Pipeline Corrosion in the Water Industry: A Survey

www.surveyx.cn

Abstract

Pipeline corrosion in the water industry is a pervasive issue that significantly impacts the integrity and efficiency of Water Distribution Networks (WDNs). This survey paper provides a comprehensive examination of both uniform and pitting corrosion processes, highlighting their detrimental effects on pipeline materials through chemical reactions with water and environmental factors. The survey underscores the critical need for advanced corrosion management strategies, including the use of corrosion inhibitors and regular maintenance, to mitigate these effects. Key findings emphasize the importance of employing cutting-edge monitoring techniques such as Optical Frequency Domain Reflectometry (OFDR) and robotic Non-Destructive Testing (NDT) methods for timely detection and intervention. Furthermore, integrating machine learning and data-driven approaches into corrosion management presents significant potential for improving predictive accuracy and optimizing maintenance schedules. The development of environmentally friendly corrosion inhibitors, including those derived from natural sources, aligns with sustainability goals and regulatory frameworks. The survey also explores innovative methodologies, such as phase-field models, for simulating corrosion processes. In conclusion, the paper advocates for a multidisciplinary approach to corrosion management, leveraging technological advancements and sustainable practices to ensure the long-term reliability and resilience of water distribution systems. Future research should focus on refining these strategies and incorporating real-world data to address emerging challenges in pipeline infrastructure.

1 Introduction

1.1 Significance of Pipeline Corrosion

Pipeline corrosion significantly impacts Water Distribution Networks (WDNs), leading to severe techno-socio-economic consequences [1]. It compromises safety and operational integrity, necessitating effective monitoring methods to mitigate risks [2]. The degradation of steel, a prevalent material in pipelines, is a primary cause of structural failures across various sectors, incurring substantial economic costs [3]. In water distribution, corrosion results in considerable water loss and operational inefficiencies, particularly in aging infrastructure [4]. If undetected, corrosion can also lead to environmental pollution and economic losses [5].

The importance of preventing failures in corroded steel structures is particularly evident in offshore oil and gas operations, highlighting the broader implications of corrosion management [6]. Addressing corrosion in API 5L steel pipelines is essential to avert operational failures and safety hazards, underscoring the need for robust mitigation strategies [7]. Corrosion affects the efficiency and reliability of water distribution systems, akin to improvements in texture classification methods that enhance performance [8]. The integrity of water infrastructure is compromised by corrosion, impacting its longevity and functionality [9]. Furthermore, corrosion increases the seismic vulnerability of water distribution systems, especially in aged cast iron pipelines, posing additional risks in seismically active regions [10]. Understanding the potential-of-zero-charge (PZC) for materials like aluminum is crucial for addressing corrosion issues in water distribution systems [11]. The role of T-phase

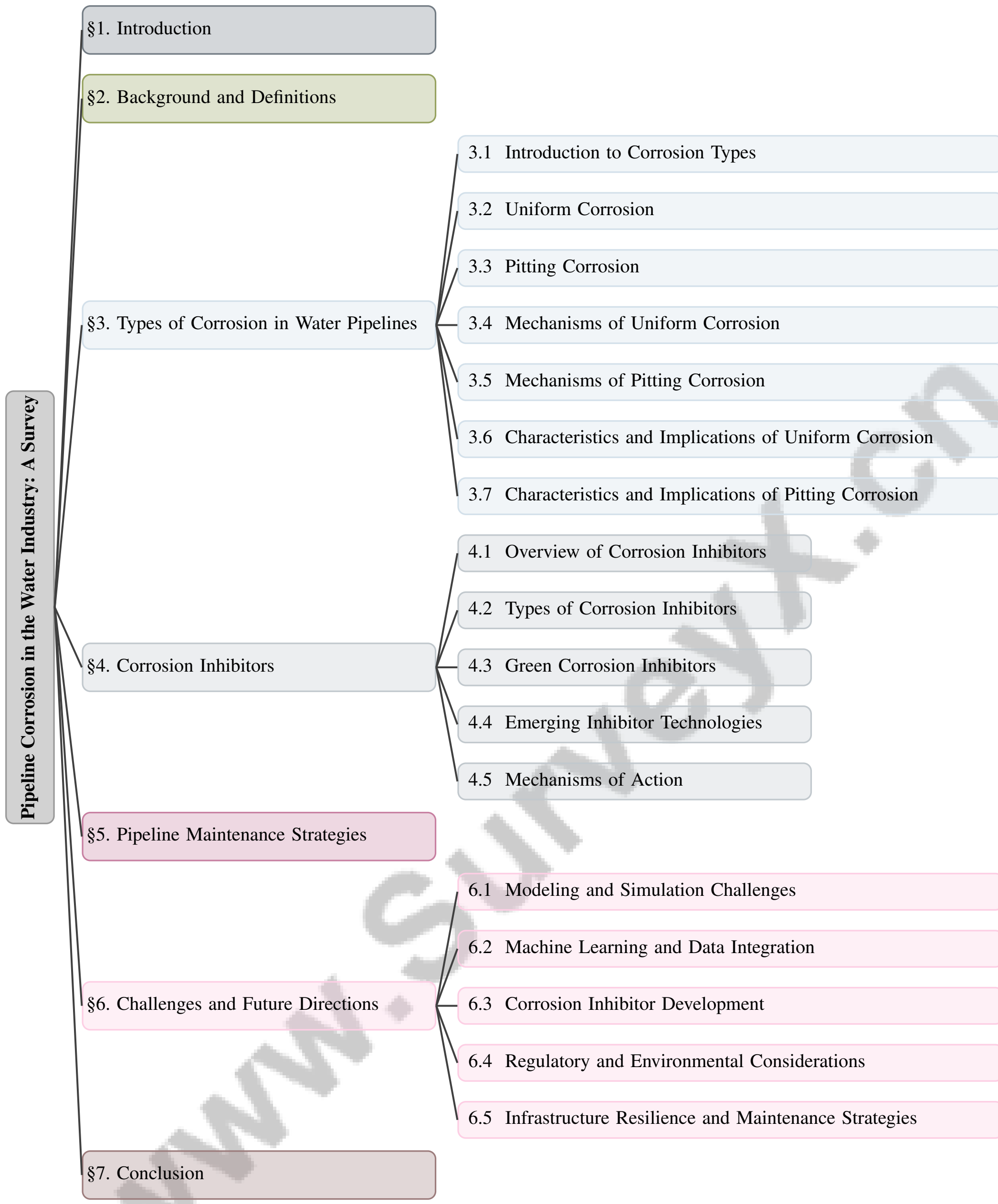


Figure 1: chapter structure

dispersoids and S-phase precipitates in controlling grain growth and enhancing corrosion resistance further emphasizes the significance of metallurgical factors in corrosion mitigation [12].

1.2 Impact on Water Distribution Systems

Pipeline corrosion undermines the efficiency and reliability of water distribution systems by compromising pipeline structural integrity, leading to potential failures and service disruptions. Pitting corrosion, in particular, poses a severe threat as it creates localized weaknesses, increasing the likelihood of leaks and bursts. Accurate prediction and monitoring of pitting corrosion depth, as evidenced in oil and gas pipelines, are critical to preventing accidents and mitigating economic losses [6]. Similar predictive measures are essential in water distribution systems to maintain operational continuity and prevent water loss, especially in aging infrastructure. Corrosion-related failures incur significant economic costs due to repairs, water loss, and potential environmental contamination, making effective corrosion management strategies vital for the long-term sustainability and resilience of water distribution networks.

