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DEVELOPMENT OF PLANT INTEGRITY INSPECTION ON THE API 5L X65 MATERIAL UNDER HUMID CONDITIONS: EMERGING FITNESS FOR SERVICE ASSESSMENT APPROACH

Sidhi Aribowo
Corresponding author
Master of Science, Senior Engineer
Prof Johny Wahyuadi Laboratory*
E-mail: saribowo@gmail.com

Johny Wahyuadi Soedarsono
Doctor of Engineering, Professor
Prof Johny Wahyuadi Laboratory*

Christy Sicilia
Master of Engineering, Senior Engineer
Pertamina International EP
Gatot Subroto Kav str., 32-34, Jakarta, Indonesia, 12950

Rini Riastuti
Doctor of Engineering, Senior Lecturer
Prof Johny Wahyuadi Laboratory*

Agus Paul Setiawan Kaban
Master of Engineering, Graduate Student
Prof Johny Wahyuadi Laboratory*

*Department of Metallurgical and Materials Engineering
Universitas Indonesia
Kampus Baru UI Depok, Jawa Barat, Indonesia, 16424

This work reports the development and corresponding monitoring of pipeline integrity inspection in the arid zone, which typically experiences external corrosion. The recent method poses the challenge which indaquate to synchronize the internal and external corrosion monitoring of API 5L X65 material trunklines and flowlines owing to imperfect types of inspection on the external progressive damage only. Red-clay soil, soil porosity, oxygen content, and moisture become critical parameters for controlling the corrosion of the above conditions. The combination of ultrasonic guided wave test, visual inspection, and design life calculation is implemented to address the above challenges. Based on the results, trunkline B (12-inch) is more severe than A (18-inch), with the shorter measured remaining thickness and remaining life of 4.35 mm and 1.9 years. External corrosion and visual inspection results show that sand threatens corrosion. The external corrosion product is evident at the 3 and 6 o'clock positions, corresponding to the exposure of the buried pipelines to moisture. The maximum metal loss in the trunk is 14.5 %, which confirms the environment of trunkline B. The internal corrosion has little effect on the integrity of the plant.

Despite the three fluid phases inside the flowlines and trunklines, the measured corrosion rate on the coupon is relatively lower. The highest recorded corrosion rate is 0.443 mmpy, while the contribution to internal corrosion from the rest of the monitor well is insufficient. This research is designed to model the strategy to utilize instrumentation of Ultrasonic tests and human intervention in corrosion mitigation

Keywords: corrosion mitigation, external corrosion, flowline-trunkline corrosion mitigations, plant integrity, ultrasonic inspection

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1. Introduction

Pipeline integrity is critical to ensure the natural gas, hydrocarbon, and the source of energy delivered [1]. As an integral part of ensuring safer operation, the regular and recurring inspection frequency is essential to conduct on a time frame basis. Moreover, the fitness-for-service assessment is equally vital, particularly in assessing the structural integrity of flowlines and pressure vessels. It is beneficial to hindering unprecedented flaws or defects during their service [2]. However, it is noteworthy to remember that the defects or anomalies primarily may appear to be corrosion. When the bare metal is in contact with the environment and carrying electrolytes, the corrosion process begins, leading to metallic properties degradation [3]. Accordingly, without stringent inspection and monitoring, threatens the integrity of pipelines. The recent report of the Corrosion Engineers Organization claims that industrial losses due to corrosion raise an extra expenditure of the domestic gross product by around 5 % [4]. Therefore, it is pristine to conduct inspections and monitoring, which are integrated with the reparation plan when the defects are beyond the maximum allowable operation condition, including the pressure and thickness.

Inline inspections (ILI) and long-range ultrasonic testing (UT) are known as practical inspection tools. Typically, the intelligent system had been implemented to assess and analyze the distribution of corrosion attacks and their spatial defects when long-distance measurements were conducted [5]. With this in mind, ILI is categorized as a non-destructive examination to identify corrosion, cracks, and corrosion products responsible for mitigating pipeline failure [6]. This recent achievement technology allows the tool deployment and moves along the pipeline to capture the sizes and anomalies of the in-service pipelines. On the other hand, most engineers worldwide have expressed interest in using UT to inspect and characterize materials degradation and defects at various sizes [7]. In this work, the ultrasonic test implies the Ultrasonic guided waves, which provide the flowline defect screening and are typical of non-destructive tests. In this instance, the mechanical wave propagates throughout the structure being inspected to use the minimum ultrasound frequency to minimize the requirement for transducers and human intervention [8].

