion mapping, weld inspection, and other applications.

High-Temperature Inspection Application

Zhang et al. (2016) introduced the NDT method, which can be used to perform inspections during plant operations in a high-temperature environment. Infrared thermal imaging (IR), UT, and pulsed eddy currents can perform well at high temperatures, but PT and MT have limitations.

The solution for detecting plant corrosion during plant operation is to use ultrasonic thickness gauging (UTG), which can be used at temperatures up to 200°C. However, the uncertainties of different technicians and equipment may not be accurate at the same UTG point. The study points out that the challenge of piezoelectric and couplant is challenging to work with high temperatures, and the solution by the paper is to mount a fixed point UTG on the pipe with a waveguide and gold plate to undertake piezo material and a couplant challenge to continue corrosion monitoring up to 200°C. However, it shows productivity and only a spot thickness measurement that cannot detect localised corrosion (Cheong et al., 2017).

On the other hand, Jory (2019) reported that UTG can measure materials with surface temperatures approaching 500°C. However, Inspection of refinery equipment poses challenges owing to the high temperatures. Elevated heat levels can compromise the accuracy and efficiency of measurements. Improper handling of heat may lead to damage and the restriction of transducer life, as many can only tolerate temperatures up to 52°C.

Turcu et al. (2018) determine a workable solution for PAUT corrosion mapping during plant operation; the study approach uses a Dual Linear Probe to experiment with test samples with flat-bottom holes (FBH) up to 150°C. The results show that it is challenging when the temperature rises to 150°C. The challenge includes couplant selection, the probe contact to the hot surface time, velocity change when the temperature changes, and the PAUT scanner selection. These challenges include couplant selection, probe contact to the hot surface time, velocity change when the temperature changes, and PAUT scanner selection.

Phased Array Ultrasonic Corrosion Mapping

Turcotte, Rioux, and Lavoie (2016) compared conventional UT, PAUT and 3d scanners for tank corrosion mapping inspection. Whereas traditional UT beams report only one thickness at a time, phased array scans can generate a range of thicknesses. One of the main benefits of using a phased array for corrosion mapping is that it works the same way as an array of traditional UT probes, all aligned with precise overlap and working simultaneously. In addition to the frequency, the size and number of probe elements were the main drivers.

The advantage of the PAUT compared to conventional ultrasonic thickness measurement in terms of time and coverage emphasises that the Total focusing method (TFM) provides a more accurate image than the electronic sector scanning. It takes 2.7 hours to cover the 100 mm × 100 mm grid with a 1 mm grid, assuming one second for each measurement step with conventional ultrasonic thickness measurement. Phased array corrosion mapping can cover the same area in seconds (Ber et al., 2016).

Njelle et al. (2019) carried out the actual PAUT corrosion mapping on two separators made of carbon steel. They recorded the findings to calculate the corrosion rate and remaining life of the inspection intervals.

Jamil and Yahya (2019) experimented on a carbon steel test piece with different drill holes designed and showed that the corrosion mapping results provide good detectability. Collect and analyse basic metrics from A, B, and C scan displays in results.

Mohan et al. (2019) used the HydroFORM scanner to perform PAUT corrosion mapping because of the low productivity and low efficiency of manual UTG and because the UTG may not detect localised corrosion.

Tangadi et al. (2015) studied replacing UTG with PAUT on the corrosion mapping with a carbon steel block. Scanning speed is one of the main advantages of PAUT corrosion mapping. A single SA2-0L wedge and 5L64 probe arrangement can cover a grid width of 30 mm at a time. Compared to PAUT, based on the point scan principle, UTG requires a longer scan time to cover the same 30 mm width. The limitation of this study is the test specimen design with % wall loss in simulating the general corrosion and the absence of an experiment on the localised corrosion application.