1.3 Scope and Objectives of the Survey

This survey aims to address the critical issue of corrosion in water pipelines, focusing on environmental, pipe-related, and operational factors influencing corrosion in buried water pipelines [1]. The review parallels innovative methodologies in texture classification [8] by adopting a thorough approach to understanding pipeline corrosion. It emphasizes the importance of pipeline integrity management processes, particularly in defect detection, growth prediction, and risk-based management using in-line inspection (ILI) data [13]. Additionally, it provides an extensive review of transient wave-based methods for detecting anomalies in fluid pipes, addressing the necessity for effective monitoring and maintenance strategies in aging systems [4].

The survey explores the interplay between metallurgical factors, such as T-phase and S-phase in Al-Cu-Mg alloys, and their impact on mechanical and electrochemical properties influencing corrosion resistance [12]. It highlights the need for real-time monitoring of pipeline corrosion and leakage, focusing on the innovative application of optical frequency domain reflectometry (OFDR) for simultaneous monitoring tasks [5]. Recognizing seismic resilience, the survey incorporates time-variant effects of corrosion to assess the robustness of water distribution systems in seismically active regions [10]. It also addresses specific corrosion challenges in API 5L steel pipelines, including sweet corrosion, sour corrosion, and microbiologically influenced corrosion (MIC), to provide a comprehensive view of corrosion phenomena affecting water pipelines [7].

1.4 Structure of the Survey

This survey is meticulously structured to explore pipeline corrosion within the water industry, beginning with an introduction that establishes the significance and impact of corrosion on water distribution systems. Following the introduction, a detailed background section defines key concepts such as pipeline corrosion, water distribution systems, uniform corrosion, and pitting corrosion, alongside the chemical and environmental factors contributing to these phenomena.

The core of the survey delves into the types of corrosion affecting water pipelines, focusing on uniform and pitting corrosion. This section is subdivided to discuss mechanisms, characteristics, and implications of each type, offering a thorough understanding of their impact on pipeline integrity and functionality.

Subsequent sections explore corrosion inhibitors, detailing various types employed in the water industry, including environmentally friendly options and emerging technologies. The mechanisms by which these inhibitors operate are examined, providing insights into their effectiveness in preventing corrosion.

The survey further investigates pipeline maintenance strategies, highlighting non-intrusive monitoring techniques, the use of optical fiber technology, and robotic non-destructive testing methods. It discusses preventive maintenance and cost-effective asset management strategies to enhance the long-term integrity of water distribution systems, emphasizing regular inspections and assessments in identifying corrosion and other defects, alongside the importance of risk-based management approaches to mitigate potential failures and ensure reliable water supply during adverse conditions, such as seismic events [10, 13, 1].

Finally, the survey examines the multifaceted challenges and future directions in managing pipeline corrosion, highlighting complexities in modeling and simulation, the integration of machine learning and data analytics for predictive maintenance, and the ongoing development of innovative corrosion inhibitors. It emphasizes the need for enhanced non-destructive testing (NDT) methods and effective data management strategies to improve pipeline integrity and safety across diverse environmental conditions [14, 1]. Regulatory and environmental considerations are evaluated, alongside strategies to enhance infrastructure resilience against corrosion. The conclusion summarizes key findings, emphasizing the importance of effective corrosion management in maintaining the integrity and efficiency of water distribution systems.The following sections are organized as shown in Figure 1.

AI-generated, for reference only.

2 Background and Definitions

2.1 Pipeline Corrosion: An Overview

Pipeline corrosion is a critical issue in the water industry, characterized by material degradation due to chemical and environmental interactions [10]. This degradation affects the seismic performance of water distribution systems, threatening structural integrity and causing operational failures. Understanding corrosion forms, particularly in API 5L steel pipelines, is essential due to their potential to cause severe disruptions [7]. Corrosion is driven by chemical and electrochemical interactions involving factors like oxide/hydroxide films in aqueous environments, affecting materials such as aluminum [11]. Localized corrosion, such as pitting in 316L stainless steel, complicates integrity management due to potential weaknesses and failures [15]. Real-time monitoring is crucial for assessing and mitigating corrosion-induced morphological changes [3].

Crystallographic relationships between T-phase dispersoids and S-phase precipitates significantly influence mechanical and electrochemical properties, affecting corrosion resistance [12]. Insights into pore formation in passive layers, modeled through stochastic lattice approaches, enhance understanding of ion transport and corrosion processes [16]. The implications of pipeline corrosion extend beyond material degradation, impacting the integrity and reliability of transportation structures in both water and oil and gas industries [5]. Therefore, addressing pipeline corrosion is vital for ensuring the safety, reliability, and efficiency of water distribution networks.

2.2 Water Distribution Systems

Water distribution systems, essential components of urban infrastructure, deliver potable water from treatment facilities to consumers. These systems comprise pipelines, pumps, storage tanks, and valves engineered for efficient water delivery while meeting quality standards. Corrosion significantly threatens these systems' integrity and performance, necessitating pipeline integrity management. Regular inspections and assessments detect defects such as corrosion and cracks. Advanced methodologies, including in-line inspection technologies and deep reinforcement learning algorithms, optimize maintenance strategies and enhance resilience against environmental challenges and seismic events [17, 13, 10, 1, 14]. The structural integrity and operational efficiency of these systems are critical for public health and economic stability, as pipeline corrosion can lead to leaks, bursts, and contamination, necessitating robust management strategies.

Beyond transportation, water distribution systems maintain water pressure and flow rates to meet varying consumer demands. The design and material selection for pipelines, often dictated by economic and environmental factors, significantly influence corrosion susceptibility. Steel, a common pipeline material, is particularly vulnerable to corrosion in environments with fluctuating pH levels and chlorides [3], underscoring the need for regular monitoring and maintenance to uphold system integrity.

Effective corrosion management in water distribution systems involves a multi-faceted approach, incorporating predictive modeling, real-time monitoring, and corrosion inhibitors. Techniques such as optical frequency domain reflectometry (OFDR) facilitate early detection of anomalies, enabling timely interventions [5]. Additionally, understanding the electrochemical properties of pipeline materials, particularly those influenced by T-phase dispersoids and S-phase precipitates, is essential for developing corrosion-resistant materials [12].

2.3 Chemical and Environmental Factors

Pipeline corrosion in water distribution systems is influenced by a complex interplay of chemical and environmental factors, categorized into environmental, pipe-related, and operational perspectives, which collectively contribute to material degradation [1]. The presence of water and dissolved gases like CO_2 and H_2S presents substantial internal corrosion challenges [18]. The interaction between chloride ions and oxygen vacancies in oxide films is critical for pitting corrosion mechanisms [19], involving a complex electrochemical process shaped by environmental conditions and alloy compositions [15].

A significant challenge in understanding corrosion processes is the limited knowledge regarding the crystallographic relationships between T-phase dispersoids and S-phase precipitates, crucial for

AI-generated, for reference only.

corrosion resistance [12]. Pitting corrosion on aluminum surfaces can occur at potentials exceeding -0.5 V relative to the standard hydrogen electrode (SHE) [20]. Furthermore, the chemical and environmental factors affecting hot salt corrosion (HSC) resistance in titanium -alloy Ti–2.5Al–2.6Zr illustrate intricate interactions between different corrosion types, including intergranular corrosion (IGC) and pitting corrosion [21].

Localized corrosion leads to uneven dissolution rates across electrodes, posing significant challenges for prediction and detection, necessitating improved monitoring methods [3]. Traditional corrosion detection methods often fall short for real-time monitoring over long distances, highlighting the need for advanced techniques [2]. The interplay of charges at the oxide/electrolyte interface and within the oxide film significantly contributes to pitting corrosion mechanisms [11].