However, utilizing UT to control the external corrosion inspection has not been sought, and how their utilization helps to prevent the integrity of oil and gas plants. It is essential to note that this work focuses on utilizing UT and external corrosion inspection. In this instance, the tool develops the sensor, and it becomes an important aspect to detect the frequency. The ultrasonic coupling is achieved when the mechanical or pneumatic pressure is re-applied to the transducers to maintain contact with the inspected pipe [9]. Moreover, the guided wave is propagated due to the wave's frequency and the material's thickness to detect the thickness change in the pipe wall. Therefore, research on the development of external corrosion is relevant using ultrasonic technology and becomes more scientifically sound when applied to mitigate corrosion.

2. Literature review and problem statement

The paper of [10] presents the study result that the oil and gas pipelines are prone to failure risk, from diverse operating conditions to unforeseen defects when dealing with liquid and hydrocarbon energy transportation, showing that the industry thrives on tackling the effect of corrosion since it is a widespread issue, especially for pipelines. Corrosion is an electrochemical process that involves direct contact between the metals and the environment when water or electrolyte appears. However, there were unresolved issues related to the condition of the trunklines and flowlines. Focus on factors corresponding to corrosion mitigation under humid conditions can reveal any existing non-conformity in inspection methods that may cause external and internal corrosion events. Particularly, in the event of restricted access to pipelines, the non-destructive testing of UT can unveil flaws, including their size. Corrosion prevention is recognized as the primary solution to cause extensive expenses involving cathodic protection [11]. Cathodic protection is an urgent need to address external corrosion when the coating defect cannot protect the metal to restore the initial potential of metals against corrosion. Inspection using non-destructive [12] and destructive methods, however, is beneficial to reveal the condition of the trunkline, which is attributed to their recent internal condition, without shutting down the production. For instance, the utilization of ultrasonic and ILI to reveal any potential defects internally. While external corrosion is critical, internal corrosion. The most common treatment to remedy internal corrosion is injecting corrosion inhibitors to form a film, which passesivates the metals and protects the metal internally [13]. The scaling problem can endanger the flowline as the precipitation of $FeSO_4$ and $FeCO_3$ can form it. In this case, the scale inhibitor provides the resistance of the pipelines from the deposition of carbonate and sulfate (scales), which may lower the flow rate of the fluid. The scale inhibits the likeliness of precipitation of carbonate and sulfate in the inner side of flowlines [14]. Since corrosive gases such as CO_2 and H_2S are inevitable to dissolve in water, the gas corrosion inhibitor is most likely to interfen the corrodent by forming cationic surfactants on the surface of metals and contains imidazole derivative compounds [15].

Oil and gas industry operations have now structured their strategy to overlay their plan to mitigate internal and external corrosion. The recent standard practices of NACE SP0169-2007 [16] and ANSI/NACE SP0502-210 [17] govern the standard for controlling and assessing external corrosion for the industry. The NACE standard provides a guideline for the effective control of external corrosion when submerged using a few strategies such as coatings and cathodic protection. In comparison, the ANSI/NACE standard emphasizes the external corrosion direct assessment to unveil the impact of external corrosion to assert the pipeline integrity. Notwithstanding, the above documents require the industry to develop the time and place to mitigate the development of external corrosion. It is shown that the corrosion under arid zones is preferential due to the few possibilities of rain and the high resistivity of the soil. However, the unresolved question related to them is the corrosion management to control under the red clay soil and water content variation.

The reason can be determining the external and internal corrosion in the flowline and trunkline of the facilities, and inspection becomes a critical stage to maintain the integrity of materials. Several publications have elaborated on the significance and recommendation of the threat under arid conditions. The paper of [18] reports the method to explore various types of corrosion reinforcements in steel. The research team provides a lucid idea of the multi-state assessment of corrosion to tackle the brittle fracture issue. The probe functionality under harsh conditions at high temperatures and impact is the best model for stable corrosion measurement, as highlighted by [19]. The study includes the installation of probes to obtain substantial monitoring data to monitor the corrosion process continuously. Based on the analysis of [20], installing sensors for oil and gas flowlines to detect external corrosion cannot be undermined. They use a semicircular plastic strip and optical fiber sensor to detect the depletion of sacrificial metal in corroded areas and record the data.

