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Methodology for Measuring Corrosion Growth of Drill Rods in Operating Conditions †

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Abstract

This article proposes a methodology for rapid measurement of corrosion growth in drill rods. Oil and gas production in real field conditions is associated with frequent interruptions, measurements, failures, and, above all, high risk. Usually, methods used to determine corrosion growth are time-consuming and expensive. In field conditions, it is useful to immediately determine the rod condition. This will ensure accident-free operation over an extended period and will provide security to personnel and facilities. In addition, increasing security will improve technical, economic, and social positive effects. Therefore, this is done to achieve sustainable development criteria. Applying on-site measurement methods avoids continuous tracking of temperature, pressure, and other factors related to corrosion rate. The proposed methodology supports high-efficiency oil and natural gas production and environmental protection, in accordance with sustainable development criteria. It provides a good basis for future development not only for the workers to implement new methods of work tracking but also for the company to achieve increased efficiency in mining. Future work includes validating the methodology with real measurements and building a rod wear model.

Keywords: corrosion; sensors; inhibitor protection; rods

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1. Introduction

Metal corrosion is one of the most significant factors determining the reliability, safety, and economic efficiency of equipment in the oil and gas industry. Drill rods operate in media with high mineralization, dissolved gases, and variable temperature–pressure regimes, while being subjected simultaneously to chemical attack and intensive mechanical loading [1]. In this context, acid treatments with hydrochloric acid (HCl) are technologically important for improving well productivity, but they represent the most aggressive corrosion stage for steel string elements [2].

During acid treatments, aqueous HCl solutions (typically 10 ÷ 32%) are introduced into the well; they effectively dissolve carbonate minerals and remove blockages in the near-wellbore zone [3]. At the same time, HCl is an electrolyte that accelerates anodic iron dissolution and the cathodic hydrogen reaction. This leads to rapid wall thinning, local pitting corrosion, and an increased risk of crack initiation under cyclic loads (corrosion

fatigue). The practical problem is expressed in potential drill rod failures, unplanned downtime, and significant repair and replacement costs [4]. To improve the extraction efficiency, a methodology is proposed for rapid corrosion-rate measurement to prevent rod breakage and downtime, in line with sustainable development principles [5].

The objective is to analyze the main electrochemical corrosion mechanisms of steels in HCl and the corrosion rate during acid treatments under mechanical loading. Based on this, the paper proposes a methodology for rapid corrosion measurement and tracking of damage progression to avoid downtime and increased process cost.

2. Materials

To achieve the research objective, a standard material used for manufacturing drill rods is considered: API 2 3/8″ REG, OD 76 mm, ID 64 mm, t = 6 mm, made of X95 steel class according to API 5DP [6]. Specimens for the experiment are 10 mm long, and after cutting, their edges are processed with deburring technology to reduce thermal influence. This material is regularly used in practice and is a widely adopted strength class. It is suitable for evaluating corrosion behavior during acid treatments under standard operating regimes. The characteristics are presented in Table 1.

Table 1. Geometric characteristics of the coupon (ring) OD 76 × 6, L = 10 mm.

Parameter	Formula	Value
Length	L	10.0 mm
Cross-section pi	$\pi(Ro^2 - Ri^2)$	1319 mm^2
Volume	$A \cdot L$	13.19 cm^3
Theoretical mass	$\rho \cdot V$	103.58 g
Exposed area	$Ao + Ai + 2A$	70.37 cm^2

The strength properties of the tested and approved working material are as follows:

- Rp0.2 (min) = 655 MPa;
- Rp0.2 (typ.) = 655–862 MPa;
- Rm (min) >= 724 MPa;
- A (min) >= 15%.

Other materials also exist, but they are high-strength or intended for deep drilling, which would increase project cost.

3. Corrosion of Steels in HCl

Corrosion processes in carbon and low-alloy steels in acidic media (hydrochloric acid, HCl) are considered with a focus on oil and gas sector conditions. The presentation covers the electrochemical nature of corrosion, main anodic and cathodic reactions in HCl, factors governing the corrosion rate, and typical damage forms (uniform corrosion, pitting, and hydrogen-induced mechanisms).

