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Comparative Analysis of Ultrasonic Inspection Techniques for Corrosion Monitoring in Petrochemical Plants Using Analytic Hierarchy Process (AHP)

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ABSTRACT

Selecting non-destructive inspection methods for corrosion monitoring and detection in petrochemical plants frequently relies on personal preferences rather than a rigorous assessment of the underlying rationale for specific testing techniques. Unchecked corrosion can lead to catastrophic failure; however, many of these inspection techniques are inefficient. Plant owners often struggle to select an inspection technique that is both time-efficient and provides good detectability. This study applied the Analytical Hierarchy Process (AHP) to identify the best ultrasonic testing technique for corrosion monitoring in process plants. Three techniques were evaluated: pulse-echo ultrasonic testing (UT A-Scan), ultrasonic thickness gauging (UTG), and phased-array ultrasonic testing corrosion mapping (PAUT-CM). Four attributes—time efficiency, defect detection, accuracy, and personnel training time—were identified from an initial set of eight attributes through expert surveys to construct the AHP framework. PAUT-CM demonstrated the highest efficiency, detectability, and accuracy, while UTG had the lowest training requirements. The AHP results indicated that PAUT-CM achieved the highest score of 0.4846, reflecting its effectiveness in extensive corrosion mapping scenarios. In contrast, UTG or UT A-Scan may yield higher scores in situations where only a limited number of spot detections are required. By implementing the systematic approach proposed in this study, engineers can mitigate subjective bias and make informed decisions when selecting the most suitable testing method.

Keywords: AHP, non-destructive testing, phased array ultrasonic testing, ultrasonic testing

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INTRODUCTION

Petrochemical plants have long encountered deterioration problems (Groysman, 2017), mainly due to the metallic material being the main application for fabrication and the environment being surrounded by corrosive substances such as carbon dioxide (CO_2), which is mainly produced from combustion processes and chemical reactions, and hydrogen sulfide (H_2S), generated during crude oil refining, sour gas processing, and certain wastewater treatment processes (Zhao et al., 2018).

The current industry increasingly utilizes advanced materials, such as glass fiber-reinforced and polyethylene composite pipes, to replace metals and mitigate corrosion issues. However, carbon steel remains the most widely used material due to its favorable mechanical properties and low cost (Ameh et al., 2018). Common failures in industrial settings stem from equipment aging, fatigue, and corrosion, which, if not properly managed, can lead to serious accidents, including fires, explosions, and hazardous substance leaks that pose significant risks to safety and production (Elwerfalli et al., 2016; Shih et al., 2017). Since 2000, one in five major refinery accidents in the European Union have been attributed to corrosion failure. Research by Wood et al. (2013) analyzed 99 corrosion-related accidents over the past 50 years in EU and OECD countries, emphasizing the need for ongoing vigilance regarding critical refinery equipment. Wan and Yang (2021) indicated that 80% of pressure vessel failures in plants are related to corrosion, while Laza (2017) noted that pipelines account for approximately 40% of significant plant losses, largely because many asset integrity management systems overlook piping systems in favor of more prominent components like pressure vessels and heat exchangers.

Corrosion can be classified into two main types: general and localized. General corrosion, or uniform corrosion, occurs when metal loses electrons uniformly, leading to gradual thinning of the material (Fajobi et al., 2019). This type of corrosion typically develops in the presence of chlorides, sulfides, and carbon dioxide on bare metal surfaces. In contrast, localized corrosion, specifically pitting corrosion, is characterized by small diameter but deep pits (Tai, Grzejda, et al., 2023). The detection of localized corrosion is particularly challenging, as it involves a process of pitting nucleation, metastable pit development, and steady-state pitting (Wang et al., 2021). If large pits are ignored, they can lead to leaks once they penetrate the material (Du et al., 2020; Shekari et al., 2017). Various non-destructive testing (NDT) methods, such as ultrasonic inspection, are utilized in petrochemical plants for several reasons. These methods feature portable equipment, making inspections easier to conduct. They provide real-time results, facilitating immediate decision-making and minimizing operational downtime. Additionally, NDT methods are versatile and can be applied to a wide range of materials. Their non-hazardous nature ensures safe inspections without risks to personnel or the environment.

Importantly, these methods are effective in detecting internal flaws, allowing for early identification of potential issues and contributing to the overall safety and reliability of the equipment.

The propagation properties of ultrasonic waves are directly linked to the mechanical properties of materials, such as density and modulus of elasticity (Sampath et al., 2021). Ultrasonic waves are also widely used in on-stream inspections to measure material thickness, aiding in the calculation of corrosion rates and the remaining life of components (Mohan et al., 2019).

Ultrasonic inspection encompasses three primary techniques: Ultrasonic thickness gauging (UTG), Pulse-echo ultrasonic testing (UT A-scan), and Phased array ultrasonic testing corrosion mapping (PAUT-CM). UTG measures the time it takes for ultrasonic waves to travel through a material and reflect back, providing a direct reading of material thickness. However, it is limited to spot measurements, which can be time-consuming for large areas (Ber et al., 2016). The Pulse-Echo method uses a transducer to generate ultrasonic waves and detect echoes, displaying the results as an A-scan, which graphically represents the amplitude of the reflected signals and can also be used to calculate ultrasonic velocity (Bazulin & Sadykov, 2018). PAUT-CM is an advanced technique that integrates ultrasonic testing with corrosion mapping, offering detailed information on the extent and location of corrosion within materials (Jamil & Yahya, 2019). Recent studies have highlighted the efficacy of PAUT-CM in providing comprehensive corrosion assessments, demonstrating its ability to detect and precisely locate corrosion features by utilizing multiple beam angles and depths, thereby significantly enhancing the accuracy and reliability of inspections (Lamarre, 2016; Turcotte et al., 2016).

Although each of these testing techniques has distinct advantages, engineers at petrochemical sites often select a specific technique based on personal preferences, which may lead to practical variations that do not yield the desired outcomes. When asked why a particular testing technique was chosen, it is not always feasible to obtain a satisfactory answer; this may be due solely to personal choices without an in-depth evaluation of the rationale behind the selection.

This study aims to explore the requirements of petrochemical plants in detail and demonstrate the selection procedure for choosing the best testing technique through the Analytic Hierarchy Process (AHP). In comparison to existing studies that have utilized the AHP for NDT, this research demonstrates a novel application specifically centered on ultrasonic testing techniques.

