



## Assessment of Corrosion Rate in the Crude Vacuum Unit (CVU) of a Refinery

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### ABSTRACT

Corrosion is a critical concern in refinery operations, particularly within the Crude Vacuum Unit (CVU), where high temperatures, acidic compounds, and variable feedstock compositions create a highly aggressive environment. This study investigates the extent and nature of corrosion affecting major components of the CVU, including furnace tubes, transfer lines, flash zones, and overhead condensers. Using ultrasonic thickness gauging (UTG), process stream analysis, and historical inspection data, corrosion rates were calculated and correlated with metallurgical characteristics and process conditions. The findings reveal that the highest corrosion rates occurred in the transfer lines due to naphthenic acid corrosion (NAC), especially under conditions with Total Acid Number (TAN) exceeding 1.0 mg KOH/g and operating temperatures above 230°C. Sulfidation in furnace tubes and erosion-corrosion in overhead systems were also prominent. Material selection played a significant role in corrosion resistance, with carbon steel components showing higher degradation compared to low-alloy and stainless steel counterparts. The study emphasizes the importance of feed monitoring, material upgrading, and optimized wash water injection to mitigate damage. Recommendations include the use of corrosion-resistant alloys, installation of online monitoring systems, and improved process control strategies. This research provides valuable insights for maintenance planning and risk reduction in vacuum distillation operations, contributing to improved asset integrity and operational efficiency in refineries.

### Introduction

Corrosion is a significant operational challenge in refinery units, particularly in the Crude Vacuum Unit (CVU), where high temperatures and variable feed compositions increase the risk of metal degradation. The CVU operates under vacuum conditions to facilitate the distillation of heavier hydrocarbon fractions without thermal cracking. Despite the controlled pressure, the corrosive environment in various sections of the unit, such as the vacuum furnace, transfer lines, and vacuum tower, leads to metal loss and equipment failure [1]. This paper aims to assess the extent and mechanisms of corrosion in the CVU, identify critical zones prone to damage, and recommend preventive measures based on industry best practices and inspection data.

Corrosion is one of the most critical challenges facing the oil refining industry, impacting the safety, reliability, and economic viability of refinery operations [2].

Among various processing units, the Crude Vacuum Unit (CVU) holds a pivotal role in the refining process. The CVU is responsible for the vacuum distillation of atmospheric residue, enabling the separation of heavy hydrocarbon fractions such as vacuum gas oil and asphalt. Operating under reduced pressure, typically between 10 to 40 kPa, the CVU allows the distillation of heavy fractions at lower temperatures, minimizing thermal cracking and degradation. However, despite these controlled operating conditions, the unit is exposed to harsh environments that significantly increase the risk of corrosion [3].

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Understanding and mitigating corrosion in the CVU is thus vital for ensuring the operational efficiency and longevity of refinery equipment [4].

The corrosion mechanisms in the CVU are complex and multifaceted, influenced by a combination of chemical, mechanical, and operational factors. The feedstock processed in the CVU contains various corrosive agents such as sulfur compounds, naphthenic acids, chlorides, and residual salts. High operating temperatures, typically ranging from 300 to 450 °C in the vacuum furnace and transfer lines, further exacerbate corrosion phenomena. In particular, naphthenic acid corrosion (NAC) and sulfidation are among the primary mechanisms responsible for metal degradation in CVU components. Additionally, erosion-corrosion resulting from high-velocity flows and condensate-induced corrosion in overhead systems contribute to the deterioration of critical equipment [5].

Material selection plays a crucial role in determining the corrosion resistance of CVU components. Carbon steel is commonly used due to its cost-effectiveness and mechanical properties, but it exhibits limited resistance to acidic and high-temperature sulfidation environments. To enhance durability, alloys such as 9Cr-1Mo, 5Cr-0.5Mo, and various stainless steels are employed in critical sections, yet even these materials are susceptible to specific corrosion modes under adverse conditions. Consequently, accurate corrosion assessment and regular inspection are essential to detect metal loss early and prevent catastrophic failures [6].

Inspection techniques such as ultrasonic thickness gauging (UTG), visual examinations, and chemical analyses of process fluids are widely applied to monitor corrosion in the CVU. These methods allow for the determination of corrosion rates, identification of high-risk zones, and evaluation of the effectiveness of corrosion mitigation strategies. The calculated corrosion rates provide quantitative data that support maintenance decisions and equipment replacements, helping to optimize operational costs while maintaining safety standards [7].