Phased Array Ultrasonic Weld Inspection

Kim et al. (2021) studied the application of PAUT on ASS welds. NDT using ultrasound is complex due to the anisotropy and inhomogeneity of austenitic steels in the weld. Because of their complex microstructure, it is challenging to describe actual welds accurately, and they are known to contain coarse grains. Based on simulation and experimental results for six defects, only a frequency of 4 MHz can provide a reliable A-scan signal for the top crack. The lack of fusion at the top portion is identified using shear waves but not longitudinal ones. However, it can be challenging to assess faults when using shear waves due to scattered and diffracted signals.

Fousianis et al. (2018) focused on two case studies of the PAUT technique on-stream inspection to detect hydrogen-induced crack (HIC) at weldments. PAUT could provide faster inspection speed, detailed defect orientation, and recoverability, and HIC damage usually comes in three stages or types. Examples include hydrogen blisters, sparse laminar discontinuities, and massive clusters of in-plane discontinuities, which add to a surface-breaking structure.

Small-diameter pipes in power plants have small outer diameters and thin pipe walls. The conventional ultrasonic inspection makes scanning the welds difficult, leading to missed inspections. Liu et al. (2021) applied a PAUT technique to work on small diameter pipes, and the experiment concluded that the PAUT inspection could detect a 1 mm profound defect below the pipe's surface.

Phased Array Ultrasonic in Non-metallic Material

The high-density polyethene (PE) pipe is the alternative to replace metallic pipes in nuclear power plants because it has lower maintenance costs. When applying PAUT to the PE pipe, ultrasonic waves cause dispersion and attenuation because of the velocity. The PAUT detected PE defects such as cracks, poor fusion interface, void, structural deformity, and cold welding (Zheng et al., 2018).

Thorpe et al. (2018) studied the application of PAUT to PE pipe weld (butt fusion and electrofusion joints) and demonstrated the detectability and reliability.

De Almeida and Pereira (2019) experimented with the PAUT for glass fibre-reinforced polymer pipe laminated joints. The inherent anisotropy and heterogeneity of composite materials and the high absorption capacity of polymers lead to significant energy losses through scattering, deflection, and absorption, especially in thicker parts of the assembly. The experiment revealed that five out of the six artificial defects were detected. Defect six may be due to its proximity to the surface, and it was only partially spotted by the PAUT.

Like other researchers, Fetzer (2021) described the challenge of PAUT applied to carbon fibre-reinforced polymer material owing to the non-homogeneous material's properties and countered the challenge with beam steering the incident angle of PAUT. The steering angle was compensated for attenuation and a high standard deviation in the ramping zone.

Phased Array Ultrasonic in Other Applications

Singh et al. (2017) experimented on low-carbon steel (ASTM Number SA516 Gr 70) with different heat-treated samples with machined 1.5 mm side drill holes (SDH). The result shows that the noise and attenuation factor is changed with different heat treatments. The reflected amplitude signal varies in different heat-treated. It is required to apply to average and filtering for detectability improvement.

Gunasekar and Sastikumar (2020) compared the PAUT calibration by SDH and electrical discharge machining (EDM) notch. Based on ASME Section V code recommendations, the ultrasonic testing operator chooses SDH for flat components and surface notches for curved structures like pipes and tubes. Drilling SDH in curved pieces is challenging. However, this is practically doable for jobs with larger diameters and thicknesses. Only a notch is used for tubes with lesser diameters. The experiment revealed that the SDH response was good, but the notch varied up to 20 decibels (dB) depending on the probe angle.

Lozev et al. (2020) experimented on the actual HTHA defect specimens, and the results show that it can be optimised by using PAUT FMC/TFM methods. The HTHA is complicated damage that occurs locally. In carbon and low-alloy steels exposed to the high partial pressure of hydrogen at extreme temperatures, HTHA forms in welds, weld heat-affected zones, and base materials.

Galán-Pinilla et al. (2021) experimented on eight ASTM A36 carbon steel test specimens with EDM slots and a welded specimen without penetration defect to determine the PAUT signal accuracy and dimension characterisation. They found that the PAUT beam, the same as conventional UT, will get an optimised signal perpendicular to the beam and less amplitude if parallel to the sound beam.