3.1. Basic Corrosion Concepts and Electrochemical Model

For steels in aqueous HCl solutions, corrosion is almost always electrochemical in nature. This means that anodic reactions (metal dissolution) and cathodic reactions (reduction of solution components) occur simultaneously on different micro-areas of the surface [3].

In the electrochemical model, each corroding surface can be treated as a system of microelements (micro-anodes and micro-cathodes), electrically connected through the metal and ionically through the electrolyte. The driving force is the potential difference between anodic and cathodic regions, while the rate is determined by electrode-reaction kinetics and mass-transfer conditions (diffusion, convection) in solution.

3.1.1. The Anodic Process in Steel Corrosion Is Iron Oxidation (Dissolution)

$$Fe \rightarrow Fe^{2+} + 2e^{-} \quad (1)$$

Released electrons are transferred through the metal to cathodic regions, where they participate in reduction reactions. In acidic media (low pH), the dominant cathodic process is hydrogen evolution:

$$2H^{+} + 2e^{-} \rightarrow H_2\uparrow \quad (2)$$

When dissolved oxygen is present, oxygen reduction may also occur (especially at higher pH), but in concentrated HCl, the hydrogen reaction is generally dominant.

3.1.2. Polarization and Corrosion Potential

Polarization is the deviation of electrode potential from its equilibrium value due to current flow. Increased cathodic-reaction kinetics (for example, at higher H^{+} concentration) leads to higher i_corr and therefore a higher corrosion rate.

3.2. Hydrochloric Acid HCl

Low pH and high electrical conductivity of aqueous HCl create conditions for intensive electrochemical corrosion of carbon and low-alloy steels. This leads to the following:

- Anodic dissolution and formation of iron salts; the presence of Fe^{2+} and Fe^{3+} in solution is a useful indicator of corrosion intensity and is used in laboratory testing with test strips [7];
- Cathodic hydrogen reaction and reduced material ductility, i.e., embrittlement.

3.3. Factors Determining Corrosion Rate in HCl

In real drilling operations, material changes depend on environmental parameters such as temperature, flow regime, concentration, contact time, and others. Therefore, the corrosion risk must be assessed under specific conditions. The influence of these factors is shown in Figure 1.

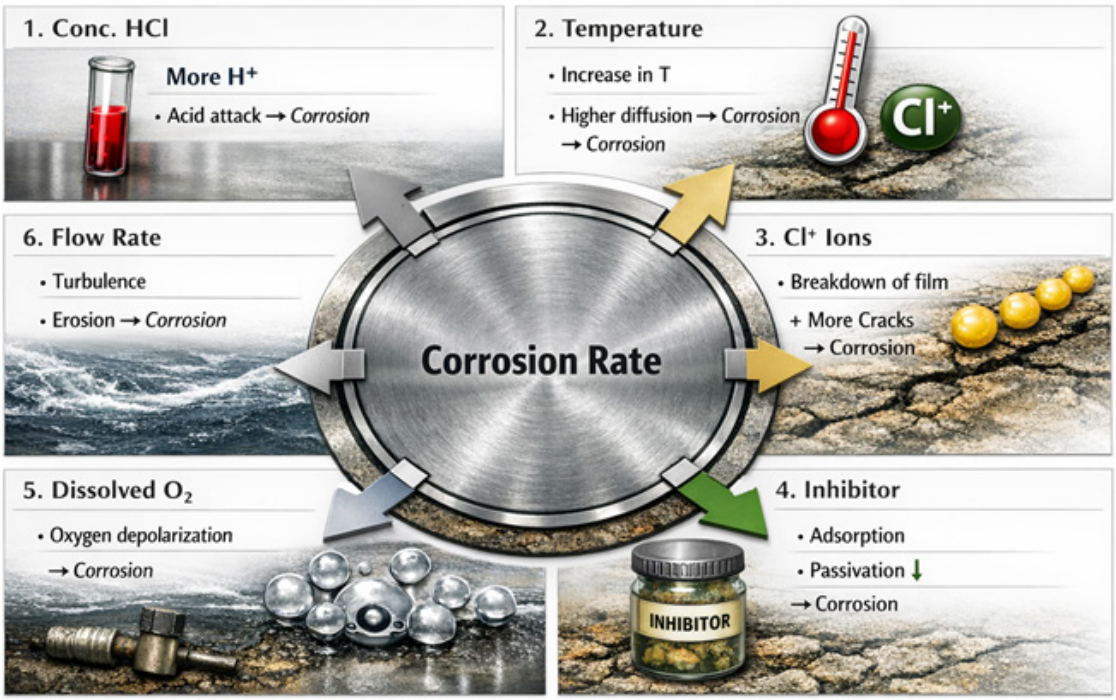


Figure 1. Main factors and expected outcome on corrosion.