For instance, studies by Omar and Nehdi (2016) and Liu et al. (2022) have highlighted the importance of criteria like capability and cost-effectiveness in NDT methods. However, they did not focus on the comparative efficiency of ultrasonic techniques in the specific context of corrosion monitoring within petrochemical plants.

This approach aims to provide a model for future petrochemical plant owners, enabling them to select a valid and convincing testing technique based on actual conditions rather than purely personal preference.

Time efficiency, defect detection, accuracy, and personnel training time were selected from eight attributes to construct the AHP based on the survey's higher score. Time efficiency is essential as it minimizes downtime, allowing plants to quickly identify and address corrosion issues, thereby maintaining productivity and reducing financial losses. The capability of defect detection is vital for preventing minor corrosion problems from escalating into major failures, ensuring the integrity of critical equipment and enhancing safety. Accuracy in measurement is crucial for making informed maintenance decisions; inaccurate assessments could lead to misguided repairs or replacements, potentially resulting in catastrophic failures. Lastly, reducing personnel training time is important for ensuring that operators can swiftly adapt to advanced testing techniques, promoting a safer working environment and more reliable inspections.

The AHP provides a structured, objective, and multi-criteria decision-making (MCDM) framework by breaking down complex decisions into manageable components. It enables decision-makers to organize their thoughts by defining a hierarchy of criteria and sub-criteria relevant to the decision at hand. Each criterion is then weighed up based on its importance, allowing for a systematic comparison of different options. AHP quantifies subjective judgments through pairwise comparisons, transforming them into numerical values that facilitate objective analysis. This process culminates in a comprehensive range of alternatives based on their overall scores, helping decision-makers identify the most suitable choice. By integrating both qualitative and quantitative assessments, AHP supports informed decision-making that considers multiple factors, ultimately leading to more robust and justifiable outcomes in selecting testing techniques for corrosion assessment in petrochemical plants.

METHODOLOGY

The methodology is divided into several key steps to determine the most effective ultrasonic testing technique for corrosion monitoring in petrochemical plants using the AHP: Survey design and administration, experimental setup, AHP analysis, and sensitivity analysis (Figure 1).

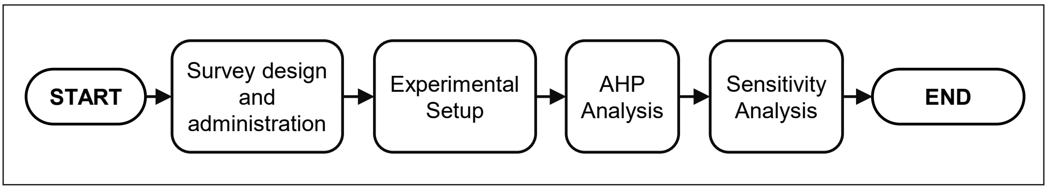

Figure 1. Process flow chart

Survey Design and Administration

The survey aimed to gain insights into the priority needs of petrochemical plants regarding NDT techniques. This information was crucial for selecting the most critical attributes for evaluating various NDT methods. Participants included two engineers from petrochemical plants, one project manager, three project engineers, one quality engineer from plant maintenance contractors, one NDT Level 3 technical manager, and two engineers from NDT companies. The survey involved two management-level candidates and eight engineers; however, they preferred not to disclose their company names.

The questionnaire was designed using the think tank method to ensure comprehensive and consensus-based feedback. This approach involved assembling a small group of experts from relevant sectors, including management-level candidates and engineers, to provide diverse perspectives. These experts participated in face-to-face discussions and video conferences to brainstorm and refine the eight attributes, along with their definitions, that were deemed important and measurable.

The survey evaluated eight attributes: cost-effectiveness, defined as low costs in terms of equipment, resources, and overall implementation; consistency, which ensures the uniform identification of defects over time and among different personnel; competence, indicating that the inspection process is conducted by qualified and certified personnel; detectability, assessing the effectiveness of identifying target defects; accuracy, highlighting the precise identification of defects; efficiency, characterized by minimal preparation and inspection time; safety, focused on minimizing potential risks; and compatibility, ensuring seamless coexistence with other industrial operations. These attributes were selected based on industry standards, expert recommendations, and their potential impact on operational efficiency and safety. Each participant rated the attributes on a scale from 1 to 8, with 8 indicating the most important attribute and 1 the least important.

The survey administration was conducted both face-to-face and via video conference to accommodate scheduling difficulties. The results revealed that “accuracy” received the highest score (73), followed by “detectability” (71), “efficiency” (64), and “competence” (50). In contrast, lower scores were assigned to “safety” (35), “compatibility” (34), “cost-effectiveness” (20), and “consistency” (13). Based on these findings, four key attributes—accuracy, detectability, efficiency, and competence—were selected to construct the hierarchical structure of AHP, as shown in the network diagram in Figure 2.

Experimental Setup

Once the four most important attributes have been identified, the next step is to assign weights to the three testing techniques, with the exception of competence, which will be assessed based on the time required to train personnel using international indicators. The other three attributes will be compared through actual experiments.

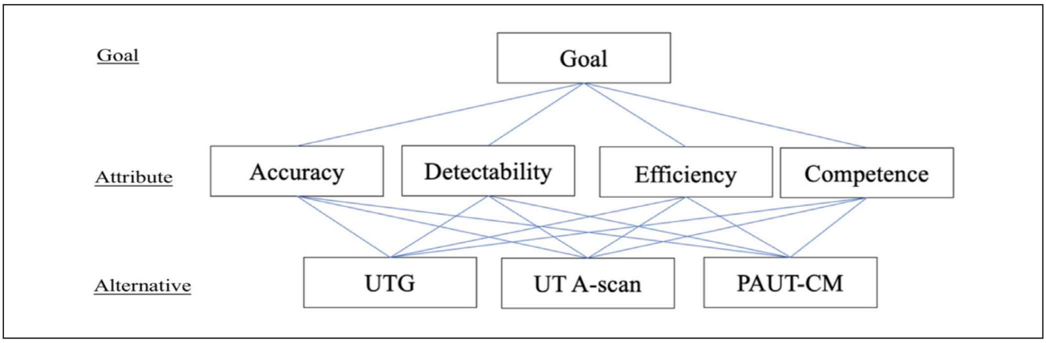

Figure 2. AHP hierarchy structure

A specimen with artificial marks was designed to compare the attribute weights of the three testing techniques (UTG, UT A-scan, and PAUT-CM). As shown in Figure 3, a 300 mm × 280 mm carbon steel plate with an uneven surface represents general corrosion, and some deep abrasion marks represent localized corrosion defects. Three different testing techniques were performed on the same specimen to obtain accuracy, detectability, and efficiency attribute weight results.