Caulder (2018) introduced the benefit of applied PAUT FMC/TFM techniques and the evolved types, such as Advanced FMC/TFM, Adaptive TFM, and TFMp. Signal imaging is more transparent and precise than PAUT imaging. FMC is a data-collecting method, whereas TFM is a postprocessing image reconstruction procedure used for FMC data.

Bergman et al. (2018) introduced a GE Un-bored Rotor Ultrasonic system (URIS™ technology) to inspect steam turbine rotors. It shows the broad application of the PAUT technique. Both UT and PAUT require a smooth surface to carry out an inspection. Mirchev et al. (2021) introduced a scan PAUT on the rough surface by immersion technique using a water bath to serve as a couplant.

Holloway and Ginzel (2020) sought a new PAUT technique (Phased array composite angle technique) to detect corrosion under pipe support. The theory has been proven, and the researcher works on hardware and software development. Reverdy et al. (2016) introduced the most advanced PAUT technique, the TFM/FMC application and its advantages. It has an excellent ability to detect fine cracks, and the thickness measurement accuracy is about 0.5 mm.

Literature Review Summary

Figure 2 summarises the types of damage mechanisms studied by other researchers. General corrosion comprises 20% of the overall damage mechanism and is considered the second largest group of damage mechanisms. Localised corrosion includes pitting at 26%, crevice corrosion at 6%, intergranular cession at 2%, and CO_2 corrosion and naphthenic corrosion at 1%.

The pie chart shows 77% corrosion types of damage mechanisms, with galvanic corrosion at 8%, MIC at 7%, sulfidic corrosion at 3%, and erosion-corrosion at 4%. Cracks related to corrosion consist of SCC 10% and other SCC 7%. Hence, 94% of the reviewed literature revolves around corrosion type or corrosion-related damage mechanisms to answer research question one.

Similar to other research, Liu et al. (2018) studied plant failure cases between 1990 and 2017 and found that about 46% of the total failures were caused by corrosion. The most affected material by corrosion is stainless steel, which consists of 41%, followed by carbon steel, 14%, and alloy steel, 14%.

The stainless-steel summaries in this literature review consist of 26% compared with the majority of 51% of carbon steel. Other materials, such as ferritic alloy steel, low alloy steel, martensitic steel, duplex stainless steel, and copper alloys, are shown in Figure 3 for a better understanding of research question two.

PAUT is already at a mature stage and is widely recognised by the public. Currently, it is not only the initial weld inspection. It is also widely used for corrosion mapping and different base materials such as alloy and composite materials.