Environmental factors such as pore saturation and electrolyte conductivity are crucial for understanding non-uniform corrosion in pipelines [9]. Pore formation in passive layers affects corrosion processes and passive layer growth, complicating overall corrosion dynamics [16]. The time-dependent nature of corrosion, often overlooked in assessments, significantly influences pipeline strength and vulnerability, particularly in seismically active regions [10]. Additionally, the suboptimal selection of hyper-parameters in existing predictive models complicates maintenance planning and necessitates more accurate prediction methodologies [6]. The intricate mechanisms of corrosion and its economic implications underscore the need for effective prevention methods [7]. Comprehensive research and modeling are essential to manage and mitigate corrosion's impact on water distribution systems effectively.

3 Types of Corrosion in Water Pipelines

Corrosion in water pipelines poses significant threats to Water Distribution Networks (WDNs), necessitating a clear categorization of corrosion types to identify risks and develop mitigation strategies. This section delves into various corrosion forms, underscoring their impact on water distribution systems. Figure 2 illustrates the hierarchical classification of corrosion types in water pipelines, highlighting the primary categories of uniform and pitting corrosion, along with their mechanisms and characteristics. This visual representation underscores the importance of understanding these corrosion forms to develop effective mitigation strategies in water distribution networks.

3.1 Introduction to Corrosion Types

Corrosion in water pipelines primarily manifests as uniform and localized types, such as pitting, both contributing to material degradation and potential system failures [1]. Uniform corrosion involves consistent material loss, necessitating advanced models to capture its non-uniform characteristics [9]. In contrast, pitting corrosion leads to localized attacks, influenced by factors like chloride ions and oxygen vacancies [18], and is particularly prevalent in liquid-gas transition zones due to environmental fluctuations [18]. These corrosion types exacerbate seismic vulnerabilities, increasing failure rates during seismic events [10].

Corrosion types are influenced by environmental, material, and operational factors, with sweet, sour, and microbiologically influenced corrosion (MIC) presenting distinct challenges. Analytical methods like fault tree analysis and fuzzy analytical hierarchy processes help categorize and rank corrosion causes, highlighting the operational environment's role in corrosion susceptibility [7, 18, 22, 10, 1]. A comprehensive understanding of these mechanisms is crucial for effective mitigation strategies to protect water distribution systems.

3.2 Uniform Corrosion

Uniform corrosion is characterized by even material loss across pipeline surfaces, leading to gradual wall thinning and potential structural failures. It is driven by electrochemical reactions accelerated by factors like moisture, temperature, and corrosive agents [8]. The susceptibility of materials, such as titanium -alloys, to specific corrosion types underscores the degradation potential under operational conditions [21].

The implications of uniform corrosion are significant, as material loss compromises pipeline integrity, increasing the risk of leaks and failures. Mitigation involves selecting corrosion-resistant materials,

AI-generated, for reference only.

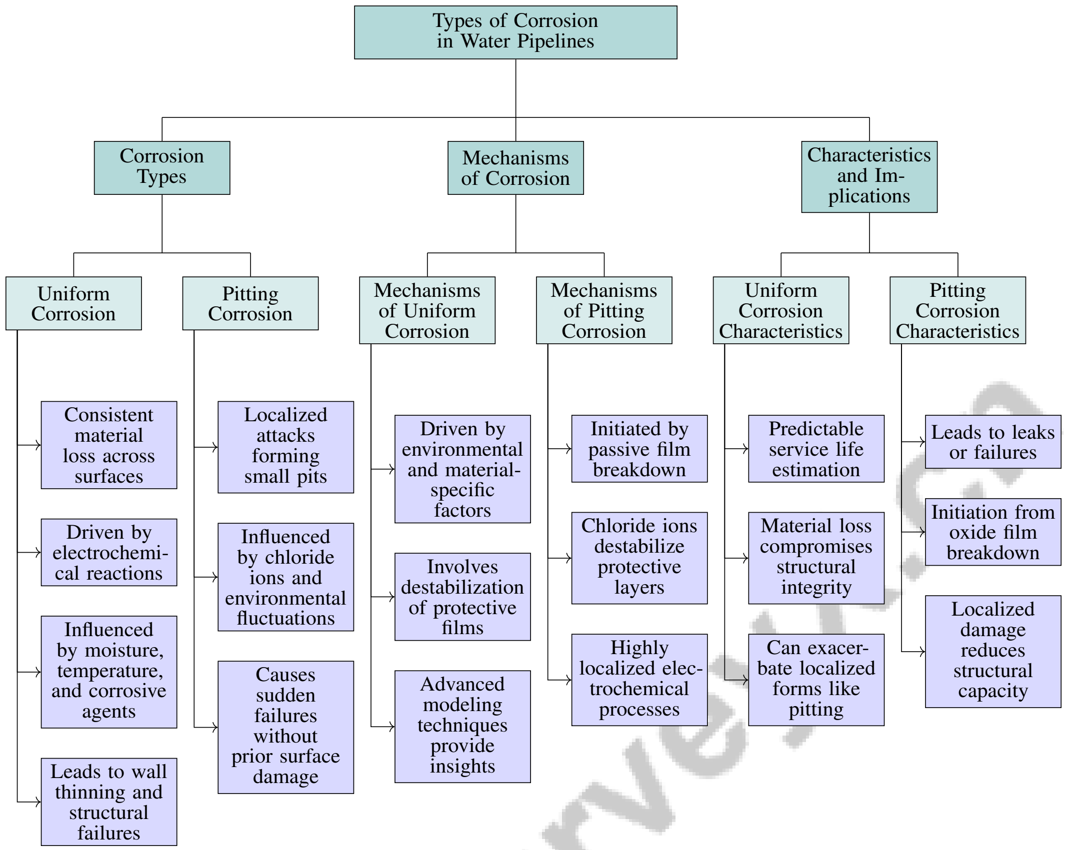


Figure 2: This figure illustrates the hierarchical classification of corrosion types in water pipelines, highlighting the primary categories of uniform and pitting corrosion, their mechanisms, and characteristics. It underscores the importance of understanding these corrosion forms to develop effective mitigation strategies in water distribution networks.

applying protective coatings, and maintaining rigorous schedules for early detection and intervention [7, 23, 1, 24, 25]. Innovative solutions, such as organic inhibitors and ionic liquids, enhance protection, ensuring pipeline reliability.

3.3 Pitting Corrosion

Pitting corrosion poses a severe threat to pipeline integrity due to its localized nature, forming small pits that can rapidly penetrate metal surfaces [26]. This corrosion form can lead to sudden failures without prior surface damage. The mechanisms involve the breakdown of protective oxide layers, often initiated by chloride ions that destabilize passive films [19]. The electrochemical nature of pitting entails localized anodic and cathodic reactions, with chloride ions playing a crucial role [20].

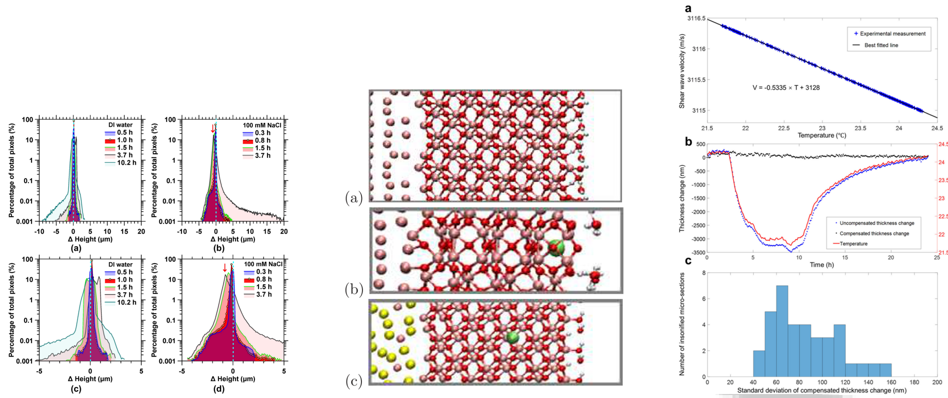
Advanced modeling techniques, such as hybrid Support Vector Regression (SVR) models, predict pitting corrosion depth and improve risk assessment [6]. Localized damage from pitting can lead to catastrophic failures, necessitating robust monitoring and mitigation strategies to safeguard water distribution systems.