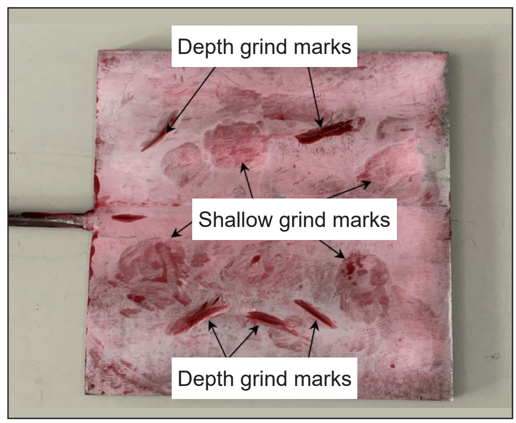

Figure 3. Artifact test specimen

Pulse-echo Ultrasonic Testing

The straight beam probe used for the experiment was a 4 MHz frequency single-crystal probe with a 20 mm diameter (Thanh et al., 2015). The test specimen was marked with a 20 mm × 20 mm grid from A1 to N15 to ensure full coverage during scanning (Figure 4). The 20 mm circle represents the probe diameter, and data was collected from the grid's center point to guarantee complete coverage.

The ultrasonic tests were calibrated using a V1 calibration block, with water used as the contact medium (Tariq et al., 2011). Three sets of readings were taken at each grid point to reduce human error; variations may have resulted from different pressures applied to the probe during the data acquisition (Wall et al., 2009). As illustrated in Figure 5, the A-scan data were referenced to the first backwall echo and verified using the second backwall echo. The total time taken to plot the grid lines and acquire data from 210 test points for a 300 mm × 280 mm test specimen using the UT A-Scan was one hour and twenty minutes, which facilitated the comparison of efficiency attributes.

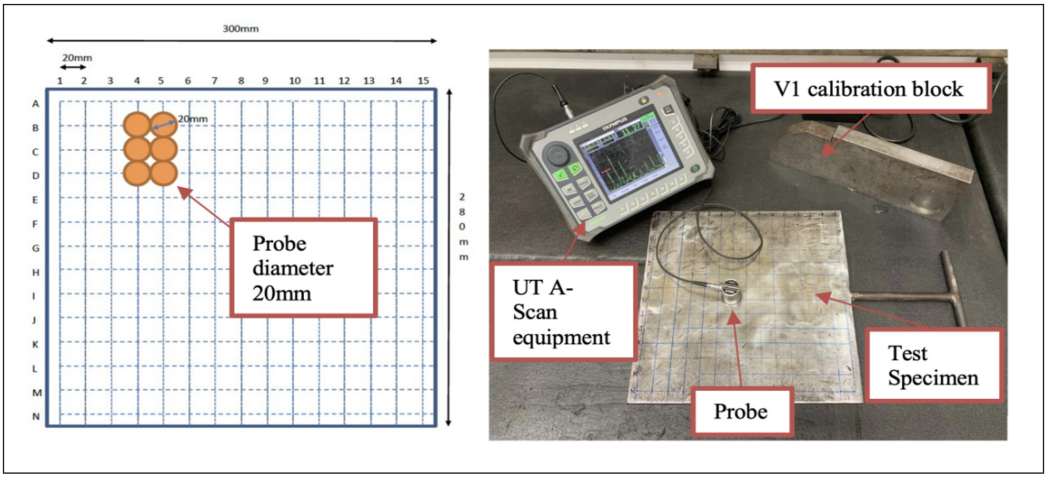

Figure 4. UT A-Scan grid line and setup

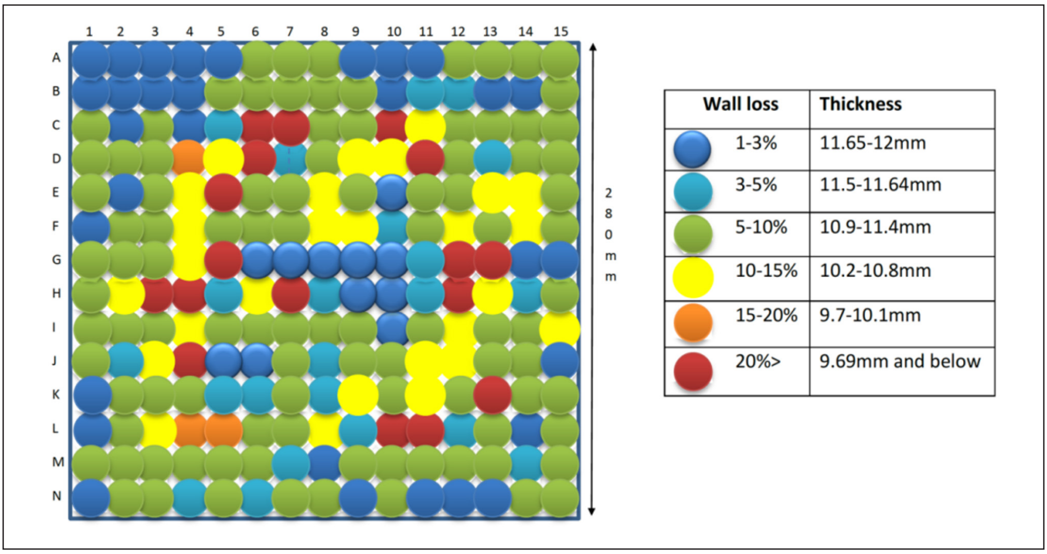

Figure 5. UT A-Scan result presentation

The UT A-Scan results demonstrated the ability to detect a thickness as low as 9.07 mm from a nominal thickness of 12 mm, which is higher than the 20% loss of wall thickness used to assess detectability attributes. To compare accuracy attributes, Figure 5 includes a specified color code to enhance visualization, which the authors added manually.

Ultrasonic Thickness Gauging

UTG is another common testing technique applied in the field to measure material wall loss (Bouchy et al., 2023). A grid was designed for UTG, similar to that used for the UT

A-scan, as shown in Figure 6. The difference was that the UTG probe had a diameter of 10 mm, resulting in a grid design of 10 mm × 10 mm.

Figure 5 illustrates a 5 MHz twin crystal probe with a 10 mm diameter using water as the contact medium. The UTG requires 783 test spots to ensure complete testing coverage of the entire test specimen. The total time taken to plot the grid lines and acquire data from the 783 points is shown in Figure 7, amounting to two hours and forty-five minutes. The authors manually plotted Figure 7 to facilitate attribute comparisons with the other testing techniques.