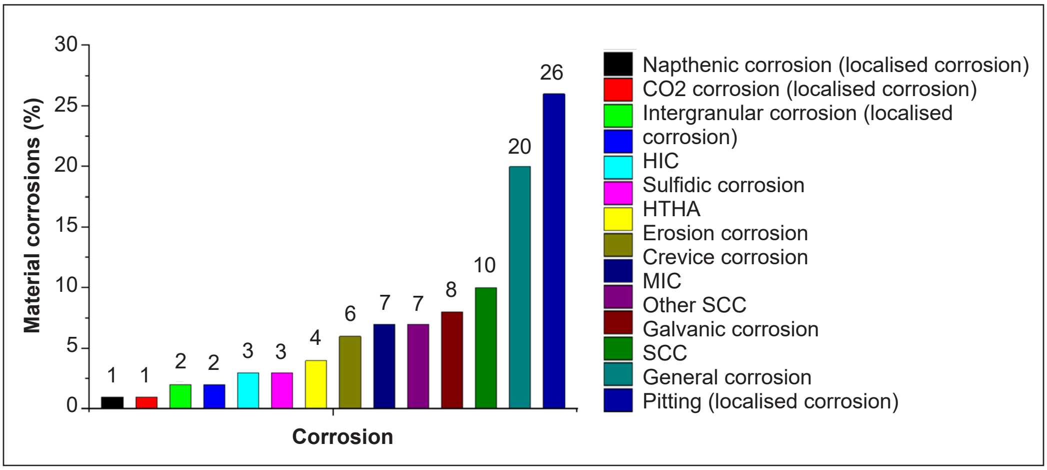

Figure 2. Type of damage mechanism studies by other researchers

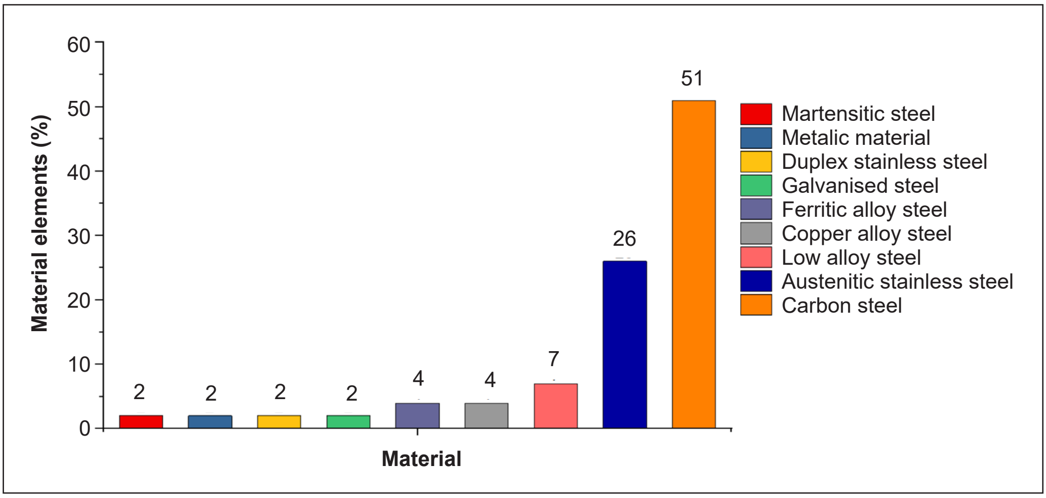

Figure 3. Damage affected material grade summaries

This review suggests a prevalent trend among researchers to substitute UTG with phased array corrosion mapping. However, it is noteworthy that most of these studies concentrate on a singular material, carbon steel, and are limited to ambient-temperature applications. It highlights a potential avenue for further exploration, as corrosion impacts various materials, and real-world plant operations often involve non-ambient temperature applications.

The typical methodology used by other researchers is to experiment on the fabricated specimen with SDH or FBH to determine the detectability. In addition, some papers introduced the new PAUT TFM/FMC application that could produce better image presentations for future studies.

CONCLUSION

In petrochemical process plant maintenance, the piping system is a larger compartment that some plant owners usually overlook among all the damage mechanisms at the process plant, either in general corrosion or localised corrosion. The corrosion-related damage, such as stress corrosion cracking, is over 80%. The affected material includes carbon steel, 300 & 310 series SS, and super duplex material.

Some UTGs that can inspect the hot material surface up to 500°C have been reported (Jory, 2019). The advantage of the UTG is that it requires less training and is easy to operate, and the equipment's cost is lower than that of other testing techniques. However, drawing and taking readings grid by grid requires more time if targeted to detect localised corrosion, which is the main disadvantage. The reading may also vary because of the probe pressure applied by the different technicians during the inspection.

On the other hand, PAUT has recently gained wide application in different industries and various materials. PAUT corrosion mapping, with the advantage of faster speed, detects general and localised corrosion reported by other researchers. The majority of the PAUT corrosion mapping is conducted at ambient temperature. Only Turcu et al. (2018) reported that the experiment on corrosion mapping carried out by Dual Linear Probe achieved up to 150°C.

The challenge in the following research on applying phased array corrosion mapping in elevated temperatures may need to be studied further by highlighting the ultrasound principle and the support from the current equipment and accessories. However, this literature review has provided a better understanding of the current damage mechanism and shows that an extended study in this area is possible.

ACKNOWLEDGEMENT

The authors thank Universiti Putra Malaysia for the financial support through Geran Inisiatif Putra Siswazah (GP-IPS) with grant number 9739200. The authors also express their gratitude to the Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, and the Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Product (INTROP), Universiti Putra Malaysia (HICoE) for their close collaboration in this study.