3.4 Mechanisms of Uniform Corrosion

Uniform corrosion involves consistent material degradation across pipeline surfaces, driven by electrochemical reactions influenced by environmental and material-specific factors [19, 22, 15, 27]. Environmental elements, including water and dissolved gases, facilitate electrochemical processes, destabilizing protective films. Localized phenomena like pitting can exacerbate uniform corrosion through autocatalytic mechanisms [19, 22, 16, 27, 15].

AI-generated, for reference only.

Advanced modeling techniques, including non-autonomous and autonomous models, provide insights into corrosion dynamics, simulating transport and evolution processes [27]. Visual Surface Inspection (VSI) techniques capture steel surface morphology changes during corrosion, offering valuable insights into microstructural changes [22]. Understanding uniform corrosion mechanisms is essential for effective mitigation strategies.



(a) Comparison of Height Distribution of Cells in DI Water and 100 mM NaCl Solutions over Time[22]

(b) Graphene Nanoribbon with Adsorbed Molecules[19]

(c) Temperature-Induced Shear Wave Velocity and Thickness Change in a Thin Film[3]

Figure 3: Examples of Mechanisms of Uniform Corrosion

Figure 3 illustrates uniform corrosion's impact on pipeline longevity and functionality, showcasing the interplay between environmental conditions and material degradation. The figures emphasize the influence of chemical environments, microstructural interactions, and temperature effects on corrosion mechanisms.

3.5 Mechanisms of Pitting Corrosion

Pitting corrosion severely compromises pipeline integrity by forming small, deep pits on metal surfaces. Initiation and propagation are influenced by passive film breakdown, aggressive ions, and the electrochemical environment [19]. Chloride ions destabilize protective layers, leading to localized anodic dissolution and pit formation.

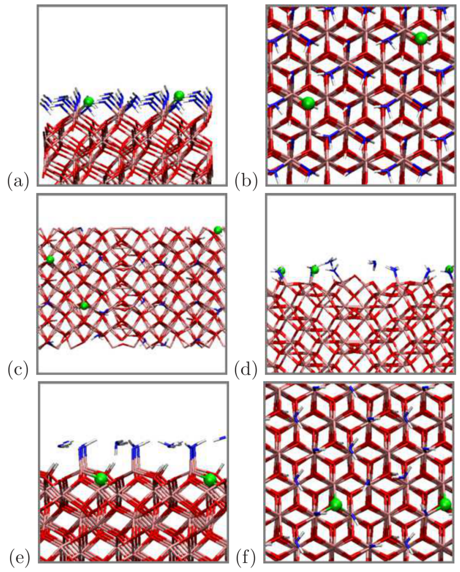
Electrochemical processes in pitting corrosion are highly localized, with environmental factors such as pH, temperature, and oxidizing agents accelerating corrosion. The porosity and composition of passive films determine susceptibility to pitting [20]. Advanced computational techniques, like adaptive moving mesh methods, simulate pitting progression with accuracy, aiding in predictive model development [26].

Understanding pitting corrosion mechanisms is crucial for developing targeted prevention strategies. This knowledge enhances structural integrity and addresses multifaceted corrosion factors, employing methodologies like fault tree analysis and fuzzy analytical hierarchy processes for effective mitigation [7, 10, 1].

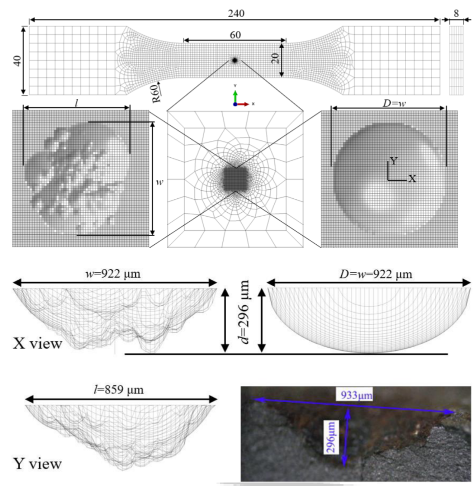
Figure 4 highlights pitting corrosion mechanisms, with images illustrating nanoscale molecular interactions and material degradation. These visualizations underscore the need for comprehensive corrosion management strategies.

3.6 Characteristics and Implications of Uniform Corrosion

Uniform corrosion features consistent thinning of metal surfaces due to uniform electrochemical reactions, allowing for predictable service life estimation [22]. This predictability aids maintenance planning, minimizing costs and unexpected failures. Techniques like deep reinforcement learning and in-line inspection data analysis optimize maintenance, ensuring timely interventions [29, 17, 13, 1].



(a) Graphene Nanotube with Adsorbed Molecules[19]



(b) Microscopic Image of a Cracked Surface[28]

Figure 4: Examples of Mechanisms of Pitting Corrosion

Despite predictability, uniform corrosion's material loss compromises structural integrity, increasing leak and rupture risks. Its cumulative effect can exacerbate localized forms like pitting by providing a weakened substrate [22]. Comprehensive corrosion management must address both degradation forms, incorporating systematic analyses and advanced methodologies to enhance system resilience [13, 7, 10, 1].

3.7 Characteristics and Implications of Pitting Corrosion

Pitting corrosion, characterized by small, deep pits, poses significant threats to pipeline integrity, leading to leaks or failures. Initiation often results from protective oxide film breakdown due to aggressive ions like chlorides [19]. The localized electrochemical nature involves anodic dissolution at pit bases and cathodic reactions on surrounding surfaces, with environmental factors accelerating the process [20].

The implications of pitting corrosion are profound, as localized damage reduces structural capacity and increases failure risks. Its insidious nature complicates detection, highlighting the need for comprehensive monitoring and mitigation strategies to maintain system integrity [13, 10, 1]. Advanced techniques, such as adaptive moving mesh methods, provide insights into pit growth dynamics, aiding in model development and maintenance strategies [26].

4 Corrosion Inhibitors

4.1 Overview of Corrosion Inhibitors

Corrosion inhibitors are crucial for safeguarding pipeline materials by forming protective barriers that mitigate electrochemical reactions responsible for corrosion, thus preserving the structural integrity and operational efficiency of water distribution systems. Recent advancements emphasize biodegradable and non-toxic options, such as organic green corrosion inhibitors (OGCIs) derived from plant extracts, which are particularly effective for aluminum and its alloys in diverse corrosive environments [24, 25]. The efficacy of these inhibitors is closely linked to their interaction with metal surfaces, which modifies electronic interactions at metal/oxide interfaces, a critical aspect for designing effective inhibitors [11]. Advanced simulation techniques, including Density Functional

Theory (DFT), provide insights into corrosion processes, guiding the development of more effective inhibitors [11].

Corrosion inhibitors are categorized into types such as ionic liquids, polyionic liquids, and graphene-based inhibitors, each possessing distinct properties and mechanisms [23]. Incorporating porosity and varying diffusion coefficients in corrosion models enhances mechanical interaction accuracy, aiding in preventing localized attacks like pitting [16]. Innovative approaches, such as Optical Frequency Domain Reflectometry (OFDR), enable real-time monitoring of corrosion and leakage, improving inhibitor effectiveness assessments in practical applications [5, 2]. The ongoing development of advanced corrosion inhibitors is critical for enhancing the durability and reliability of water distribution systems, as effective management extends system lifespan and reduces repair costs and environmental impacts associated with failures [7, 30, 10, 1]. Leveraging cutting-edge research can yield inhibitors that protect against corrosion while supporting environmental sustainability.