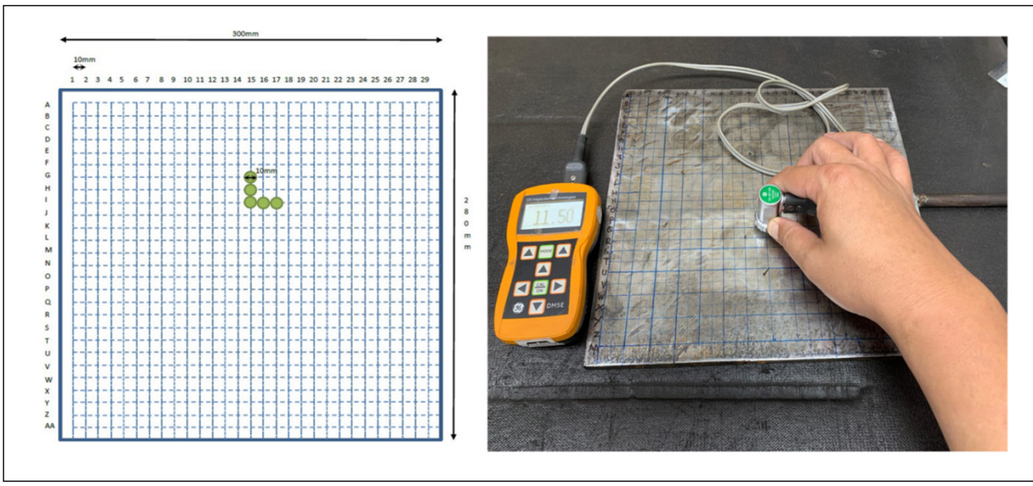

Figure 6. UTG grid line and setup

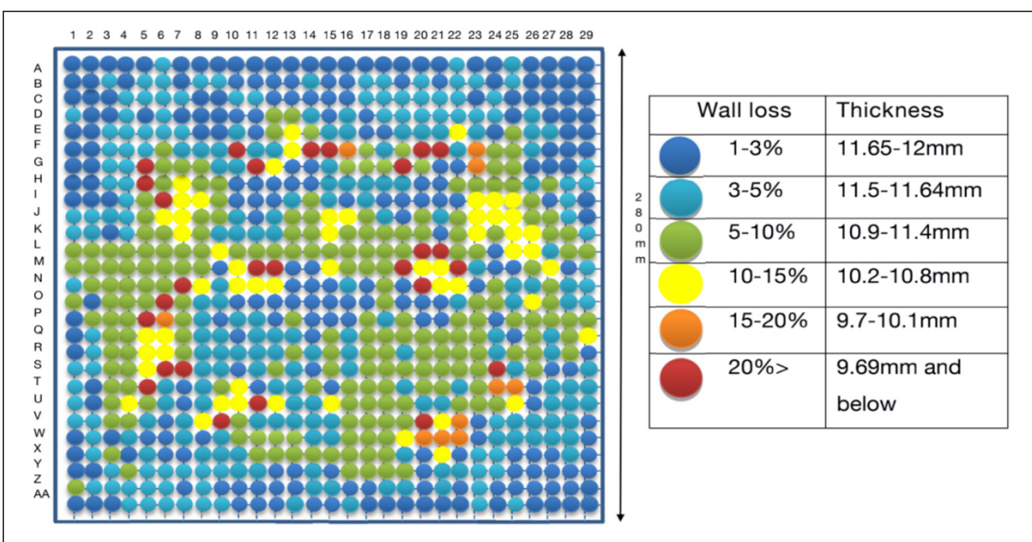

Figure 7. UTG result presentation

Phased Array Corrosion Mapping

PAUT-CM uses a 5L64 A12 probe, an SA12-0L wedge, and water as the contact medium. This technique's advantage is that it can scan a width of 30 mm in a single pass, as shown in Figure 8. Therefore, only 10 scans were required for full coverage, taking a total of 15 minutes.

The PAUT generates a plan view, which significantly reduces manual input by the author and provides a colored visual aid to identify different material depths. It allows extracted thickness readings using the cursor to point to the area of interest (Tai, Sultan, et al., 2023). As illustrated in Figure 9, the dark blue area represents the nominal material thickness of 12 mm, while the dark red indicates the thinnest area at 8.34 mm, showing a clear defect orientation. This feature enhances the accuracy and detectability attributes.

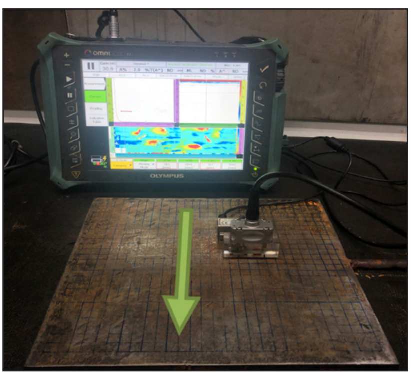

Figure 8. PAUT-CM with 5L64 A12 probe

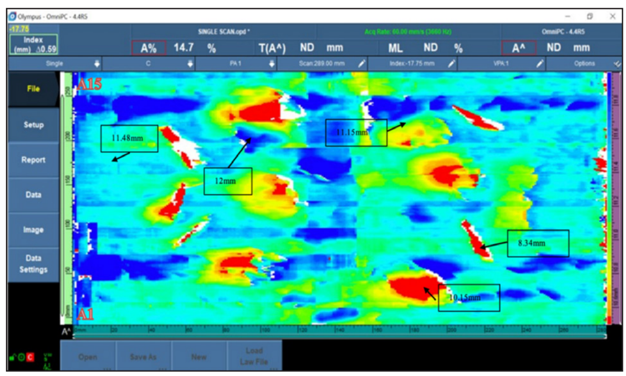

Figure 9. PAUT-CM result presentation

Summary of an Experiment Test

In terms of efficiency, the UT A-Scan required 1 hour and 20 minutes to obtain material thickness data, while the UTG required 2 hours and 45 minutes, and the PAUT-CM only required 15 minutes.