REFERENCES

Aliprandi, P., Guglielmino, E., & Sili, A. (2020). Mechanical characterisation of the ASTM A335 P5 steel and reliability of radiant tubes after long operating time in a petrochemical industry furnace. *Metallurgia Italiana*, *112*(10), 45-53.

Almazrouee, A. I., Al-Fadhalah, K. J., Alhajeri, S. N., & Alfehaid, S. (2018). High temperature corrosion of martensitic steel of reheater pipes in a desalination power plant. *Engineering Failure Analysis*, *85*, 89-96. https://doi.org/10.1016/j.engfailanal.2017.12.003

Ameh, E. S., Ikpeseni, S. C., & Lawal, L. S. (2018). A review of field corrosion control and monitoring techniques of the upstream oil and gas pipelines. *Nigerian Journal of Technological Development*, *14*(2), 67-73. https://doi.org/10.4314/njtd.v14i2.5

API. (2011). *API recommended practice 571: Damage mechanisms affecting fixed equipment in the refining industry*. American Petroleum Institute. https://www.apiwebstore.org/standards/571?__hstc=23321061.45041909c1713c2f47776c88c555a58e.1717118461018.1717118461018.1717118461018.1&__hssc=23321061.1.1717118461019&__hsfp=1989271524

Baby, N. V., Paricha, B., & Naik, S. J. (2016). Determination of corrosion rates and remaining life of piping using API and ASME standards in oil and gas industries. *International Research Journal of Engineering and Technology*, *3*(6), 772-777.

Ber, L. L., Benoist, G., & Dainelli, P. (2016). Corrosion detection and measurement improvement using advanced ultrasonic tools. *19th World Conference on Non-Destructive Testing*, *554*, 1-8.

Bergman, R., Mauro, A. S., & Brian, M. (2018). Advanced volumetric phased array inspection for un-bored steam turbine rotors. In *27th ASNT Research Symposium* (pp. 27-30). The American Society for Nondestructive Testing. https://doi.org/10.32548/rs.2018.002

Caulder, A. (2018). Full matrix capture and total focusing method: The next evolution in ultrasonic testing. *Materials Evaluation*, *76*(5), 591-597.

Cheong, Y. M., Kim, K. M., & Kim, D. J. (2017). High-temperature ultrasonic thickness monitoring for pipe thinning in a flow-accelerated corrosion proof test facility. *Nuclear Engineering and Technology*, *49*(7), 1463-1471. https://doi.org/10.1016/j.net.2017.05.002

Cheshideh, H., Nasirpouri, F., Mardangahi, B., & Jabbarpour, A. (2021). Failure analysis and preventive recommendations against corrosion of steel tubes of gas risers in natural gas urban distribution lines. *Engineering Failure Analysis*, *122*, Article 105240. https://doi.org/10.1016/j.engfailanal.2021.105240

Chidambaram, S., Ashok, K., Karthik, V., & Venkatakrishnan, P. G. (2018). Microbiological corrosion of ASTM SA105 carbon steel pipe for industrial fire water usage. *IOP Conference Series: Materials Science and Engineering*, *314*, Article 012027. https://doi.org/10.1088/1757-899X/314/1/012027

Colombo, A., Oldani, L., & Trasatti, S. P. (2018). Corrosion failure analysis of galvanised steel pipes in a closed water cooling system. *Engineering Failure Analysis*, *84*, 46-58. https://doi.org/10.1016/j.engfailanal.2017.10.008

Cui, C., Ma, R., & Martínez-Pañeda, E. (2021). A phase field formulation for dissolution-driven stress corrosion cracking. *Journal of the Mechanics and Physics of Solids*, *147*, Article 104254. https://doi.org/10.1016/j.jmps.2020.104254

De Almeida, P. D., & Pereira, G. R. (2019). Phased array inspection of glass fiber reinforced polymers pipeline joints. *Journal of Materials Research and Technology*, *8*(5), 4736-4740. https://doi.org/10.1016/j.jmrt.2019.08.020