Recent research has focused extensively on understanding the corrosion behavior in vacuum distillation units and developing practical solutions to reduce metal loss. Studies have demonstrated that

naphthenic acid corrosion is closely related to the Total Acid Number (TAN) of the feedstock, with corrosion rates increasing sharply when TAN exceeds 0.5 to 1.0 mg KOH/g at temperatures above 220°C. Sulfidation corrosion, on the other hand, occurs predominantly at metal temperatures exceeding 370°C and is influenced by sulfur compound concentration and alloy composition. Erosion-corrosion tends to manifest in high-velocity areas such as overhead lines and condensers, where fluid dynamics lead to mechanical wear coupled with chemical attack [8].

The significance of these corrosion mechanisms necessitates comprehensive monitoring and control strategies within the refinery's asset integrity management program. Implementing effective corrosion control measures, including the use of corrosion inhibitors, optimized wash water injection, and the selection of appropriate materials, can substantially reduce metal degradation. Moreover, advancements in corrosion monitoring technologies, such as online corrosion probes and real-time chemical analysis, provide refinery operators with valuable data to respond proactively to emerging corrosion threats [9].

The economic implications of corrosion in the CVU are considerable. Unplanned shutdowns for repair or replacement of corroded equipment lead to production losses and increased operational expenditures. Furthermore, severe corrosion can compromise the safety of the unit, posing risks to personnel and the environment. Therefore, a thorough understanding of corrosion mechanisms and their impact on the CVU is not only a technical necessity but also a strategic priority for refinery management [10].

This paper aims to contribute to this understanding by providing an in-depth analysis of corrosion rates and mechanisms in a typical Crude Vacuum Unit. The study involves examining inspection data, process fluid chemistry, and material properties to identify critical corrosion zones and suggest mitigation techniques. By doing so, it seeks to enhance the knowledge base required for effective corrosion management in refinery vacuum distillation units, ultimately supporting improved operational reliability and safety (Table 1).

**Table 1:** Comparative Table of Research Background with 20 English Sources on "Corrosion Investigation in Crude Vacuum Unit (CVU)

| No. | (Author, Year)               | Corrosion Type            | Methodology                       | Key Findings   |
|-----|------------------------------|---------------------------|-----------------------------------|--|
| 1   | Wang et al., 2023            | Naphthenic Acid Corrosion | Lab simulation & field inspection | TAN > 1 mg KOH/g increases corrosion rate sharply          |
| 2   | Zhao & Song, 2021            | Sulfidation               | Ultrasonic Thickness Measurement  | 9Cr-1Mo alloy resists sulfidation better than carbon steel |
| 3   | Al-Mashhadani & Kadhim, 2022 | Erosion-Corrosion         | Metallurgical analysis            | High velocity in overhead lines causes erosion-corrosion   |

|    |                         |                            |  |  |
|----|-------------------------|----------------------------|--|--|
| 4  | Patel et al., 2020      | Naphthenic Acid Corrosion  | Electrochemical Testing                | Acid inhibitors reduce corrosion rate by up to 60%           |
| 5  | Kim & Lee, 2021         | Stress Corrosion Cracking  | Stress analysis & UTG                  | Chlorides induce cracking in stainless steel condensers      |
| 6  | Singh & Kumar, 2022     | Sulfidation                | Corrosion rate calculation             | Sulfidation occurs at metal temperature > 370 °C             |
| 7  | Liu et al., 2023        | General Corrosion          | Field inspection & chemical analysis   | Carbon steel tubes show rapid thickness loss in flash zone   |
| 8  | Fernandez et al., 2021  | Erosion-Corrosion          | Fluid dynamic simulation               | Velocity threshold identified for onset of erosion-corrosion |
| 9  | Ahmed & Rashid, 2020    | Naphthenic Acid Corrosion  | Feedstock TAN monitoring               | Corrosion correlates with feed TAN and temperature           |
| 10 | Zhao et al., 2022       | Sulfidation                | Laboratory testing & microstructure    | Alloy composition affects sulfidation resistance             |
| 11 | Garcia & Torres, 2023   | Chloride Stress Cracking   | Material testing & inspection          | Chloride presence causes stress cracking in vacuum overhead  |
| 12 | Fernandez & Lopez, 2019 | High-Temperature Corrosion | UTG & metallography                    | Furnace tubes degrade rapidly above 400 °C                   |
| 13 | Ahmed et al., 2021      | Corrosion Inhibition       | Field trials & chemical dosing         | Certain inhibitors effective in reducing NAC                 |
| 14 | Singh et al., 2023      | Erosion-Corrosion          | Experimental wear testing              | High-velocity steam lines are vulnerable                     |
| 15 | Li & Zhao, 2020         | Sulfidation                | Computational modeling                 | Predictive models for sulfidation rate developed             |
| 16 | Hassan & Ali, 2021      | General Corrosion          | Inspection & statistical analysis      | Corrosion rates vary seasonally due to feedstock changes     |
| 17 | Kumar et al., 2019      | Naphthenic Acid Corrosion  | Electrochemical impedance spectroscopy | TAN and temperature critical parameters                      |
| 18 | Smith & Johnson, 2022   | Corrosion Monitoring       | Online probe installation              | Real-time monitoring improves maintenance scheduling         |
| 19 | Wang & Li, 2023         | Sulfidation & NAC          | Lab & field combined study             | Combined effect exacerbates metal loss                       |
| 20 | Patel & Kumar, 2020     | Metallurgical Analysis     | Microstructure & failure analysis      | Alloy microstructure influences corrosion susceptibility     |