For detectability, Figure 10 illustrates a comparison of the three test techniques with the actual material surface. The labeled numbers 1, 2, and 3 represent examples constructed from the results obtained using different techniques at the same location. This comparison shows that PAUT-CM achieves a high level of detectability, accurately locating defects associated with both general and localized signs of corrosion. In contrast, the UT A-Scan has lower detectability, as it relies on a 20 mm grid size for measurements, leading to inaccurate localization, similar to a low-pixel image that exhibits low resolution. Compared to the UT A-Scan, the UTG has a higher detection and resolution owing to the smaller grid size; however, it requires more time to acquire data because of the increased number of points and additional time needed to manually transfer and record the data. Despite this, its accuracy remains lower than that of PAUT-CM.

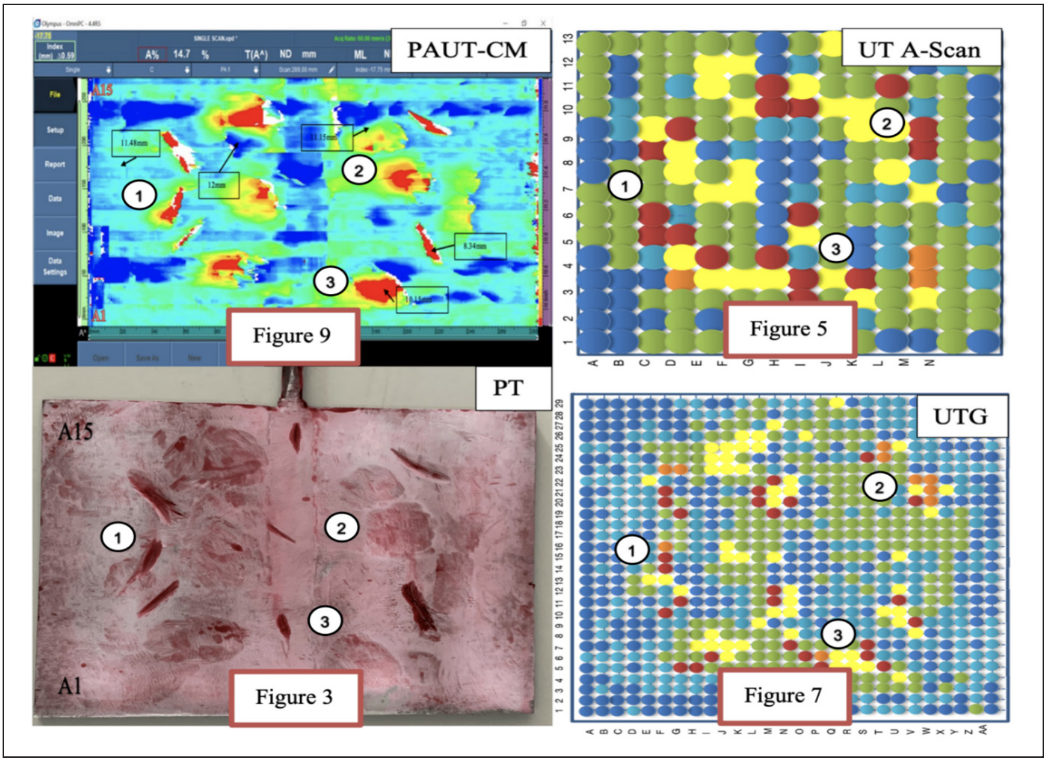

Figure 10. Compare results presentation in three techniques

The third attribute that can be compared to the experiment is accuracy. The PAUT effectively captures all actual damaged surfaces identified by the PT, and the digital cursor allows for measuring uneven surfaces and ground marks, providing depth information. Although the UTG, with its smaller diameter probe and more data points, offers better image quality and detectability than the UT A-Scan, it still showed less sensitivity due to its larger grid with fewer points, resulting in lower accuracy.

AHP Selection Criteria

The experiment assigned weights to the three attributes. In terms of the detectability attribute, PAUT-CM revealed all general and localized defects, matching both shape and location. Each participant was assigned a score of 10. UTG can detect most defects but lacks sufficient detail because the results are obtained via spot measurement; thus, a score of 7 was assigned to the UTG. A score of 4 was assigned to the UT A-Scan due to the board beam of the 20 mm diameter probe, which produced average spot thickness readings.

PAUT-CM scored 10 points for efficiency because of its fast processing capability. In contrast, UT A-Scan and UTG received scores of 5 and 3, respectively, indicating that the UTG required more time to achieve a comparable score. The advantage of 10 points for PAUT-CM is illustrated in Figure 8, which highlights its excellent accuracy. UTG received 7 points, whereas the UT A-Scan received 3 points, reflecting their noteworthy resolution capabilities.

According to the American Society for Non-destructive Testing's recommendation practice SNT-TC-1A, personnel qualification and certification in non-destructive testing require 8 hours of training to reach level 2 in UTG, 24 hours UT A-Scan, and a prerequisite to UT level 80 hours plus another 80 hours for PAUT (https://inspectioneering.com/tag/snt-tc-1a). Therefore, the highest 10 scores were allocated to UTG, followed by 8 for UT A-Scan and 5 for PAUT-CM, as summarized in Table 1 for the competence attribute.

In summary, PAUT-CM offers superior detectability and efficiency, allowing for precise identification of both general and localized defects while facilitating rapid processing. However, it requires significant personnel training, which may limit its immediate applicability in some contexts. The advantages of UTG include lower training requirements and ease of use, making it accessible for operators with less expertise. Nonetheless, it lacks the detailed information provided by PAUT-CM and may require more time to achieve comparable results. UT A-Scan is beneficial for quick spot checks and simple assessments, making it suitable for specific applications. However, its broad beam limits its ability to detect finer defects and generally offers lower efficiency and resolution compared to the other methods.

The next step was to compare the four attributes and define their importance. Detectability emerged as the most critical attribute, followed by efficiency as the second most important, and accuracy next. The least important factor is competence, primarily because Level 2 technicians can be trained before testing is conducted.

When comparing accuracy to competence, accuracy is deemed more important, as it is typically determined after the inspection site has worked with the tested data. This makes it more critical than one's competence. Table 2 shows the Saaty matrix for the attributes, including the final comparison between competence and its lesser importance (Saaty, 2004).

Table 1
Summary of attribute weight

Attribute	UT A-Scan	UTG	PAUT-CM
Detectability	4	7	10
Accuracy	3	7	10
Efficiency	5	3	10
Competence	8	10	5

Table 2
The Saaty matrix for attributes

	Detectability	Accuracy	Efficiency	Competence
Detectability (A1)	1	5/1	2/1	7/1
Accuracy (A2)		1	1/3	2/1
Efficiency (A3)			1	5/1
Competence (A4)				1

RESULTS AND DISCUSSION

In the detailed AHP matrix calculation, the scale identifies and interprets rating values 1-9 by pairwise comparison of similar element pairs at each level with criteria at the next level. Next, priority calculations were performed on the four attributes to produce the feature vectors listed in Table 3.