Du, L., Wang, Q., Li, X., & Yan, H. (2020). Cause analysis and suggestion on corrosion leakage of pipe in atmospheric and vacuum pressure unit. *IOP Conference Series: Materials Science and Engineering*, *711*, Article 012015. https://doi.org/10.1088/1757-899X/711/1/012015

Fajobi, M. A., Loto, R. T., & Oluwole, O. O. (2019). "Crude distillation overhead system": Corrosion and control. *Journal of Physics: Conference Series*, *1378*, Article 042090. https://doi.org/10.1088/1742-6596/1378/4/042090

Fetzer, B. (2021). *Phased array beam steering techniques used for composite inspection*. The American Society for Nondestructive Testing.

Fousianis, P., Anastasopoulos, A., Bouchagier, L., Kastanis, P., Papasalouros, D., Ladis, I., & Kourousis, D. (2018, October 22-23). *Ultrasonic detection of hydrogen induced cracking (HIC) in oil and gas industry* [Conference session]. 1st International Conference on Welding & NDT, of HSNT and WGI, Athens, Greece.

Galán-Pinilla, C. A., Quintero-Ortiz, L. A., & Herrera-Ortiz, J. O. (2021). Dimensional characterisation with phased array ultrasonic testing of induced discontinuities in ASTM A36 steel by EDM and SMAW welding processes. *UIS Engineering Magazine*, *20*(3), 147-154. https://doi.org/10.18273/revuin.v20n3-2021010

Groysman, A. (2017). Corrosion problems and solutions in oil, gas, refining and petrochemical industry. *Corrosion and Material Protection Journal*, *61*(3), 100-117. https://doi.org/10.1515/kom-2017-0013

Gunasekar, S., & Sastikumar, D. (2020). Comparison of side drilled holes and surface notch response for phased array sectorial beams calibration process. *Journal of Non Destructive Testing and Evaluation (JNDE), 19*(2), 22-27.

Holloway, P., & Ginzel, R. (2020). Ultrasonic phased array approach to detection and measurement of corrosion at pipe supports. *e-Journal of Nondestructive Testing*, *25*(3), 1-10.

Mazumder, M. A. J. (2020). Global impact of corrosion: occurrence, cost and mitigation. *Global Journal of Engineering Sciences*, *5*(4), 1-5. https://doi.org/10.33552/gjes.2020.05.000618

Jamil, J., & Yahya, S. Y. S. (2019). Corrosion assessment using advanced ultrasonic measurement technique. *IOP Conference Series: Materials Science and Engineering*, *554*, Article 012004. https://doi.org/10.1088/1757-899X/554/1/012004

Jordan, P., & Maharaj, C. (2020). Asset management strategy for HAZ cracking caused by sigma-phase and creep embrittlement in 304H stainless steel piping. *Engineering Failure Analysis*, *110*, Article 104452. https://doi.org/10.1016/j.engfailanal.2020.104452

Jory, C. (2019). Tips for internal corrosion using the echo to echo technique with compression. *The NDT Technician*, *18*(3), 8-11.

Kansara, D. P., Sorathiya, A. P., & Patel, H. R. (2018). Corrosion monitoring and detection techniques in petrochemical refineries. *IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)*, *13*(2), 85-93.

Khan, R., Ya, H. H., Pao, W., & Khan, A. (2019). Erosion–corrosion of 30◦, 60◦, and 90◦ carbon steel elbows in a multiphase flow containing sand particles. *Materials*, *12*(23), Article 3898. https://doi.org/10.3390/ma12233898

Khouzani, M. K., Bahrami, A., Hosseini-Abari, A., Khandouzi, M., & Taheri, P. (2019). Microbiologically influenced corrosion of a pipeline in a petrochemical plant. *Metals*, *9*(4), Article 459. https://doi.org/10.3390/met9040459