4.2 Types of Corrosion Inhibitors

Corrosion inhibitors mitigate pipeline material degradation in water distribution systems by slowing electrochemical reactions. They are classified into categories such as biopolymers, plant extracts, and ionic liquids, which are increasingly viewed as environmentally friendly alternatives to traditional toxic inhibitors [30]. Green corrosion inhibitors, derived from natural materials like plant extracts, gums, and oils, are noted for their biodegradability and non-toxic properties [31]. These inhibitors operate through active functional groups such as -OH, -NH2, and -COOH, which interact with metal surfaces to prevent corrosion [24]. Their protective capabilities are often analyzed using adsorption isotherms, providing insights into their efficiency [25].

Emerging materials like ionic liquids, polyionic liquids, and graphene-based inhibitors exhibit enhanced corrosion resistance due to their unique properties, improving performance and durability in protective coatings [23]. For instance, benzotriazole (BTAH) effectively inhibits copper corrosion by adsorbing onto metal surfaces [32]. The strategic deployment of these inhibitors is part of a comprehensive corrosion prevention approach, including material selection and protective coatings [7]. Integrating innovative and sustainable corrosion inhibitors into existing practices can significantly enhance the longevity and reliability of water infrastructure while aligning with environmental goals.

4.3 Green Corrosion Inhibitors

Green corrosion inhibitors are integral to sustainable pipeline corrosion management, providing eco-friendly alternatives to traditional chemical options. Derived from natural sources like plant extracts, these inhibitors are biodegradable and non-toxic, suitable for various industries [24]. Their eco-friendly nature meets the growing demand for sustainable solutions in corrosion management, effectively mitigating corrosion while minimizing environmental impact [25]. Green inhibitors function by adsorbing active functional groups onto metal surfaces, forming a protective film that impedes electrochemical reactions. The effectiveness of these inhibitors is influenced by factors such as chemical structure and corrosive medium conditions [23, 31, 25, 24]. Functional groups like hydroxyl, amino, and carboxyl enhance adsorption, which is crucial for their protective capabilities.

Beyond environmental advantages, green corrosion inhibitors are cost-effective and widely applicable. Integrating advanced materials and technologies in water distribution systems enhances resilience while requiring minimal infrastructure changes, maintaining water supply continuity during seismic events and addressing corrosion-related challenges [10, 1]. Incorporating green inhibitors into corrosion management strategies not only improves pipeline longevity and reliability but also supports broader sustainability objectives. The development of OGCIs from plant extracts represents a significant advancement in corrosion management. These biodegradable alternatives effectively prevent corrosion in materials like aluminum and its alloys while addressing environmental concerns. Recent research emphasizes their cost-effectiveness, non-toxic nature, and insights into their mechanisms and classifications. By balancing performance with ecological responsibility, OGCIs present a promising solution for mitigating corrosion challenges across engineering fields [31, 24].

4.4 Emerging Inhibitor Technologies

Emerging technologies in corrosion inhibitors are transforming pipeline corrosion mitigation, emphasizing effectiveness and sustainability. Recent developments have introduced innovative materials such as ionic liquids, polyionic liquids, and graphene, which enhance performance while minimizing environmental impact. These next-generation inhibitors possess superior barrier properties and are designed to protect metal surfaces against corrosion effectively [1, 24, 23, 30]. Adaptive inhibitor technologies that dynamically respond to corrosion environment changes represent a key innovation. By utilizing advanced computational techniques, such as the adaptive moving mesh method, researchers can simulate corrosion processes and changes in pit geometry accurately [26]. This provides insights into inhibitor interactions at corrosion sites, facilitating the design of more effective formulations.

Moreover, integrating machine learning and optimization algorithms can significantly improve the predictive accuracy of corrosion models. Future research should leverage these computational tools to optimize inhibitor performance and broaden their application across engineering challenges [6]. Machine learning can help identify optimal inhibitor compositions and dosages, enhancing overall efficiency in corrosion prevention strategies. The exploration of novel materials like ionic liquids and graphene-based inhibitors offers promising directions for inhibitor technology. These materials exhibit unique properties, such as high thermal stability and excellent adsorption capabilities, improving protective performance in harsh environments. The demand for sustainable corrosion management drives the development of eco-friendly inhibitors, particularly those from natural sources like plant extracts, gums, and oils. While they may face limitations in severe corrosion conditions, their growing popularity across applications—from the oil and gas industry to historical artifact preservation—underscores their potential to promote environmentally friendly practices in corrosion protection [31, 25, 30].

Advancements in emerging inhibitor technologies promise to enhance corrosion prevention strategies in water distribution systems. By harnessing innovative research and methodologies, the industry can develop inhibitors that provide robust corrosion protection while supporting environmental sustainability and operational efficiency. Future research should continue to explore these technologies' potential applications in real-world scenarios and their integration into comprehensive corrosion management frameworks [18].

4.5 Mechanisms of Action

Corrosion inhibitors function by forming protective barriers on pipeline materials, thus reducing the rate of electrochemical reactions leading to degradation. The mechanisms of action vary based on the inhibitor type, whether synthetic or natural. Natural inhibitors, derived from plant extracts and organic sources, tend to be less toxic and more sustainable than synthetic alternatives [31]. They often contain active functional groups, such as hydroxyl and carboxyl groups, which adsorb onto metal surfaces to impede corrosive processes [25]. The adsorption of inhibitors onto metal surfaces is critical for their effectiveness. Research employing modified density functional theory (DFT) has elucidated the adsorption mechanisms of inhibitors like benzotriazole on copper surfaces, emphasizing the role of van der Waals interactions in forming stable protective layers [32]. This adsorption creates a barrier that limits corrosive species' access to the metal, thereby reducing corrosion rates.

Advanced monitoring techniques, such as Optical Frequency Domain Reflectometry (OFDR), are vital for assessing corrosion inhibitors' effectiveness in real-time applications. By measuring Rayleigh backscatter in optical fibers, OFDR detects changes in strain and temperature along pipelines, providing essential data for monitoring pipeline integrity and inhibitor performance. Integrating real-time monitoring data into Multi-Physics Finite Element Models (MPFEM) enhances predictive capabilities for corrosion management, allowing for more accurate assessments of inhibitor performance [9]. Understanding the mechanisms of action of corrosion inhibitors is essential for developing effective strategies to prevent pipeline degradation. This understanding, particularly concerning natural inhibitors, is crucial for advancing corrosion management practices and ensuring the long-term integrity of water distribution systems. Further research is needed to enhance the effectiveness of natural inhibitors and optimize their application in various corrosive environments [25].

5 Pipeline Maintenance Strategies

Effective pipeline maintenance is crucial for ensuring the longevity and integrity of water distribution systems. Table 1 summarizes the key methods and technologies utilized in modern pipeline maintenance strategies, emphasizing their categories, features, and associated methodologies. Additionally,

AI-generated, for reference only.

Category	Feature	Method
Non-Intrusive Monitoring Techniques	Detailed Detection	UTMLC[3]
Optical Fiber Monitoring	Spatial Monitoring	OFDR[2], DOFS[5], SVR[6]
Robotic NDT Inspection Methods	Autonomous Navigation	RNDI[33]
Preventive Maintenance and Scheduling	Decision Support Systems	RAPMS[29]
Cost-Effective Asset Management	Predictive Strategies	DRL-RP[17]

Table 1: This table provides a comprehensive summary of various methods employed in pipeline maintenance strategies, categorized by their specific features and techniques. It highlights non-intrusive monitoring techniques, optical fiber monitoring, robotic NDT inspection methods, preventive maintenance and scheduling, and cost-effective asset management, along with the corresponding methods and references to key studies.