However, the unresolved question is how to use the low-frequency guided waves to understand the degradation of flowlines and trunklines better. The reason can be determining the remaining life and remaining thickness is another aspect to help the engineer tackle the effect of corrosion. An option to overcome the difficulties is applying the sensor, which can effectively transmit the data before processing. The researcher [21] states that the low frequency of ultrasonic-guided waves is practical for measuring the depletion thickness of the concrete by utilizing and propagating 0–100 kHz waves. They conclude that the grouting material significantly impacts the characteristic propagation of the wave. The advantage of this method is its capability to conduct the rapid screening to nearly 50 m test range, as depicted in [22]. On the other hand, using the same method was merely applied in plate inspection using experimental and finite element simulation. The group successfully developed the defect detection method with an experimental error of above 10 % [23].

There are a few unsolved problems related to how to bridge the data of metal loss and the engineering decision to maximize the inspection, monitoring, and repair system using ultrasonic instrument on the flowline and trunkline, which may be offset by previous studies. This becomes a critical factor to determine the thinning, which occurs inside the pipeline considering the corrosion process occurrence. Accordingly, while the mentioned factor is critical, the evaluation on the damage mechanism in the internal flowline and the solution towards it is equally essential, which may not have been seen in recent studies conducted under arid conditions.

3. The aim and objectives of the study

The aim of the study is to assess the integrity of API 5L X65 pipelines with the associated risk of external corrosion in which there is continuous contact between the sand, air, and metals. This will make it possible to control the external corrosion threat of the pipelines through the inspection evaluation using long-distance ultrasonic tests in practice.

To achieve this aim, the following objectives are accomplished to make it possible:

– to calculate remaining useful life in-service compared to the metal loss defects for a better perspective and decision related to the priority of flowline and trunkline repairs using the UT instrument;

– to review the obtained data from design thickness calculation and UT test to provide a possible integrity threat investigation and recommendation based on the corrosion allowance;

– to evaluate the effect of internal corrosion of flowlines and their corresponding operational data to suggest mitigation.

4. Materials and methods

4. 1. Object and hypotheses of the study

The object of the work is API 5L X65, which is in service for the three-phase fluid (oil, gas, and water) from the well to operation surface facilities equipment. The total distance of inspection was 5,330 meters. The position of the flowlines was dwelling in the shifting dunes, road crossings, locations close to roads, and vegetation where regular water spraying was conducted. At least three areas were inspected and identified, including the 8-inchflowlines and 18-inch (A) and12-inch (B) trunklines. With 5 % CO_2 gas content, seven ppm H_2S content, and low sulfate-reducing bacteria (SRB) colonies per milliliter, external corrosion is believed to be a primary cause of the material degradation. The location conditions where the trunklines and flowlines are depicted are as follows: trunkline A is laid on the humid red clay with moderate porosity and moderate water retention, the trunkline B is buried on the red clay at a slightly lower temperature and near vegetation with high water content, and the 8-inch flowlines are laid on the sand location.

4. 2. Design thickness measurement

(1) shows the pipeline thickness calculation [24]:

$$\{S = 0.72 \times E \times SMYS\}. \qquad (1)$$

In (1), S, E, and $SMYS$ are correlated to Allowable stress value, welded joint efficiency, and Specified Minimum Yield strength. The justification of allowable stress value calculation is to measure the maximum stress of the trunkline and flowline to endure under operational normal conditions. With this in mind, under engineering condition design, the trunkline remains at their safe limits to hinder premature deformation or failure. In consonance, when the actual stress is beyond this limit, the material suspects to fail.