Table 3
The priorities calculation

C	*A1*	*A2*	*A3*	*A4*	*A1*	*A2*	*A3*	*A4*	***Sum of rows* (A)**	**A/*n* (w)**
A1	1.00	5.00	2.00	7.00	(1/1.84) = 0.5435	(5/9.5) = 0.5263	(2/3.53) = 0.5666	(7/15) = 0.4667	2.103	0.5258
A2	0.20	1.00	0.33	2.00	(0.2/1.84) = 0.1087	(1/9.5) = 0.1053	(0.33/3.53) = 0.0935	(2/15) = 0.1333	0.4408	0.1102
A3	0.50	3.00	1.00	5.00	(0.5/1.84) = 0.2717	(3/9.5) = 0.3158	(1/3.53) = 0.2833	(5/15) = 0.333	1.2041	0.301
A4	0.14	0.50	0.20	1.00	(0.14/1.84) = 0.0761	(0.5/9.5) = 0.0526	(0.2/3.53) = 0.0567	(1/15) = 0.0667	0.252	0.063
	1.84	9.50	3.53	15.00	1	1	1	1		
The sum of individual columns (S)					*Standardized matrix The sum of each column = 1*				*Eigenvector*	*Priority vector*

The priority vectors obtained from the normalized feature vectors were assigned the following weights: detectability (w1) 0.5258, accuracy (w2) 0.1102, efficiency (w3) 0.301, and competence (w4) 0.063

The consistency ratio (CR) was calculated to assess the consistency of the pairwise comparison matrix. The CR is obtained by dividing the consistency index (CI) value by the random consistency index (RI). CI is derived by comparing the principal eigenvalue of the pairwise comparison matrix (denoted as λmax) with the matrix size (denoted as n). The formula for calculating CI is (λmax − n)/(n-1). The RI values can be found in Table 4 and are recommended by Saaty (2004). If CR exceeds 10%, the evaluation may exhibit high randomness or inconsistency. Conversely, if the CR is less than or equal to 10%, the consistency of the assessment is considered acceptable.

The value of λmax represents the maximum eigenvalue of the analysis. Indicating the main factor or criterion that influences selection. The calculations for the maximum eigenvalues are presented in Table 5.

Table 4
Random consistency index

Matrix dimension	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Random consistency (RI)	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

A consistency index of 0.0066 was obtained using this algorithm. Using the RI values listed in Table 4, a CR of 0.007 was obtained. Since the CR is less than 10%, this indicates acceptable consistency in the assessment.

The attribute weights were normalized across the inspection techniques and are listed in Table 1. The calculation of the weighting values and the normalized attribute weights, as indicated in Table 6, presents the calculated normalized attribute weights. These weights are used further to determine the higher score testing technique, as shown in Table 7. According to AHP analysis, the best option was PAUT-CM = 0.4864.

The final step was to conduct a sensitivity analysis to assess the stability and robustness of the optimal solution in the event of changes in the model parameters (Balakrishnan et al., 2022). The first scenario involved altering the weighting method: What if all the weights were equal? The results in Table 8 indicate that the PAUT-CM scores were higher at 0.4373.

The second scenario examines what happens if the efficiency weight of the UTG increases while the efficiency weight of the UT A-Scan remains unchanged and the PAUT-CM efficiency weight decreases due to the higher weight achieved by PAUT-CM. Table 9 lists the equal-importance techniques for the UTG and PAUT-CM. In this scenario, the

Table 5
Maximum eigenvalues calculation

Eigenvector (w)	w1(0.5258)	w2(0.1102)	w3(0.301)	w4(0.063)
The sum of individual columns (S)	1.84	9.50	3.53	15
Maximum eigenvalue (λmax)	(1.84x0.5258) + (9.50x0.1102) + (3.53x0.301) + (15x0.063) = 4.02			

Table 6
Normalize attributes weight

	Competence	Norm	Efficiency	Norm	Accuracy	Norm	Detectability	Norm
UT A-Scan	8	0.3478	5	0.2778	3	0.15	4	0.1905
UTG	10	0.4348	3	0.1667	7	0.35	7	0.3333
PAUT-CM	5	0.2174	10	0.5555	10	0.5	10	0.4762
	23	1	18	1	20	1	21	1

Table 7
The higher scores in testing technique

	Detectability	Accuracy	Efficiency	Competence	Evaluation Results
Weighting Values	0.5258	0.1102	0.301	0.063	-
UT A-Scan	0.1905	0.15	0.2778	0.3478	0.2222
UTG	0.3333	0.35	0.1667	0.4348	0.2914
PAUT-CM	0.4762	0.5	0.5555	0.2174	0.4864
	1	1	1	1	1

weight of efficiency for UTG has increased from 0.1667 to 0.4904, whereas the weight for PAUT-CM is reduced from 0.5555 to 0.2318.

The third scenario considers what happens if the detectability weight of UTG increases while the detectability weight of the UT A-Scan remains unchanged and the PAUT-CM detectability weight decreases since the detectability weighting values comprise half of the overall weight. Table 10 lists the equal-importance techniques for the UTG and PAUT-CM. In this scenario, the detectability weight for UTG is increased from 0.3333 to 0.0.5187, whereas the weight for PAUT-CM is reduced from 0.4762 to 0.2908.

The PAUT-CM technique scored the highest, primarily because efficiency, detectability, and accuracy were ranked at the top among the three inspection techniques. Although competence had the least attribute of weight, it was the least important factor contributing to the overall result.