4. Measurement Methods

Avoiding long and inconvenient laboratory measurements is key to drilling efficiency. For rapid measurement in field conditions, the following methods are used:

4.1. Gravimetric Method (Mass Loss)

The gravimetric method is a fundamental approach for corrosion assessment. A specimen with known area is exposed for a defined time, then cleaned from corrosion products, and dried, and its mass Δm is measured [3]. The average corrosion rate is calculated from Δm. Critical for accuracy is using an electronic balance with 0.001 g precision and a repeatable cleaning protocol (to avoid removing base metal).

Common engineering form for corrosion rate in mm/year:

$$CR\ (mm/year) = 87.6 \times W/(A \times t \times \rho) \quad (3)$$

where W is the mass loss (mg), A is the specimen area (cm^2), t is the exposure time (h), and rho is the material density (g/cm^3). The factor 87.6 is the unit conversion constant. Alternatively, the general relationship can be used through thickness loss $\Delta x = \Delta m/(A \cdot \rho)$ and conversion to annual speed.

4.2. Wall-Thickness Measurement (Ultrasonic Thickness Gauge)

An ultrasonic thickness gauge enables non-destructive measurement and is useful for evaluating the real residual thickness. In uniform corrosion, results can be directly compared with mass-loss calculations. In pitting, the measurement may produce underestimated or scattered values depending on the location; therefore, multiple points and clearly fixed comparison positions are recommended.

4.3. Indicator Measurements: pH, Fe^{2+}, and Fe^{3+}

pH measurement (test strips) provides operational control of whether the medium remains in the planned range during the experiment. The approximate determination of Fe^{2+} and Fe^{3+} in solution (test strips) serves as an indicator of dissolved iron and corrosion intensity [7]. These methods are semi-quantitative and are used as complements to the main quantitative methods (mass loss and thickness).

5. Expected Corrosion Changes

Observations in the literature indicate that corrosion in flushing fluids is enhanced by a combination of technological and chemical factors, among which the most frequently cited are as follows:

- Presence of dissolved oxygen (air entrainment during mixing, leaks, aeration);
- Dissolved acid gases CO_2 and H_2S [3];
- High mineralization and chlorides (increased conductivity);
- High temperature and gradients along the column;
- High flow velocity and abrasion and erosion by solid particles;
- Microbiological activity (especially sulfate-reducing bacteria—SRB), forming biofilm and local cells [8];
- Presence of stresses and cyclic loading, which leads to corrosion fatigue and accelerated crack development [9].

The following scenarios are typical for steels in such environments:

- Microgalvanic corrosion (Fe–Fe_3C and structural inhomogeneities): local anodic and cathodic areas, accelerated at high conductivity of the environment [3];

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- Oxygen corrosion: dissolved O_2 enhances the cathodic reaction and favors pitting through differential aeration cells (local O_2 depletion, different potential);
- "Sweet" corrosion in CO_2: dissolution of CO_2 and H_2CO_3, lowering of pH and accelerated general corrosion; formation of protective $FeCO_3$ layers is possible at certain T, pH, and supersaturation [10];
- "Sour" corrosion in H_2S: formation of FeS layers with different protective properties; risk of hydrogen saturation, sulfide stress cracking (SSC), and combined forms of corrosion-fatigue [11];
- MIC (microbiologically induced corrosion): biofilm, local changes in pH and Eh, formation of H_2S and organic acids; strong localization of the process and formation of pitting and subsurface cavities [8].

From the theory presented, it follows that, with increasing HCl concentration, an increase in the corrosion rate is expected due to the acceleration of the hydrogen cathodic reaction and increased conductivity. An example is shown in Figure 2.