Meanwhile, equation (2) and (3) were used to calculate the nominal and pressure design wall thickness:

$$\{t_n = t + A\}, \qquad (2)$$

$$\left\{t = \frac{P_i \times D}{2 \times S}\right\}. \qquad (3)$$

In equation (2), t_n is the nominal wall thickness, t is the pressure design wall thickness, D is the outside diameter of the pipe (219.1 mm, 323.9 mm, 457.2 mm), A is the total allowance including their corrosion, grooving, and protection, P_i is the internal pressure of gauge. In this case, the calculation was performed only for 12-inch and 18-inch trunklines, while the 8-inch flowlines underwent visual inspection because they were buried under the soil.

4. 3. External corrosion monitoring using Ultrasonic inspection and visual inspection

Plant Integrity Teletest's essential equipment was equipped with the wireless ultrasonic focus, with 6, 8,12,16,18 collars of 5-ring torsional wave modes in this work (Fig. 1). The instrument was connected to a personal computer and was processed using additional software. The probe was hydrofoam and UT Twin Probes. Furthermore, the inspection condition is relatively low and humid and exposed to insufficient rain, with less than 4 inches per year. However, the maximum temperature was 50 °C, and the lowest was near –5 °C, and sand and wind were inevitable.

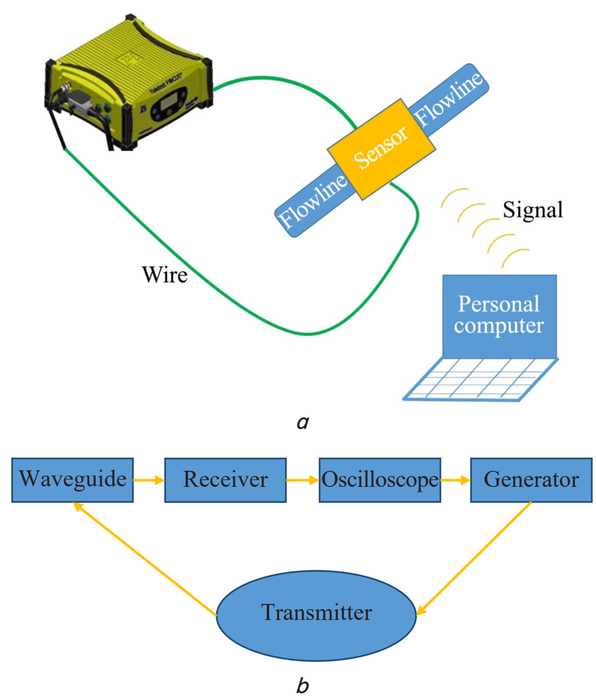

Fig. 1. The schematic illustration of: *a* – instrument and experimental ultrasonic guided wave instrument; *b* – ultrasonic operation system

It is important to note that guided wave excitation uses various modes and is enhanced by signal excitation and directional selectivity [25]. Data were collected using the standard procedure with the testing system comprising the wave generator, an oscilloscope, and twin ultrasonic transducers. In this instance, the high-temperature adhesive was used to couple the probe and the flowline surface. The Hanning window is the input signal to reduce the interference at high frequency and energy loss. Various frequencies of 120 and 200 kHz were generated using the waveform generator before it was recorded in the oscilloscope. The repetition of signal reading was recorded three times, with the highest signal providing the final reading data. Moreover, the visual inspection was performed manually to observe the possible dent, gouge, and combination to mitigate the mechanical damage.

4. 4. Internal corrosion monitoring

The effect of fluid inside the flowline and trunkline was studied. The corrosion coupon was installed in the perpendicular direction towards the fluid flow (Fig. 2). In this instance, the selected line was injected with a corrosion inhibitor at various wells (1 to 5).

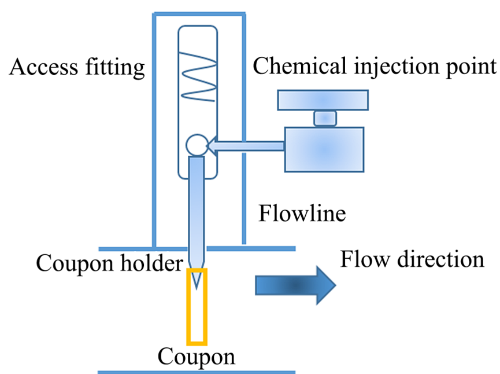

Fig. 2. The schematic illustration of the injection point to sample the fluid

In this case, several coupons were installed inside the access fitting on each flowline to monitor the effect of corrosive gasses such as CO_2 and H_2S and the result of sand or flow affecting the thickness of flowlines. Before installation, the coupon of AISI C1018 with the dimension of 1×10 cm was weighed before it was allowed in contact with the fluid.