Kim, Y. L., Cho, S., & Park, I. K. (2021). Analysis of flaw detection sensitivity of phased array ultrasonics in austenitic steel welds according to inspection conditions. *Sensors*, *21*(1), Article 242. https://doi.org/10.3390/s21010242

Liu, S. W., Lv, J. H., & Wang, W. Z. (2018). Failure cases analysis in petrochemical industry. *International Journal of Civil and Environmental Engineering*, *11*(5), 1-5. https://doi.org/10.5281/zenodo.1316600

Liu, X. Y., Su, J. L., Zhang, L., & Su, X. Y. (2021). Power plant small-diameter tube phased array inspection verification and inspection technology. *Journal of Physics: Conference Series*, *2005,* Article 012198. https://doi.org/10.1088/1742-6596/2005/1/012198

Lozev, M., Neau, G. A., Yu, L., Eason, T. J., Orwig, S. E., Collins, R. C., Mammen, P. K., Reverdy, F., Lonne, S., Wassink, C., Cence, H., & Chew, J. (2020). Assessment of high temperature hydrogen attack using advanced ultrasonic array techniques. *Materials Evaluation*, *78*(11), 1223-1238. http://dx.doi.org/10.32548/2020.me-04183

Martins, C. M. B., Moreira, J. L., & Martins, J. I. (2014). Corrosion in water supply pipe stainless steel 304 and a supply line of helium in stainless steel 316. *Engineering Failure Analysis*, *39*, 65-71. https://doi.org/10.1016/j.engfailanal.2014.01.017

Mirchev, Y., Mihovski, M., & Chukachev, P. (2021). Ultrasonic testing of rough surfaces using phased array probe. *Engineering Sciences*, *LVIII* (1), 64-79. https://doi.org/10.7546/engsci.lviii.21.01.05

Mohan, B. C., & Jeyasekhar, M. C. (2019). Oil and gas assets condition monitoring by high sensitive paut hydroform corrosion monitoring technique for integrity assessment.

Njelle, V., Ikeh, O. Cornelius, O., & Obiukwu-ıfeanyi, N. (2019). Study of corrosion rate of low and medium carbon steel pressure vessel in Nigeria oil and gas industry using ultrasonic testing (UT). *Engineering Sciences, 15*(3), 151-158.

Piri, B., Amini, R., Asadinia, E., Vardak, S., Mehdilouee, R., & Mojarrad, A. (2021). Investigation of failure mechanisms and remaining life prediction of firewater pipelines used in industrial applications. *Engineering Failure Analysis*, *124*, Article 105301. https://doi.org/10.1016/j.engfailanal.2021.105301

Reverdy, F., Benoist, G., & Ber, L. L. (2016). Advantages and complementarity of phased-array technology and total focusing method. *19th World Conference on Non-Destructive Testing 2016*, 1-8.

Schempp, P., Preuß, K., & Tröger, M. (2016). About the correlation between crude oil corrosiveness and results from corrosion monitoring in an oil refinery. *Corrosion*, *72*(6), 843-855. https://doi.org/10.5006/1940

Shafeek, H., Soltan, H. A., & Abdel-Aziz, M. H. (2021). Corrosion monitoring in pipelines with a computerised system. *Alexandria Engineering Journal*, *60*(6), 5771-5778. https://doi.org/10.1016/j.aej.2021.04.006

Shekari, E., Khan, F., & Ahmed, S. (2016). A predictive approach to fitness-for-service assessment of pitting corrosion. *International Journal of Pressure Vessels and Piping*, *137*, 13-21. https://doi.org/10.1016/j.ijpvp.2015.04.014

Shekari, E., Khan, F., & Ahmed, S. (2017). Economic risk analysis of pitting corrosion in process facilities. *International Journal of Pressure Vessels and Piping*, *157*, 51-62. https://doi.org/10.1016/j.ijpvp.2017.08.005

Singh, D., Banerjee, A., & Das, S. (2017, December 14-16). *A comparative study of PAUT and TOFD responses with the changes in microstructure of various materials - A step towards reliable detection* [Conference session]. NDE 2017 Conference & Exhibition of the Indian Society for NDT (ISNT), West Bengal, India.