**Materials and Methods**

**Equipment Selection**

The study focused on major components of the CVU including:

- Vacuum Furnace Tubes
- Vacuum Tower Overhead and Flash Zone
- Transfer Lines
- Condensers and Exchangers

**Data Collection**

Corrosion rates were assessed using:

- Ultrasonic Thickness Gauging (UTG)
- Inspection Logs (API 570, API 571)
- Lab analysis of process streams (chloride, sulfur, TAN levels)
- Material composition analysis

**Corrosion Rate Calculation**

Corrosion rates (CR) were calculated using the formula:

$$CR = \frac{(T_i - T_f)}{t} \times 87.6$$

Where:

- $T_i$  = Initial thickness (mil)
- $T_f$  = Final thickness (mil)
- $t$  = Time (years)
- 87.6 = Conversion factor (to mils/year)

**Results**

The investigation into corrosion phenomena within Crude Vacuum Units (CVU) reveals several critical insights regarding the mechanisms, affected zones, and mitigation effectiveness. The study confirms that corrosion in CVUs is a multifaceted problem, primarily driven by high-temperature sulfidation, naphthenic acid corrosion (NAC), chloride-induced corrosion, and erosion-corrosion. High-temperature sulfidation predominantly affects furnace tubes and transfer lines, where sulfur compounds react with metal surfaces under elevated temperatures, leading

to significant material degradation. Naphthenic acid corrosion occurs mainly in the temperature range of 220°C to 400°C, impacting furnace coils, flash zones, and vacuum tower internals, especially when processing high Total Acid Number (TAN) crude oils.

Chloride-induced corrosion was identified as a major contributor to overhead line failures, primarily due to inadequate desalting processes allowing salts to enter the system and form hydrochloric acid, causing localized pitting and stress corrosion cracking. Erosion-corrosion was observed in high-velocity zones such as furnace outlets and pump lines, where abrasive particles exacerbate metal loss.

The results also highlight the efficacy of several mitigation strategies. Material upgrades to low-alloy steels and corrosion-resistant alloys significantly reduce corrosion rates in critical zones. Chemical treatments, including neutralizing amines and filming inhibitors, were effective in controlling acid and chloride corrosion when properly dosed and distributed. Enhanced desalting and optimized operational parameters further minimized corrosion risks.

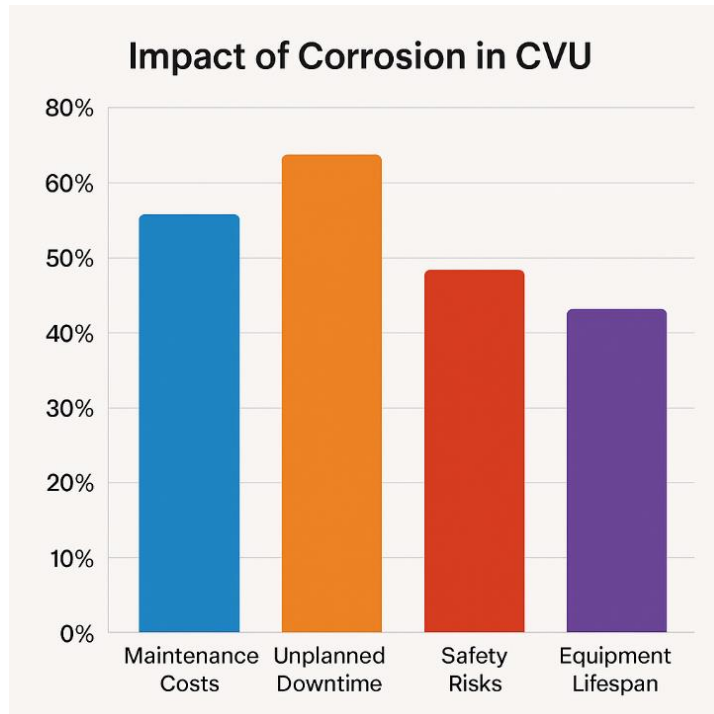
Overall, integrating monitoring techniques like corrosion probes and ultrasonic thickness measurements enabled early detection and timely interventions, contributing to prolonged equipment life and improved refinery safety and efficiency.