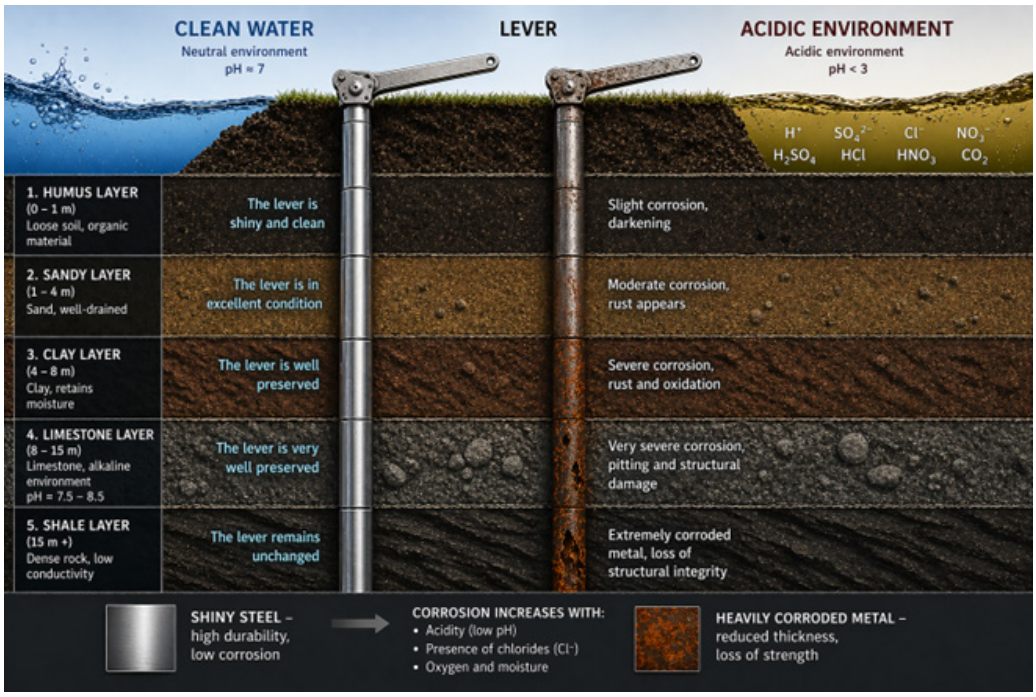


Figure 2. Corrosion changes.

Therefore, the corrosion risk in the well is determined by the "environment–metal–load" set. The mechanisms presented show that, in acid treatments, the corrosion of the drill rods is primarily an electrochemical process, enhanced by low pH and chloride ions, and exhibits a tendency to localization (pitting). The engineering hazard is the synergy with cyclic loads, leading to corrosion fatigue [12].

6. Methodology for Rapid Measurement

For field conditions, suitable methods that are practically applicable and provide quantitative assessment with limited laboratory equipment are as follows [6,13]:

- Gravimetric method for corrosion-rate determination through specimen cleaning and average corrosion-rate calculation [14];
- Ultrasonic wall-thickness measurement for roughness, pitting, and calibration; for this purpose, the AT-140-T6 ultrasonic field thickness gauge is proposed (P-E: 0.65–600 mm; E-E: 3–60 mm);

- pH control indicating medium aggressiveness and its changes with temperature;
- Approximate determination of Fe^{2+} and Fe^{3+} in solution as dissolved-iron indicators (mg/L), affected by precipitate presence.

7. Experiments and Results

Based on real drilling practice and specialist analyses, the following methodology is proposed for monitoring the condition of three identical specimens (Figure 3). The pH is monitored continuously. Any change requires a new specimen wall-thickness measurement, especially when HCl concentrations predispose rapid corrosion development.