Siswantoro, N., Priyanta, D., & Ramadhan, J. (2021). Implementation of risk-based inspection (RBI) in condensate separator and storage vessel: A case study. *International Journal of Marine Engineering Innovation and Research*, *6*(1), 1-10. https://doi.org/10.12962/j25481479.v6i1.7565

Spisák, B., & Szávai, S. (2019, May 23-24). *Mechanisms of stress corrosion cracking* [Conference session]. MultiScience-XXXIII MicroCAD International Multidisciplinary Scientific Conference, University in Miskolc, Hungary.

Subramanian, C. (2018). Localised pitting corrosion of API 5L grade A pipe used in industrial fire water piping applications. *Engineering Failure Analysis*, *92*, 405-417. https://doi.org/10.1016/j.engfailanal.2018.06.008

Tangadi, S., Telidevara, N. K. S. P., & Maddi, H. K. (2015). PAUT as tool for corrosion damage monitoring. *Special Issue of e-Journal of Nondestructive Testing, 22*(6), 1-7.

Thorpe, N., Acebes, M., Wylie, D., Troughton, M., Gilmour, O., Roy, O., Benoist, G., & Dweik, R. (2018). Ultrasonic phased array non-destructive testing and in-service inspection system for high integrity polyethylene pipe welds with automated analysis software. *Special Issue of e-Journal of Nondestructive Testing (eJNDT)*, *23*(8), 1-9.

Trimborn, N. (2016). Detecting and quantifying high temperature hydrogen attack (HTHA). *Special Issue of e-Journal of Nondestructive Testing (eJNDT), 21*(7), 1-4.

Turcotte, J., Rioux, P., & Lavoie, J. (2016). Comparison corrosion mapping solutions using phased array, conventional UT and 3D scanners. *Special Issue of e-Journal of Nondestructive Testing (eJNDT), 21*(7) 1-10.

Turcu, F., Jedamski, T., & Treppmann, DR. D. (2018). In-service corrosion mapping—Challenges for the chemical industry. *Special Issue of e-Journal of Nondestructive Testing (eJNDT), 23*(8), 1-8.

Uchida, S., Chimi, Y., Kasahara, S., Hanawa, S., Okada, H., Naitoh, M., Kojima, M., Kikura, H., & Lister, D. H. (2019). Improvement of plant reliability based on combining of prediction and inspection of crack growth due to intergranular stress corrosion cracking. *Nuclear Engineering and Design*, *341*, 112-123. https://doi.org/10.1016/j.nucengdes.2018.10.021

Vanaei, H. R., Eslami, A., & Egbewande, A. (2017). A review on pipeline corrosion, in-line inspection (ILI), and corrosion growth rate models. *International Journal of Pressure Vessels and Piping*, *149*, 43-54. https://doi.org/10.1016/j.ijpvp.2016.11.007

Wan, Z., & Yang, J. (2021). Research on corrosion management technology of petroleum pipeline and pressure vessel. *IOP Conference Series: Earth and Environmental Science*, *692*(4), Article 042057. https://doi.org/10.1088/1755-1315/692/4/042057

Wang, F., Shan, Q., Zhang, F., Lu, F., Li, J., Yu, T., & Qu, C. (2021). Pitting corrosion behavior of metal materials and research methods. *IOP Conference Series: Earth and Environmental Science*, *651*(3), Article 032039. https://doi.org/10.1088/1755-1315/651/3/032039

Zhang, Z. G., Feng, H. X., & Zhao, W. H. (2016). The NDT methods under high temperature service environment. *MATEC Web of Conferences*, *40*, Article 04001. https://doi.org/10.1051/matecconf/20164004001

Zheng, J., Zhang, Y., Hou, D., Qin, Y., Guo, W., Zhang, C., & Shi, J. (2018). A review of non-destructive examination technology for polyethylene pipe in nuclear power plant. *Frontiers of Mechanical Engineering*, *13*, 535-545. https://doi.org/10.1007/s11465-018-0515-9