After 90 days, the coupon was retrieved, cleansed with several solvents, and re-weighed to obtain the final corrosion rate. Equation (4) shows the calculation of the corrosion rate (*CR*) based on the NACE SP 0775 standards [26]:

$$\left\{CR = \frac{3.65\times10^5\times W}{A\times T\times D}\right\}. \quad (4)$$

In this case, *W*, *A*, *T*, and *D* are the mass loss (grams), initial exposed surface area (mm^2), exposure time (days), and density of the coupon (g/cm^3).

5. Results of the pipeline integrity inspection

5. 1. The design thickness measurements

Table 1 shows the result of the remaining thickness and remaining life of the inspected flowlines and trunkline.

Based on the above result, it is evident that trunkline A has better protection than that of 12 inches as it possesses a longer remaining life and minimal thickness (Table 1). The visual inspection result showed that the sand and moisture in the humid area dominate the root cause of corrosion, as highlighted in [27]. Accordingly, the commissioning date, which reaches over a decade, implies that the trunkline is prone to corrosion.

Table 1

The result of the most severe wall reduction based on UT and visual inspection

Types of line	Nominal thickness (mm)	Minimal thickness (mm)	Remaining life (years)	Inspection result
A	11.80	4.55	2.9	External corrosion due to sand
B	11.80	4.35	1.9	External corrosion with no sand but moist

Fig. 3 shows the result of the visual inspection of 8-inch flowlines, which represents the effect of corrosion. CA1 and CA2 imply the corrosion anomaly in areas 1 and 2.

The thickness of the corrosion product dominates the three and six o'clock positions, and the spans are observed simultaneously. The buried pipe was gradually exposed to the environment and experienced general corrosion in this location. Also, the influence of the splashing water from the surrounding area due to nearness to vegetation damages the carbon steel [28]. According to the visual survey, the anomalies were found in at least two locations, 20.48 m and 21.88 m away from the initial inspection. A possible reason for the anomalies is the third-party intervention and road crossing. Moreover, a metal loss feature is claimed to have an approximate cross-sectional area equivalent to 9 % of the pipe wall cross-section.

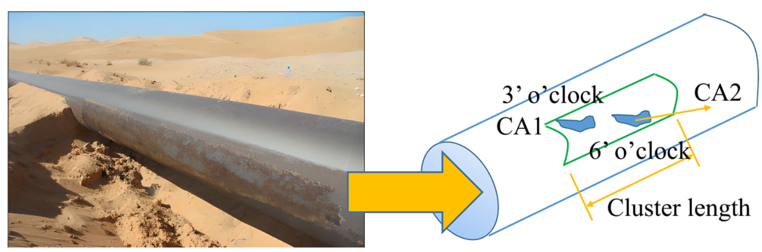

Fig. 3. The visual inspection of the 8-inch flowlines

5. 2. External corrosion monitoring using Ultrasonic inspection and visual inspection

Fig. 4 shows the metal loss of the 18-inch and 12-inch trunklines based on UT readings and their respective metal loss results.

Based on the result of Fig. 4, *a*, the reported wall thickness was 11.65 mm using the test frequency of 54 kHz. The dead zone was 0.57 m through the forward and backward directions. The metal loss in B trunklines is generally higher than that of A. On the other hand, Table 2 shows several defects that were found during the visual inspection of the 8-inch flowlines.

Based on Table 2, the most dominating defect is external and creep at higher temperatures, typically the flowlines' characteristic under extreme humidity and temperature. It can also be noted that the consideration to simulate and measure the corrosion field provides threat assessments on the flowline system.