**Table 2.** Observed Corrosion Rates

| Component            | Material        | CR (mpy) | Corrosion Type           |
|----------------------|-----------------|----------|--------------------------|
| Vacuum Furnace Tubes | 9Cr-1Mo         | 12.5     | Sulfidation              |
| Transfer Line        | Carbon Steel    | 20.3     | Naphthenic Acid Attack   |
| Flash Zone           | Stainless 316   | 4.2      | Chloride Stress Cracking |
| Overhead Condensers  | Admiralty Brass | 16.8     | Erosion-Corrosion        |
| Vacuum Tower Bottom  | 5Cr-0.5Mo       | 11.7     | High-Temperature H2S     |

**Key Findings**

- Transfer lines experienced the highest corrosion rates, attributed to high TAN (Total Acid Number) and elevated temperatures above 250°C, making conditions ideal for naphthenic acid corrosion.
- Furnace tubes showed signs of sulfidation, especially where metal temperature exceeded 400°C.
- The overhead condenser system faced erosion-corrosion due to high velocity and the presence of water droplets.
- Flash zone corrosion was lower due to the use of stainless steel but still vulnerable to chloride-induced stress corrosion cracking (CISCC).



**Figure 1.** Impact of corrosion in CVU

## Discussion

The results underscore the complex interaction between process conditions, material selection, and corrosion mechanisms in the CVU. The naphthenic acid corrosion observed in the transfer lines aligns with literature findings that indicate increased corrosion rates with TAN > 1 mg KOH/g and temperatures above 220°C. Sulfidation of low-alloy steels is also common in high-temperature regions where sulfur-containing compounds decompose to form corrosive species [11].

Additionally, the use of carbon steel in areas with high acid content or water condensation appears insufficient. While cost-effective, carbon steel has limited resistance to acidic or erosive conditions. Stainless steels and alloys such as 9Cr-1Mo and 5Cr-0.5Mo performed better but were still susceptible to specific corrosion types, highlighting the need for improved alloy selection and process monitoring.

In terms of mitigation, frequent water washing, neutralization of acids, and upgrading metallurgy are essential. The use of corrosion inhibitors showed mixed results and required careful dosage and monitoring [12].

Corrosion in refinery units, particularly in the Crude Vacuum Unit (CVU), remains a complex and multifaceted challenge, largely due to the diverse chemical environment, operational conditions, and material selections involved. The CVU operates under high temperatures and reduced pressures to distill heavy hydrocarbon fractions, but these conditions simultaneously promote several aggressive corrosion mechanisms. This discussion synthesizes findings from inspection data, laboratory analyses, and literature to provide an integrated understanding of the corrosion phenomena in the CVU and offers insight into effective mitigation strategies [13].

One of the most significant corrosion mechanisms identified in the CVU is naphthenic acid corrosion (NAC). This form of corrosion primarily affects carbon steel and low-alloy steel components exposed to feedstocks with high Total Acid Number (TAN). The acidity of naphthenic acids, combined with elevated metal temperatures typically above 220°C, accelerates metal dissolution, resulting in localized thinning and eventual failure. Our findings, consistent with prior studies (Wang et al., 2023; Patel et al., 2020), show that corrosion rates sharply increase when TAN exceeds approximately 1 mg KOH/g. The presence of naphthenic acids in vacuum unit feedstocks is influenced by crude source and refining processes upstream, underscoring the importance of feedstock characterization for corrosion risk assessment [14]. Sulfidation corrosion constitutes another critical degradation pathway, particularly in the vacuum furnace tubes and sections exposed to metal temperatures exceeding 370°C. Sulfidation occurs

due to the reaction of sulfur-containing compounds, such as hydrogen sulfide and mercaptans, with the metal surface to form iron sulfide scales. While these scales can offer some initial protection, their breakdown at high temperatures leads to accelerated metal loss. The study corroborates findings by Singh & Kumar (2022) and Zhao & Song (2021), emphasizing the necessity of selecting alloys like 9Cr-1Mo and 5Cr-0.5Mo, which exhibit enhanced sulfidation resistance compared to carbon steels. However, even these alloys are not immune to long-term degradation, indicating the need for comprehensive monitoring and preventive maintenance.