Table 8
Sensitivity checks with equal weighting values

	Detectability	Accuracy	Efficiency	Competence	Evaluation Results
Weighting Values	0.25	0.25	0.25	0.25	-
UT A-Scan	0.1905	0.15	0.2778	0.3478	0.2415
UTG	0.3333	0.35	0.1667	0.4348	0.3212
PAUT-CM	0.4762	0.5	0.5555	0.2174	0.4373
	1	1	1	1	1

Table 9
Sensitivity checks with adjusted efficiency parameter weight

	Detectability	Accuracy	Efficiency	Competence	Evaluation Results
Weighting Values	0.5258	0.1102	0.301	0.063	-
UT A-Scan	0.1905	0.15	0.2778	0.3478	0.2222
UTG	0.3333	0.35	0.4904	0.4348	0.3889
PAUT-CM	0.4762	0.5	0.2318	0.2174	0.3889
	1	1	1	1	1

Table 10
Sensitivity checks with adjusted detectability parameter weight

	Detectability	Accuracy	Efficiency	Competence	Evaluation Results
Weighting Values	0.5258	0.1102	0.301	0.063	-
UT A-Scan	0.1905	0.15	0.2778	0.3478	0.2222
UTG	0.5187	0.35	0.4904	0.4348	0.3889
PAUT-CM	0.2908	0.5	0.2318	0.2174	0.3889
	1	1	1	1	1

A special feature of the AHP method is that the final result also changes when attribute weights change. In this case, PAUT-CM was chosen mainly because a longer detection time and relatively large area were required.

Our findings indicate that the PAUT-CM technique outperforms traditional methods like UTG and UT A-Scan in terms of detectability and efficiency. Specifically, PAUT-CM achieved a time efficiency improvement of approximately 80% over UTG, significantly reducing operational downtime during inspections.

Moreover, the AHP analysis revealed that PAUT-CM provided better detectability and allowed for rapid identification of both general and localized corrosion defects, confirming its superiority compared to methods previously analyzed in the literature. This systematic approach enhances decision-making and addresses the critical need for effective corrosion monitoring strategies in the petrochemical industry.

However, if the job requirements and circumstances have changed, and the new case involves checking only a few points for thickness measurements while requiring new technicians to be trained, then UTG or UT A-Scan may score higher. This is because the order of importance in the new scenario has shifted. PAUT-CM requires 20 times more training time than UTG, and since only point readings need to be checked, the advantage of PAUT-CM in terms of fast-checking times diminishes. Point readings can be reported without accuracy issues, making the other techniques more suitable for such a case.

This study establishes a foundational framework that offers novel insights for petrochemical engineers. Engineers can select an appropriate technique by considering practical requirements and available resources, such as the quantity and volume of materials to be tested, scheduling constraints, and the necessity for training personnel. Moreover, this systematic approach can be extended to other testing methods employed within petrochemical plants.

CONCLUSION

This study presents a systematic selection method aimed at determining the most appropriate ultrasonic detection technique based on predetermined parameters, by experimentally testing three ultrasonic inspection techniques to provide reliable data and evidence for the advantages and limitations of each technique.

The key outcomes of this study are as follows:

1. PAUT-CM Superiority: The PAUT-CM technique emerged as the most effective method, scoring the highest in detectability, accuracy, and efficiency. PAUT-CM's ability to provide detailed corrosion assessments and fast-processing capability make it a superior choice for comprehensive inspections.
2. Efficiency and Accuracy: PAUT-CM significantly outperformed UTG and UT A-scan in terms of efficiency, requiring only 15 minutes for full coverage compared

to 2 hours and 45 minutes for UTG and 1 hour and 20 minutes for UT A-scan. Additionally, PAUT-CM demonstrated superior accuracy in detecting general and localized corrosion defects.

3. Training Requirements: While PAUT-CM requires more extensive personnel training, its advantages in detectability and efficiency justify the investment. UTG and UT A-scan, though requiring less training, lack the detailed information and speed provided by PAUT-CM.
4. AHP Analysis: The AHP analysis confirmed PAUT-CM as the optimal choice, with a final score of 0.4864, followed by UTG at 0.2914 and UT A-scan at 0.2222. Sensitivity analysis further validated the robustness of these results.
5. Practical Implications: This study offers a foundational framework for petrochemical engineers to select appropriate testing techniques based on practical requirements and available resources. The systematic approach can be extended to other testing methods employed within petrochemical plants, promoting informed decision-making and enhancing overall safety and reliability.

By adopting the systematic approach proposed in this study, engineers can overcome subjective bias and make informed choices when selecting an appropriate testing method. This enhances the overall decision-making process, promotes reliability, and increases the effectiveness of field inspections. It is hoped that this research will introduce the concept of AHP to a broader engineering audience, empowering them to make more informed and reliable decisions in the future.

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REFERENCES

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), Article 67. https://doi.org/10.4314/njtd.v14i2.5

Balakrishnan, T. S., Sultan, M. T. H., Naveen, J., Shahar, F. S., Najeeb, M. I., Shah, A. U. M., Khan, T., & Sebaey, T. A. (2022). Selection of natural fibre for pultruded hybrid synthetic/natural fibre reinforced polymer composites using analytical hierarchy process for structural applications. *Polymers*, *14*(15), Article 3178. https://doi.org/10.3390/polym14153178

Bazulin, E. G., & Sadykov, M. S. (2018). Determining the speed of longitudinal waves in an isotropic homogeneous welded joint using echo signals measured by two antenna arrays. *Russian Journal of Nondestructive Testing*, *54*(5), 303–315. https://doi.org/10.1134/S1061830918050029

Ber, L. L., Benoist, G., & Dainelli, P. (2016, June 13-17). Corrosion detection and measurement improvement using advanced ultrasonic tools. In *19th World Conference on Non-Destructive Testing* (pp. 1–8). Munich, Germany.

Bouchy, S., Zednik, R. J., & Belanger, P. (2023). Ultrasonic transducers for in-service inspection and continuous monitoring in high-temperature environments. *Sensors*, *23*(7), 1–13. https://doi.org/10.3390/s23073520

Du, L., Wang, Q., Li, X., & Yan, H. (2020). Cause analysis and suggestion on corrosion leakage of pipe in atmospheric and vacuum pressure unit. In *IOP Conference Series: Materials Science and Engineering* (Vol. 711, No. 1, p. 012015). IOP Publishing. https://doi.org/10.1088/1757-899X/711/1/012015

Elwerfalli, A., Khan, M. K., & Munive, J. E. (2016). A new methodology for improving TAM scheduling of oil and gas plants. *Lecture Notes in Engineering and Computer Science*, *2224*, 807–812.

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

Groysman, A. (2017). Corrosion problems and solutions in oil, gas, refining and petrochemical industry. *Koroze a Ochrana Materialu*, *61*(3), 100–117. https://doi.org/10.1515/kom-2017-0013

Jamil, J., & Yahya, S. Y. S. (2019). Corrosion assessment using advanced ultrasonic measurement technique. In *IOP Conference Series: Materials Science and Engineering* (Vol. 554, No. 1, p. 012004). IOP Publishing. https://doi.org/10.1088/1757-899X/554/1/012004

Lamarre, A. (2016, June 13-17). High-resolution corrosion monitoring for reliable assessment of infrastructure. In *19th World Conference on Non-Destructive Testing* (pp. 1–7). Munich, Germany.