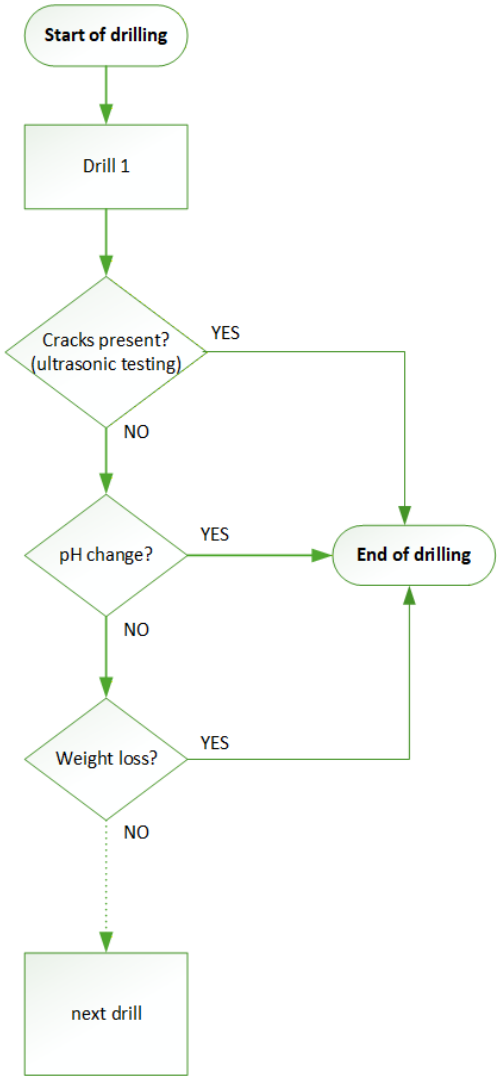


Figure 3. Procedure for corrosion checks.

For each specimen, the procedure for varying the investigated factors is followed, with limit values set for the respective specimen. The procedure is visual and uses only an ultrasonic thickness gauge to determine the critical rod mass-loss condition. Therefore, only the ultrasonic caliper can be used to speed up the measurement.

Thickness metrology—ultrasonic thickness gauge:

The thickness is measured at eight fixed points (T1–T8). For each date, the mean thickness t_bar and minimum thickness t_min are reported. Thinning is defined as Delta t = t0 − tt. This method is key for assessing local corrosion and the critical minimum thickness.

At the end of the operating period, the results can be compared with the gravimetric method. It should be considered that the presence can increase the specimen mass. For drill rods, not only is the average metal loss critical but so is the minimum thickness and pitting presence, because they act as stress concentrators and accelerate corrosion fatigue.

The results under standard conditions (ambient temperature and atmospheric pressure) are representative for comparison, but absolute corrosion-rate values in field conditions may be higher due to elevated temperature, pressure, flow, and complex fluid composition. The evaluation methods include a precision electronic balance for the gravimetric method, an ultrasonic thickness gauge (if available), and pH and Fe test strips [6].

The purpose of the laboratory experiment is to compare two quantities. The measurement procedure is presented in Table 2.

Table 2. Measurement procedures.

Series	Solution	HCl Concentration	Purpose (Control and Comparison)	Measurements
1	Distilled water	0%	control–base corrosion	Δm, t, pH
2	HCl aqueous solution	15%	acid corrosion (moderate)	Δm
3	HCl aqueous solution	15%	acid corrosion (moderate)	t
4	HCl aqueous solution	15%	acid corrosion (moderate)	pH
5	HCl aqueous solution	15%	acid corrosion (moderate)	Fe^{2+} and Fe^{3+}
6	HCl aqueous solution	32%	acid corrosion (strong)	Δm
7	HCl aqueous solution	32%	acid corrosion (strong)	T
8	HCl aqueous solution	32%	acid corrosion (strong)	pH
9	HCl aqueous solution	32%	acid corrosion (strong)	Fe^{2+} and Fe^{3+}

In this case, nine experiments are recommended, with one variable kept constant in each run. The matrix allows evaluation of two key effects, including the influence of the acid concentration and the corrosion rate.

8. Conclusions

The article examines corrosion-process issues in drilling operations and proposes a methodology oriented toward engineering practice that can be directly used as a protocol for evaluating the corrosive impact of hydrochloric-acid solutions on drill rods and components. Combining mass loss, thickness metrology, and chemical indicators provides independent criteria and more reliable interpretation of the results.

The practical impact of hydrochloric-acid treatments at elevated temperature (approximately 70 °C) and high concentration (32% HCl) is associated with an increased corrosion rate due to accelerated dissolution kinetics and depolarization processes. Therefore, the 32% HCl regime is higher-risk and requires (1) limiting the contact time between acid and metal surfaces, as well as (2) stable temperature control and minimizing the static exposure time. These disadvantages can be mitigated in field conditions by the mandatory use of an effective inhibitor at the correct dosage.