Table 2 offers a comprehensive comparison of various pipeline maintenance methods, detailing their technological frameworks and operational features. This section discusses various approaches to manage corrosion, a major threat to pipeline infrastructure, focusing on non-intrusive monitoring techniques that assess pipeline conditions without disrupting operations. These techniques are essential for establishing proactive maintenance frameworks that enhance the safety and reliability of pipeline networks.

5.1 Non-Intrusive Monitoring Techniques

Non-intrusive monitoring techniques are vital for assessing pipeline integrity and managing corrosion without interrupting water distribution. These methods employ advanced technologies to provide real-time data on pipeline conditions, enabling timely interventions. Optical Frequency Domain Reflectometry (OFDR) is a promising method, detecting internal corrosion by using Rayleigh backscatter in optical fibers to monitor strain and temperature changes, offering high spatial resolution and sensitivity to corrosion-induced deformations [2].

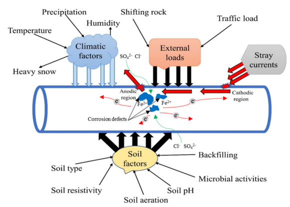
Ultrasonic testing is another widely used non-intrusive technique, valued for its ability to correlate ultrasonic signal features with morphological changes in pipelines, independent of corrosion product interference [3]. This method accurately assesses wall thickness and detects localized defects, such as pits and cracks, indicative of corrosion. Its reliability is enhanced by visualizing the internal structure of pipelines, allowing precise identification of corrosion-related anomalies.

Advancements in non-destructive testing (NDT) methods and data management strategies have significantly improved pipeline operations' reliability and safety [14]. Sophisticated algorithms for data analysis facilitate the detection of subtle changes in pipeline conditions over time. Integrating these technologies into maintenance practices ensures potential issues are identified and addressed before escalating into major failures.

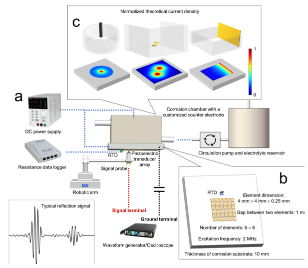
Decision support algorithms optimize preventive maintenance (PM) schedules by formulating the PM scheduling problem as a binary integer non-linear programming model, deriving optimal maintenance schedules that balance operational efficiency with regular inspections and repairs [29]. This approach minimizes disruptions and extends pipeline infrastructure's service life.

Non-intrusive monitoring techniques are indispensable for effective pipeline corrosion management. By delivering continuous, real-time insights into water pipeline conditions, these advanced techniques facilitate proactive maintenance strategies that significantly improve the longevity and reliability of water distribution systems. They address multifaceted corrosion causes, incorporate sophisticated methodologies like in-line inspection data and risk-based management, and evaluate corrosion's impact on the seismic resilience of aging infrastructure, ensuring a robust and reliable water supply, particularly in seismically active regions [10, 13, 1].

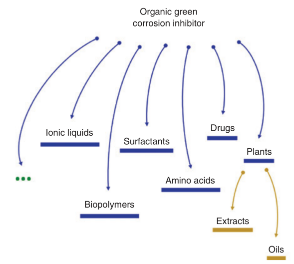
As shown in Figure 5, adopting non-intrusive monitoring techniques is pivotal for ensuring the longevity and safety of metal pipes, particularly those embedded in soil environments. This example illustrates three distinct approaches that highlight the multifaceted nature of corrosion monitoring and prevention. The first image presents a comprehensive diagram identifying various factors influencing metal pipe corrosion in soil, such as climatic conditions and external loads. The second image showcases an advanced electrochemical corrosion characterization and imaging system designed to measure and visualize corrosion patterns on various surfaces. Lastly, the third image explores the diverse origins and pathways of organic green corrosion inhibitors, crucial for environmentally



(a) The image depicts a diagram illustrating the factors affecting the corrosion of a metal pipe in a soil environment.[1]



(b) Electrochemical Corrosion Characterization and Imaging System[3]



(c) Organic Green Corrosion Inhibitor[24]

Figure 5: Examples of Non-Intrusive Monitoring Techniques

friendly corrosion prevention strategies. Together, these examples underscore the importance of integrating innovative, non-intrusive techniques in pipeline maintenance to effectively monitor and mitigate corrosion, enhancing the operational efficiency and sustainability of pipeline systems [1, 3, 24].

5.2 Optical Fiber Monitoring

Optical fiber monitoring has emerged as a cutting-edge technology in pipeline corrosion monitoring, offering capabilities for real-time, high-resolution data acquisition. This technology leverages optical fibers to detect and quantify changes in strain and temperature along the pipeline, indicative of corrosion activity. The application of Optical Frequency Domain Reflectometry (OFDR) is particularly noteworthy, enabling precise localization of corrosion-related anomalies by measuring Rayleigh backscatter along the fiber [2].

A significant advantage of optical fiber monitoring is its ability to provide continuous, distributed sensing over long distances, making it suitable for extensive pipeline networks. This capability allows for early detection of corrosion and other structural changes, facilitating timely maintenance interventions and reducing the risk of catastrophic failures. The high spatial resolution of OFDR enhances the detection of localized defects, such as pitting and cracking, critical for assessing pipeline integrity [5].

Moreover, integrating optical fiber monitoring with advanced data analytics and machine learning algorithms can significantly improve the predictive accuracy of corrosion models. By analyzing the data generated by optical sensors, these algorithms can identify patterns indicating the onset of corrosion, enabling more effective preventive maintenance strategies [6]. Continuous real-time monitoring provides operators with valuable insights into the health of their infrastructure, allowing for informed decision-making and resource allocation.

The non-intrusive nature of optical fiber monitoring ensures that pipeline operations are not disrupted during the monitoring process, preserving the operational continuity of water distribution systems. The high sensitivity and accuracy of distributed optical fiber sensing technology render it essential for modern pipeline corrosion management. This technology enables precise monitoring of both corrosion and leakage, facilitating timely interventions and enhancing the safety and integrity of pipeline operations. By employing techniques such as OFDR, operators can effectively map corrosion locations and assess severity, significantly improving pipeline safety protocols [13, 2, 5, 1].

5.3 Robotic NDT Inspection Methods

Robotic Non-Destructive Testing (NDT) methods have become integral to modern pipeline inspection strategies, offering advanced capabilities for assessing pipeline conditions without causing damage. These methods utilize robotic vehicles equipped with sophisticated sensors and instruments to navigate through pipelines, performing detailed inspections and mapping remaining wall thickness [33]. The deployment of robotic NDT systems allows for comprehensive evaluations of pipeline integrity, identifying defects such as corrosion, cracks, and other structural anomalies that may compromise safety and functionality.

The use of robotic vehicles in NDT provides several advantages over traditional inspection methods. Firstly, these systems can access hard-to-reach areas within pipelines, allowing for thorough inspections of sections that might otherwise be neglected. This capability is particularly important for pipelines located in remote or hazardous environments where manual inspections are challenging. Secondly, robotic NDT methods offer high-resolution data acquisition, enabling precise measurements of wall thickness and the detection of even minor defects. This level of detail is crucial for early identification of potential issues, allowing for timely maintenance interventions and reducing the risk of catastrophic failures.