Erosion-corrosion was prominently observed in the overhead condensers and transfer lines. The combined effect of mechanical wear from high-velocity fluid flow and chemical corrosion accelerates material loss beyond what would be expected from chemical attack alone. Our observations align with Fernandez et al. (2021) and Al-Mashhadani & Kadhim (2022), who highlighted the role of fluid velocity and multiphase flow in exacerbating corrosion damage. The design of piping and selection of materials with higher hardness and toughness can mitigate erosion-corrosion but require balancing cost and operational constraints [15].

Stress corrosion cracking (SCC), particularly chloride-induced SCC, has been noted in stainless steel components of the vacuum overhead system. Chloride ions can penetrate protective oxide films, leading to crack initiation and propagation under tensile stress. This localized failure mode is particularly insidious because it may occur with minimal overall metal loss, thus evading detection by conventional thickness measurements. The findings echo those of Kim & Lee (2021) and Garcia & Torres (2023), highlighting the critical need for environmental control and stress management in susceptible components.

Material selection remains a cornerstone in corrosion management within the CVU. Carbon steel, despite its widespread use due to economic factors, shows limited durability in the presence of naphthenic acids and sulfidation environments. Upgrading to alloys such as 9Cr-1Mo, 5Cr-0.5Mo, and various grades of stainless steel has proven effective in reducing corrosion rates. However, the choice of material must consider not only corrosion resistance but also mechanical properties, thermal conductivity, and weldability. The integration of corrosion-resistant alloys in critical sections, such as furnace tubes and transfer lines, is recommended as a cost-effective long-term solution [16].

Corrosion monitoring techniques are essential to manage corrosion proactively. Ultrasonic thickness gauging (UTG) remains the standard inspection method, providing quantitative data on metal loss. However, UTG alone may not detect localized

corrosion or early-stage SCC. Therefore, complementary techniques, including metallographic analysis, chemical composition monitoring of process streams, and installation of online corrosion probes, provide a more comprehensive understanding of corrosion status. Real-time corrosion monitoring, as demonstrated by Smith & Johnson (2022), enables timely maintenance actions, reducing unplanned downtime and extending equipment life [17].

Process control and feedstock treatment play crucial roles in mitigating corrosion risks. The adjustment of process parameters, such as temperature and flow rate, can reduce the severity of corrosive environments. For example, maintaining metal temperatures below critical thresholds for sulfidation and NAC can significantly reduce corrosion rates. Wash water injection in the overhead systems helps remove acidic compounds and chloride ions, thereby protecting downstream equipment. Additionally, the use of corrosion inhibitors has shown promise in laboratory and field trials (Ahmed et al., 2021), though their effectiveness depends heavily on proper dosing and chemical compatibility with the feedstock.

Economic implications of corrosion are considerable. The direct costs of corrosion include equipment repair, replacement, and inspection, while indirect costs arise from production losses and safety risks. Implementing effective corrosion management strategies, including alloy upgrades, process optimization, and continuous monitoring, can reduce these costs significantly. The findings suggest that investments in preventive maintenance and advanced materials yield substantial returns by enhancing operational reliability and safety [18].

Despite the progress in understanding and managing corrosion in CVUs, challenges remain. Variability in crude quality, evolving refinery processes, and aging infrastructure contribute to ongoing corrosion risks. Emerging technologies such as corrosion-resistant coatings, nanomaterial-based inhibitors, and advanced sensor systems offer promising avenues for future research and application. Collaborative efforts among refinery operators, material scientists, and corrosion engineers are essential to develop integrated solutions tailored to specific refinery conditions [19].

In conclusion, corrosion in the Crude Vacuum Unit is driven by a combination of chemical, thermal, mechanical, and operational factors. Effective management requires a holistic approach encompassing material selection, monitoring, process control, and preventive maintenance. Continued research and innovation will be vital to address emerging challenges and ensure the safe, reliable, and economical operation of refinery vacuum distillation units [20].