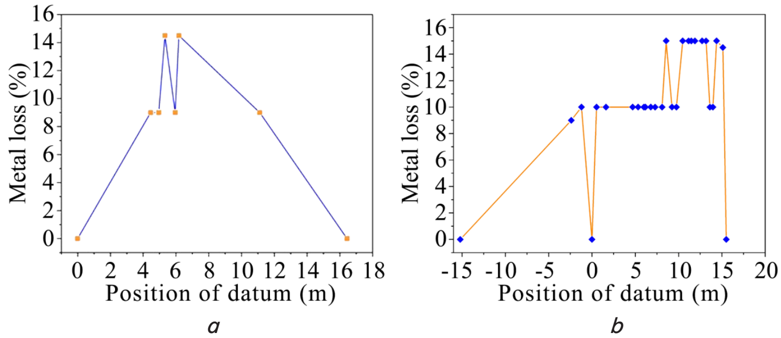

Fig. 4. The result of Ultrasonic in the form of metal loss: *a* — 18-inch; *b* — 12-inch trunklines

Table 2

The result of flowlines threat assessment

Types of anomaly	Remarks	Mitigation plan
Brittle and fracture	Negligible	Selection of material
Erosion-corrosion	Low points and gradient changes	Coupon monitoring, observation of the flow rate erosion range, and in-service inspection
External corrosion	High risk	In-service inspection
Creep and elevated temperature	High risk	Materials selection
Mechanical damage	Moderate	Mitigation by operation engineer

As depicted in Fig. 3, the grid size of measured corrosion anomalies 1 and 2 is defined as two closely spaced anomalies corresponding to external corrosion and mechanical damage (Table 2). The reported clustered pitting depth of 4.2 mm and 4.8 mm pitting corrosion is attributed to the instrument's remaining useful life (Table 1). On the other hand, the brittle and fracture are negligible as the recommendation to upgrade the SS316 L material is inevitable and reported in [29]. It is also noted that the lay section partially buried in the sand has corrosion products at the interface between the sand and air. Another type of pipe section near the vegetation is subject to pitting corrosion where the adhered scale is evident. Based on the report, salt and moisture were present in the inspected area.

5. 3. Internal corrosion monitoring results

The internal corrosion risk is an integral part of the risk due to CO_2 and H_2S gasses, and injection of inhibitor is essential. Fig. 5 shows the internal corrosion monitoring results of the plant integrity based on coupon monitoring.

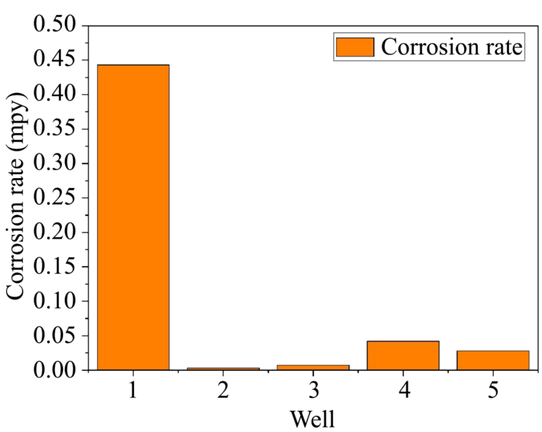

Fig. 5. The corrosion rate monitoring of the well

In this work, the corrosion rate is critical to monitoring due to the effect of corrodent, which may display anomalies and influence the overall flowlines and trunklines integrity. Fig. 5 shows the highest corrosion rate in well 1, while the rest is relatively low and moderate. The field report shows that the water cut of well 1increases the lifetime of the flowlines due to reservoir depletion.

6. Discussion of the pipeline integrity inspection

In this work, integrating internal and external corrosion inspection and monitoring is essential to tackle the effect of corrosion under harsh climate conditions. It can be noted that external corrosion is predominant compared to internal corrosion. Since the threat of internal corrosion is relatively lower, it presumes that the internal corrosion is uniform (Fig. 5). The trunkline's position lies on the sand's surface and is corrosive. Despite their nominal diameter, both materials are prone to corroding due to porosity, attributed to the aeration, dissolved salts, pH, and moisture, as stated in the visual inspection results (Table 1) [30]. Based on the calculation of the remaining useful life of the trunkline, the corrosion attack is more severe and occurs in the 12-inch trunkline and is predicted to be exposed to moisture from underground water and made possibly by a similar condition as published in [31]. The corrosion deterioration of the trunkline may also be due to the degree of saturation for the unsaturated soil when the oxygen diffusion undergoes the exposure of the metal to the atmosphere.