Moreover, robotic NDT systems are equipped with advanced data processing capabilities, facilitating real-time analysis and interpretation of inspection results. This feature significantly improves decision-making by providing operators with actionable insights derived from systematic analyses of pipeline condition data, enabling effective identification and addressing of potential corrosion causes and integrity issues in their infrastructure [14, 13, 1]. The integration of robotic NDT methods with other advanced monitoring technologies, such as optical fiber sensors, further enhances the ability to detect and manage corrosion and other forms of degradation.

5.4 Preventive Maintenance and Scheduling

Preventive maintenance (PM) is a critical component of pipeline management strategies aimed at ensuring the long-term integrity and reliability of water distribution systems. The primary objective of PM is to perform regular inspections and maintenance activities based on predictive models and historical data, preventing unexpected failures and minimizing downtime. Integrating advanced technologies, such as machine learning and AI, into PM strategies offers significant potential for enhancing real-time data analysis and developing standardized protocols for pipeline inspection and maintenance [14].

The application of decision support frameworks in PM scheduling is essential for optimizing maintenance activities and resource allocation. A notable approach combines a decision support framework with a polynomial-time algorithm to compute optimal PM schedules, providing practitioners with alternative solutions that balance operational efficiency with the need for regular inspections and repairs [29]. By leveraging these computational tools, operators can derive maintenance schedules that minimize disruptions and extend the service life of pipeline infrastructure.

Furthermore, incorporating predictive modeling techniques into PM strategies allows for more accurate forecasting of potential pipeline failures. These models utilize historical data and real-time monitoring inputs to predict the likelihood of corrosion-related defects, enabling timely interventions and reducing the risk of catastrophic failures. Ongoing enhancements of predictive models, achieved through advanced machine learning algorithms, significantly improve their accuracy and reliability in forecasting outcomes, particularly in complex systems such as water pipeline integrity management, where systematic analysis of various corrosion causes is essential for effective maintenance and risk mitigation [34, 13, 1].

Effective preventive maintenance and scheduling are crucial for maintaining the operational efficiency and safety of water distribution systems. By adopting advanced technologies and decision support frameworks, the industry can develop robust PM strategies that ensure the long-term sustainability of pipeline infrastructure. Future research should continue exploring the potential of machine learning and AI technologies in refining PM practices and establishing standardized protocols for pipeline management [14].

5.5 Cost-Effective Asset Management

Cost-effective asset management in water distribution systems is vital for pipeline maintenance strategies, focusing on optimizing resource allocation to maintain infrastructure integrity while minimizing costs. Traditional maintenance approaches, such as recurring schedules and run-to-failure strategies, often fail to address the complexities of modern pipeline systems [17]. These methods can lead to unnecessary expenditures and increased risk of unexpected failures, underscoring the need for more dynamic and predictive asset management frameworks.

The development of advanced maintenance planning frameworks, as discussed by Bukhsh et al., presents a promising solution to these challenges by integrating predictive analytics and real-time monitoring data into maintenance decision-making processes [17]. Such frameworks enable operators to prioritize maintenance activities based on the actual condition of pipeline assets, rather than relying solely on fixed schedules or reactive strategies. This approach enhances maintenance operations' efficiency and reduces the likelihood of costly unplanned repairs.

Incorporating machine learning and data analytics into asset management practices significantly improves the ability to predict and mitigate pipeline failures by enhancing defect detection, growth prediction, and risk-based management, ultimately ensuring safer and more reliable pipeline operations. This integration leverages advanced in-line inspection data and various non-destructive testing methods, allowing for more accurate assessments of pipeline integrity and timely maintenance interventions [14, 13]. By analyzing historical data and real-time inputs from monitoring technologies, these tools can identify patterns indicating potential issues, enabling proactive maintenance interventions. This data-driven approach allows for accurate forecasting of asset deterioration, facilitating strategic planning and resource allocation.

Moreover, integrating cost-effective asset management practices with regulatory compliance requirements ensures maintenance strategies align with industry standards and environmental considerations. By implementing a comprehensive and integrated approach to asset management, water distribution systems can enhance their operational resilience and sustainability. This strategy addresses the challenges posed by aging and corroded pipelines, which significantly compromise seismic performance and overall system reliability, and incorporates advanced methodologies such as deep reinforcement learning for optimal rehabilitation planning. Consequently, this holistic framework can lead to improved asset longevity and ensure a reliable water supply during and after seismic events, thereby extending the service life of critical infrastructure [17, 10, 1].

Feature	Non-Intrusive Monitoring Techniques	Optical Fiber Monitoring	Robotic NDT Inspection Methods
Technology Type	Advanced Sensors	Optical Fibers	Robotic Vehicles
Data Acquisition	Real-time Data	High-resolution Data	High-resolution Data
Maintenance Strategy	Proactive Monitoring	Continuous Sensing	Detailed Inspections

Table 2: This table provides a comparative analysis of three primary pipeline maintenance techniques: Non-Intrusive Monitoring Techniques, Optical Fiber Monitoring, and Robotic NDT Inspection Methods. It highlights the distinct technology types, data acquisition capabilities, and maintenance strategies associated with each method, offering insights into their application in modern pipeline infrastructure management.

6 Challenges and Future Directions

6.1 Modeling and Simulation Challenges

Modeling and simulating pipeline corrosion present significant challenges due to the complex nature of corrosion processes and their environmental influences. Accurately representing multi-physics phenomena like pitting corrosion involves intricate modeling of transport and reaction kinetics, often resulting in computationally intensive processes [27]. Traditional models struggle with scalability and efficiency when handling large datasets [35]. Moreover, capturing the complex interactions of multiple species in localized corrosion scenarios remains problematic [15], particularly in challenging zones like the liquid-gas transition [18]. Uniform modeling assumptions fail to depict the heterogeneous nature of real-world corrosion, necessitating more sophisticated approaches [9].

The adoption of novel materials, such as ionic liquids, for protective coatings introduces additional challenges due to their viscosity and application techniques [23]. Maintenance scheduling is complicated by the combinatorial nature of defect repair timing, requiring a balance between maintenance needs and cost-effectiveness [29, 17]. Limitations in measurement systems like Optical Frequency Domain Reflectometry (OFDR) affect leak detection accuracy [5], while robotic inspection methods demand precise scanning for effective data acquisition [33]. Incorporating time-variant effects is essential for accurate seismic risk assessments, influencing corrosion modeling under varying conditions [10].

Addressing these challenges requires advanced computational techniques and methodologies. Emerging models, including cellular automata, peridynamics, and phase-field models, incorporate kinetics of anodic reactions and ion transport to predict corrosion damage evolution [27]. A comprehensive analysis of corrosion causes in water pipelines is vital, highlighting the need for methodologies addressing environmental, operational, and material factors while identifying research gaps and future directions [1].

6.2 Machine Learning and Data Integration

Integrating machine learning into pipeline corrosion management enhances predictive accuracy and operational efficiency. Advanced algorithms process large datasets to improve anomaly detection and prediction [35], leveraging distributed processing to manage the scale and complexity of data from various inspection methods. Robust models incorporating historical and real-time data are crucial for effective pipeline integrity management [14], facilitating proactive maintenance and reducing failure risks.

Support Vector Regression (SVR), optimized with algorithms like Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Firefly Algorithm (FFA), enhances prediction accuracy in corrosion management [6]. These methods capture complex patterns in corrosion processes, supporting targeted maintenance strategies and ensuring system reliability.

Machine learning and data-driven approaches represent significant advancements in corrosion management. Utilizing technologies like fault tree analysis (FTA), fuzzy analytical hierarchy process (FAHP), and in-line inspection (ILI) tools refines corrosion predictions, maintenance schedules, and system resilience [13, 7, 10, 1]. Future research should explore machine learning's potential in refining models and developing innovative solutions.