Laza, K. (2017). The piping integrity management challenge. *Inspectioneering Journal*, *23*, 1-11.

Liu, D., Gong, C., Tang, Y., Jian, Y., Cao, K., & Chen, H. (2022). Evaluation of corrosion damage in sulfate-attacked concrete by CT, ultrasonic pulse velocity testing and AHP methods. *Sensors*, *22*(8), Article 3037. https://doi.org/10.3390/s22083037

Mohan, B. C., Jeyasekhar, M. C., Duhan, K., Land, I., Belait, K., & Manager, C. (2019, December 4-5). Oil and gas assets condition monitoring by high sensitive PAUT hydroform corrosion monitoring technique for integrity assessment. In *Proceedings of the Singapore International NDT Conference & Exhibition* (pp. 1-8). Singapore.

Omar, T., & Nehdi, M. (2016, June 1-4). Resilient infrastructure evaluation of NDT techniques for concrete bridge decks using fuzzy analytical hierarchy process. In *2016 Annual Conference of the Canadian Society for Civil Engineering* (pp. 1-10). London, UK.

Saaty, T. L. (2004). Decision making - The analytic hierarchy and network processes (AHP/ANP). *Journal of Systems Science and Systems Engineering*, *13*(1), 1–35. https://doi.org/10.1007/s11518-006-0151-5

Sampath, S., Dhayalan, R., Kumar, A., Kishore, N. N., & Sohn, H. (2021). Evaluation of material degradation using phased array ultrasonic technique with full matrix capture. *Engineering Failure Analysis*, *120*, Article 105118. https://doi.org/10.1016/j.engfailanal.2020.105118

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

Shih, J. Y., Hsiao, S. Y., & Chang, T. P. (2017). Life cycle guideline of petrochemical plant underground piping system. In *MATEC Web of Conferences* (Vol. 119, p. 01004). EDP Sciences. https://doi.org/10.1051/matecconf/201711901004

Tai, J. L., Grzejda, R., Sultan, M. T. H., Łukaszewicz, A., Shahar, F. S., Tarasiuk, W., & Rychlik, A. (2023). Experimental investigation on the corrosion detectability of A36 low carbon steel by the method of phased array corrosion mapping. *Materials*, *16*(15), Article 5297. https://doi.org/10.3390/ ma16155297

Tai, J. L., Sultan, M. T. H., Tarasiuk, W., Napiórkowski, J., Łukaszewicz, A., & Shahar, F. S. (2023). Ultrasonic velocity and attenuation of low-carbon steel at high temperatures. *Materials*, *16*(14), Article 5123. https://doi.org/10.3390/ma16145123

Tariq, F., Naz, N., Baloch, R. A., & Faisal. (2011). Characterization of material properties of 2xxx series Al-alloys by non destructive testing techniques. *Journal of Nondestructive Evaluation*, *31*(1), 17–33. https://doi.org/10.1007/s10921-011-0117-5

Thanh, P. V., Nhung, P. T. T., Thuy, L. T. M., & Nhai, N. H. (2015). Effect of temperature on ultrasonic velocities, attenuations, reflection and transmission coefficients between motor oil and carbon steel estimated by Pulse-echo technique of ultrasonic testing method. *VNU Journal of Science: Mathematics - Physics*, *31*(4), 39–48.

Turcotte, J., Rioux, P., & Lavoie, J. (2016, June 13-17). Comparison corrosion mapping solutions using phased array, conventional UT and 3D scanners. In *19th World Conference on Non-Destructive Testing 2016* (pp. 1–10). Munich, Germany.

Wall, M., Burch, S., & Lilley, J. (2009). Human factors in POD modelling and use of trial data. *Insight: Non-Destructive Testing and Condition Monitoring*, *51*(10), 553–561. https://doi.org/10.1784/insi.2009.51.10.553

Wan, Z., & Yang, J. (2021). Research on corrosion management technology of petroleum pipeline and pressure vessel. In *IOP Conference Series: Earth and Environmental Science* (Vol. 692, No. 4, p. 042057). IOP Publishing. 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. In *IOP Conference Series: Earth and Environmental Science* (Vol. 651, No. 3, p. 032039). IOP Publishing. https://doi.org/10.1088/1755-1315/651/3/032039

Wood, M. H., Arellano, A. V., & Wijk, L. V. (2013). *Corrosion-related accidents in petroleum refineries: Lessons learned from accidents in EU and OECD countries.* European Union. https://doi.org/10.2788/37909

Zhao, W., Zhang, T., Wang, Y., Qiao, J., & Wang, Z. (2018). Corrosion failure mechanism of associated gas transmission pipeline. *Materials*, *11*(10), Article 1935. https://doi.org/10.3390/ma11101935

APPENDIX

Questionnaire for Survey on NDT Techniques

This survey aimed to gather insights into the priorities and needs of petrochemical plants regarding non-destructive testing (NDT) techniques for corrosion monitoring. This survey aimed to identify the most important attributes associated with various ultrasonic testing techniques. The findings from this survey will inform the Analytic Hierarchy Process (AHP) used in this study, ensuring that the selected ultrasonic testing techniques align with the industry's most pressing needs and preferences. The results will ultimately contribute to the development of a systematic approach for selecting the most suitable corrosion monitoring methods, minimizing subjective bias and enhancing operational efficiency.

Section 1: Participant Information

Name
Position
Company (optional)
Years of Experience

Section 2: Attribute Evaluation

Please rate the following attributes on a scale from 1 to 8, where 1 indicates the least important and 8 indicates the most important for corrosion monitoring.

Attribute	Description	Rating (1-8)
Cost-effectiveness	The overall costs are associated with the equipment, resources, and implementation of the testing technique.	
Consistency	The ability to uniformly identify defects over time and across different personnel.	
Competence	Qualification and certification levels are required for personnel conducting the inspection.	
Detectability	The effectiveness of the testing technique in identifying target defects.	
Accuracy	The precision in identifying defects and providing reliable data.	
Efficiency	The time required for preparation and inspection is relative to the area being tested.	
Safety	The potential risks involved in the inspection process.	
Compatibility	The ability of the testing method to integrate seamlessly with other industrial operations.	

Section 3: Additional Comments

1. What attributes do you consider most critical for NDT techniques in petrochemical plants?
2. Do you have any other suggestions or comments regarding NDT techniques?