Fig. 3 shows the condition of the corroded surface at two distinctive locations, 3 and 6 o'clock. At six o'clock, it is possible to note the potential weak positions on the structure's right and bottom sides and indicate where the water/moisture can accumulate from pitting corrosion [32]. In addition, the 3 o'clock position reveals the contact between the soil and the metals, especially during the temperature drops, and forms moisture. Based on the illustration of Fig. 3, it is clear that corrosion anomalies 1 and 2 are established when the protection of metal is inadequate to sustain the electrochemical process. Furthermore, the possibility of water condensation and soil causes the range of pitting from 1.8–3 mm at the side of the flowlines.

Fig. 4 shows the comparison of metal loss between trunkline A and B due to the effect of corrosion and confirms the results of Table 1. The characteristics of red clay soil are more corrosive than alkaline soil, as reported in [33]. The combination of high temperatures during summer and the corrosive substances increases the corrosion rate of the metal in the soil environment and humid conditions. Hence, the metal loss of trunkline B is more severe than A. The investigation features of trunks A and B show that the clustered pitting varies depending on the corrosion susceptibility. The vegetation that retained more water content quickens the process of corrosion.

Table 2 reveals the anomalies that aligned with the metal loss and remaining life calculations. The corrosion pit depth is more likely observed in the external condition with a possible recommendation for material selection. On the other hand, mechanical damage is an additional effect of the shorter remaining life of the trunkline. In this condition, mechanical damage such as dents and gouges damages the passive layer as the protection of the metal [34]. However, the lower content of corrosive gases contributes to the partial degradation of material due to the lower corrosion rate (Fig. 5). The higher corrosion rate should be considered as the variation sampling conditions where the remarkable chloride content in soil may increase the corrosion rate.

The limitation of this study is the elaboration to assess the plant's integrity under humid conditions only where the level of rain is limited. It makes it possible that the water content is tiny and may not threaten the trunk and flowlines. It is also important to note the application UT-guided works on the specified dent and corroded area, although the types of NDT test are vulnerable to tampering. For example, the UT application scope can detect internal discontinuities (dents) without damaging the coating system of the trunklines. In consonance, the UT technique becomes a priority to ensure the inspection is sufficient and implemented while keeping the integrity of the material at its operational level to detect internal damage when the geometric shape is suspected to change. Moreover, the UT sensor would provide the dent location, often in terms of clock position, as an indication and consequence of the failure.

Moreover, focusing on utilizing UT inspection may be a disadvantage to monitoring the corroded trunkline and flowline in the long run. It is imperative to understand the degradation mechanism in the inner side of the instrument and how far they have been degraded. Hence, to eliminate this disadvantage, the ILI inspection becomes a secondary test, which can be utilized to compare the inspection results. Moreover, the test data is another consideration when obtaining the UT inspection. Therefore, in the future, it is recommended to elaborate on how the UT inspection can be merged with machine learning algorithms to quicken the analysis of corrosion to unveil and predict the corrosion mechanism and suggest appropriate recommendations.

7. Conclusions

1. The calculated remaining useful life in-service of two trunklines shows the material is subject to highly corrosive corrodent. Based on the guided wave UT test, trunkline B requires immediate corrosion mitigation and prevention since the remaining useful of trunkline A and B is 2.9 and 1.9 years. Based on this fact, the material requires immediate replacement.

2. Based on the UT data, the metal loss of trunk B (7.45 mm) is more significant than A's (7.25 mm) since the environmental conditions allow the metallic pathway to connect and begin the electrochemical process. The contribution of the propagation of ultrasonic waves reveals the wave propagation behavior to provide information related to the integrity and properties of trunkline B, which is more corroded. The general corrosion occurs on the side and bottom of the 8-inch flowlines as less external protection, such as coating and cathodic protection, has not been administered.

3. The internal corrosion monitoring using a corrosion coupon shows that the internal corrosion is insignificant in affecting the plant integrity. A low corrosion rate is generally observed in most of the wells, and injecting a corrosion inhibitor can mitigate a higher corrosion rate (0.443 mmpy).

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data cannot be made available for reasons disclosed in the data availability statement.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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