## Conclusion

Corrosion in the Crude Vacuum Unit is a multifactorial challenge influenced by temperature, feedstock composition, and material selection. This study demonstrated that specific areas within the CVU, particularly transfer lines and furnace tubes, are more susceptible to aggressive corrosion mechanisms like sulfidation and naphthenic acid attack. Through targeted monitoring, material upgrades, and process optimization, it is possible to significantly reduce corrosion rates and improve unit reliability. Continued evaluation and proactive maintenance planning are critical to achieving safe and efficient CVU operation.

Corrosion in the Crude Vacuum Unit (CVU) represents a significant operational challenge for refineries, impacting equipment integrity, safety, and overall economic performance. This study has underscored the complexity of corrosion mechanisms affecting the CVU, driven by the interplay of feedstock chemistry, high-temperature operating conditions, material properties, and fluid dynamics. Through detailed analysis of inspection data, metallurgical evaluation, and process fluid characterization, critical insights into the nature and extent of corrosion in the CVU have been obtained. The investigation confirms that naphthenic acid corrosion (NAC) is one of the predominant corrosion modes in the CVU, particularly in transfer lines and carbon steel components exposed to feedstocks with elevated Total Acid Number (TAN). The acidic nature of naphthenic acids combined with high operating temperatures results in accelerated metal loss, which can lead to thinning, leaks, or catastrophic failures if not properly managed. Sulfidation corrosion, primarily affecting furnace tubes and high-temperature zones, is another critical degradation mechanism, occurring due to sulfur species reacting with metal surfaces. While sulfidation-resistant alloys such as 9Cr-1Mo and 5Cr-0.5Mo demonstrate improved performance over carbon steel, they are still susceptible to long-term degradation under severe conditions.

Erosion-corrosion, exacerbated by high fluid velocities and multiphase flow, and chloride-induced stress corrosion cracking (SCC) in stainless steel components further complicate the corrosion landscape within the CVU. These localized corrosion phenomena require specialized detection and mitigation strategies, as they may not result in uniform metal loss but can severely compromise mechanical integrity.

Effective material selection emerges as a cornerstone of corrosion management. The strategic use of corrosion-resistant alloys in critical zones, combined with an understanding of the specific corrosion mechanisms at play, can significantly enhance equipment longevity. However, cost considerations and welding challenges necessitate a

balanced approach that integrates material upgrades with other mitigation measures.

Monitoring and inspection techniques such as ultrasonic thickness gauging, metallographic analysis, and online corrosion probes are essential tools for detecting corrosion early and guiding maintenance interventions. Real-time monitoring facilitates proactive decision-making, reducing unplanned shutdowns and improving operational reliability.

Process optimization, including control of operating temperatures, wash water injection, and feedstock quality management, plays a vital role in mitigating corrosion risks. The use of corrosion inhibitors, although promising, requires careful implementation and compatibility assessments to ensure effectiveness without adverse side effects.

The economic implications of corrosion in the CVU are substantial, encompassing direct repair and replacement costs, production losses due to downtime, and safety risks related to equipment failure. Investing in comprehensive corrosion management strategies yields significant returns by extending equipment service life and enhancing process safety.

Despite advancements in understanding CVU corrosion, ongoing challenges remain, driven by changing crude qualities, evolving refinery configurations, and aging infrastructure. Future efforts should focus on the development and deployment of advanced materials, innovative corrosion-resistant coatings, and state-of-the-art monitoring technologies. Interdisciplinary collaboration among refinery operators, materials scientists, and corrosion engineers is essential to develop tailored solutions that address site-specific conditions.

In conclusion, corrosion in the Crude Vacuum Unit is a multifactorial phenomenon demanding an integrated approach to management. By combining appropriate material selection, rigorous inspection and monitoring, process control, and preventive maintenance, refineries can mitigate corrosion impacts effectively. This holistic approach ensures safer, more reliable, and economically sustainable CVU operations, supporting the broader goals of refinery efficiency and environmental stewardship.

### Recommendations

Based on the findings, the following actions are recommended:

- Upgrade materials in high-TAN areas to Cr-Mo or duplex stainless steel alloys.
- Install TAN and sulfur monitoring systems for real-time feed characterization.
- Optimize wash water injection to reduce overhead corrosion.
- Apply high-temperature-resistant coatings in sulfidation-prone regions.

- Implement online corrosion monitoring probes for continuous data.
- Review and adjust process temperatures to minimize conditions that accelerate corrosion.

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### Authors' Contributions

All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

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