The proposed methodology is a factor for improving the safety, efficiency, and failure-free drilling in field conditions in line with sustainable development criteria. Verification with laboratory measurements is necessary and can be performed by comparing corrosion-rate determination methods. The mass-loss (gravimetric) method reflects the average corrosion effect over the entire specimen (integral metal loss), while thickness metrology identifies local thinning zones (t_min), characteristic of pitting and localized attack. In drill-rod practice, local minimum thickness values are critical for assessing the residual load-bearing capacity and risk of perforation/fracture.

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With the proposed methodology, the number of drilling operations under given working conditions can be determined. Under different conditions, reducing the number of operations may be necessary.

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References

1. Zheng, Y.; Zhang, Y.; Sun, B.; Zhang, B.; Zhang, S.; Jin, S.; Xiao, Z.; Chu, S.; Jing, Y.; Zhang, Z. Corrosion Behavior and Mechanical Performance of Drill Pipe Steel in a CO_2/H_2S-Drilling-Fluid Environment. *Processes* **2024**, *12*, 502. [CrossRef]
2. Zhang, Y.; Zhong, Z.; Mou, P.; Shao, J.; Zhang, N. Study on Stress Corrosion Characteristics of Drill Rod Joint Under Mechanical Effects. *E3S Web Conf.* **2021**, *248*, 01061. [CrossRef]
3. Landolt, D. *Corrosion and Surface Chemistry of Metals*, 1st ed.; EPFL Press: Lausanne, Switzerland, 2007. [CrossRef]
4. Cheapest_API 5CT PIPE_from China Manufacturer. Available online: https://www.zglpipe.cn/ (accessed on 21 April 2026).
5. Klyuev, R.V.; Martyushev, N.V.; Kukartsev, V.V.; Kukartsev, V.S. Analysis of geological information toward sustainable performance of geotechnical systems. *Min. Informational Anal. Bull.* **2024**, *5*, 144–157. [CrossRef]
6. Norsok M-001 Material Selection.pdf, Slideshare. Available online: https://www.slideshare.net/slideshow/norsok-m001-material-selectionpdf/260224420 (accessed on 22 April 2026).
7. Xiao, K.; Li, Z.; Song, J.; Bai, Z.; Xue, W.; Wu, J.; Dong, C. Effect of Concentrations of Fe^{2+} and Fe^{3+} on the Corrosion Behavior of Carbon Steel in Cl^- and SO_4^{2-} Aqueous Environments. *Met. Mater. Int.* **2021**, *27*, 2623–2633. [CrossRef]
8. Lv, X.; Wang, C.; Liu, J.; Sand, W.; Nabuk Etim, I.-I.; Zhang, Y.; Xu, A.; Duan, J.; Zhang, R. The Microbiologically Influenced Corrosion and Protection of Pipelines: A Detailed Review. *Materials* **2024**, *17*, 4996. [CrossRef]
9. Caltaru, M.M.; Badicioiu, M.; Dinita, A.; Zisopol, D.G.; Ripeanu, R.G.; Minescu, M. Influence of Chemical Corrosive Environment with H_2S on Drill Strings, Experimental Researches. *Rev. Chim.* **2020**, *71*, 29–37. [CrossRef]
10. Obot, I.B.; Onyeachu, I.B.; Umoren, S.A.; Quraishi, M.A.; Sorour, A.A.; Chen, T.; Aljeaban, N.; Wang, Q. High temperature sweet corrosion and inhibition in the oil and gas industry: Progress, challenges and future perspectives. *J. Pet. Sci. Eng.* **2020**, *185*, 106469. [CrossRef]
11. Zúñiga, E.M.E.; Rodríguez, M.A.V.; Chavarín, J.U.; Cruz, V.E.R. Corrosion of Carbon Steel in Sour Water From the Oil Industry: The Effect of Temperature. *Int. J. Electrochem. Sci.* **2011**, *6*, 5016–5030. [CrossRef]
12. Revie, R.W.; Uhlig, H.H. *Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering*, 1st ed.; Wiley: Hoboken, NJ, USA, 2008. [CrossRef]
13. NACE SP0169-Control of External Corrosion on Metallic Piping Systems. Available online: https://inspectioneering.com/tag/nace+sp0169 (accessed on 3 October 2025).
14. ROSEN–Empowered by Technology. Available online: https://www.rosen-group.com/en (accessed on 3 March 2026).

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