6.3 Corrosion Inhibitor Development

Advancements in corrosion inhibitor development focus on new materials and methodologies to enhance effectiveness and sustainability. Ionic liquids and graphene are promising due to their unique properties, forming protective layers that reduce electrochemical reactions [23]. Future research should emphasize green inhibitors from natural resources to align with sustainability and reduce environmental impact [25]. This involves optimizing extraction techniques and exploring synergistic effects between inhibitors. Incorporating nanotechnology into formulations offers performance improvements through precise molecular interaction control.

Refining models to include pore formation and ion transport mechanisms advances the predictive capabilities of inhibitors [16]. Combining electrochemical measurements with Visual Surface Inspection (VSI) imaging enhances understanding of pitting corrosion, informing inhibitor development [22]. Extending computational frameworks to heterogeneous materials and improving efficiency through domain decomposition will broaden model applicability [26].

Exploring benzotriazole interactions with environmental conditions and corrosive agents is vital for refining inhibitors and developing new formulations [32]. Future research should focus on cost-effective, non-toxic inhibitors and enhanced protective coatings to ensure long-term pipeline integrity [7].

A multidisciplinary approach integrating advanced modeling, sustainable practices, and experimental validation is essential for future corrosion inhibitor development. Insights from analyses of pipeline corrosion causes, innovative materials like green polymers, and understanding electrochemical mechanisms will advance corrosion management, ensuring system integrity and sustainability [30, 22, 1].

6.4 Regulatory and Environmental Considerations

Regulatory and environmental considerations are crucial in shaping corrosion management strategies. The complexity of corrosion processes and various influencing factors pose challenges in pipeline integrity management [1]. Robust regulatory frameworks guide effective corrosion management practices.

Frameworks like REACH and OSPAR provide guidelines for developing eco-friendly inhibitors [30], emphasizing sustainable materials to minimize environmental impact [23]. The integration of sustainable materials across industries aligns with the demand for responsible corrosion management solutions. Green inhibitors from natural sources support this goal by reducing reliance on traditional chemicals with environmental risks.

Implementing regulatory frameworks and sustainable practices presents challenges. Dependency on network infrastructure for distributed processing may introduce latency, affecting monitoring and predictive model efficiency [35]. Ongoing research and technological advancements are needed to enhance system reliability and responsiveness.

6.5 Infrastructure Resilience and Maintenance Strategies

Enhancing infrastructure resilience against corrosion is vital for water distribution system integrity. This involves integrating advanced technologies and methodologies to predict, monitor, and mitigate corrosion risks. Future research should optimize sustainable inhibitor synthesis, explore new natural sources, and develop hybrid materials for enhanced protection [30], aligning with sustainability goals.

Transient wave methods combined with emerging technologies offer potential for improving resilience. These methods detect and characterize corrosion-induced anomalies, providing insights into pipeline conditions [4]. Integrating transient wave techniques with monitoring technologies like OFDR enhances understanding of pipeline integrity, facilitating timely maintenance.

Future research should advance In-Line Inspection (ILI) technologies, develop better signal processing methods, and explore hybrid models combining data-driven and physics-based approaches for defect prediction [13]. These advancements will improve corrosion assessment accuracy and support effective maintenance strategies.

Robotic systems in pipeline inspection represent a promising avenue for resilience. Research should optimize robotic systems for faster inspections, develop sensor arrangements, and address challenges in relating complex geometries to Pulsed Eddy Current (PEC) signals [33]. These improvements enable efficient and accurate condition assessments, reducing failure risks.

Adopting Deep Reinforcement Learning (DRL)-based methods for maintenance planning improves outcomes over traditional strategies, lowering failure probabilities and costs [17]. Future research should explore further optimizations and applications in other domains requiring maintenance scheduling, such as power plants and medical facilities [29].

7 Conclusion

Effective management of pipeline corrosion is paramount for maintaining the structural integrity and operational efficiency of water distribution systems. This survey elucidates the multifaceted nature of corrosion, including uniform and pitting types, while examining the chemical and environmental factors that exacerbate these issues. Advanced monitoring technologies, such as Optical Frequency Domain Reflectometry and robotic Non-Destructive Testing, are pivotal for early detection and intervention. The integration of machine learning and data-driven strategies into corrosion management holds promise for improving predictive capabilities and optimizing maintenance routines.

The pursuit of environmentally sustainable corrosion inhibitors, including those derived from natural sources and advanced materials like ionic liquids and graphene, is essential for aligning with ecological goals. Furthermore, the exploration of innovative methodologies, such as phase-field models for simulating hydrogen-induced pitting corrosion, highlights the importance of novel approaches in health detection and corrosion prevention. The implementation of regulatory frameworks and sustainable practices is vital for reducing environmental impact and ensuring adherence to industry standards.

References

[1] Hassan M Hussein Farh, Mohamed El Amine Ben Seghier, Ridwan Taiwo, and Tarek Zayed. Analysis and ranking of corrosion causes for water pipelines: A critical review. *NPJ Clean Water*, 6(1):65, 2023.

[2] Tao Jiang, Liang Ren, Zi-guang Jia, Dong-sheng Li, and Hong-nan Li. Pipeline internal corrosion monitoring based on distributed strain measurement technique. *Structural Control and Health Monitoring*, 24(11):e2016, 2017.

[3] Yunda Chen, Zirui Yang, Xinru Bai, Fangxin Zou, and Frederic B Cegla. High-precision in situ 3d ultrasonic imaging of localized corrosion-induced material morphological changes. *npj Materials Degradation*, 7(1):77, 2023.

[4] Tong-Chuan Che, Huan-Feng Duan, and Pedro J Lee. Transient wave-based methods for anomaly detection in fluid pipes: A review. *Mechanical Systems and Signal Processing*, 160:107874, 2021.

[5] Liang Ren, Tao Jiang, Zi-guang Jia, Dong-sheng Li, Chao-lin Yuan, and Hong-nan Li. Pipeline corrosion and leakage monitoring based on the distributed optical fiber sensing technology. *Measurement*, 122:57–65, 2018.

[6] Mohamed El Amine Ben Seghier, Behrooz Keshtegar, Kong Fah Tee, Tarek Zayed, Rouzbeh Abbassi, and Nguyen Thoi Trung. Prediction of maximum pitting corrosion depth in oil and gas pipelines. *Engineering Failure Analysis*, 112:104505, 2020.

[7] FO Kolawole, SK Kolawole, JO Agunsoye, JA Adebisi, SA Bello, and SB Hassan. Mitigation of corrosion problems in api 5l steel pipeline-a review. *J. Mater. Environ. Sci*, 9(8):2397–2410, 2018.

[8] Núbia Rosa da Silva, Pieter Van der Weeën, Bernard De Baets, and Odemir Martinez Bruno. Improved texture image classification through the use of a corrosion-inspired cellular automaton, 2014.

[9] Shanmukha Shetty, Sauvik Banerjee, Siddharth Tallur, and Yogesh M. Desai. Effectiveness of multi-physics numerical model in simulating accelerated corrosion with spatial and temporal non uniformity, 2021.

[10] Weinan Li, Ram K. Mazumder, and Yue Li. Time-variant seismic resilience analysis model for water distribution systems, 2023.

[11] Kevin Leung. First principles determination of the potential-of-zero-charge in an alumina-coated aluminum/water interface model for corrosion applications, 2022.

[12] Jonas K. Sunde, Duncan N. Johnstone, Sigurd Wenner, Antonius T. J. van Helvoort, Paul A. Midgley, and Randi Holmestad. Crystallographic relationships of t-/s-phase aggregates in an al-cu-mg-ag alloy, 2019.

[13] Mingjiang Xie and Zhigang Tian. A review on pipeline integrity management utilizing in-line inspection data. *Engineering Failure Analysis*, 92:222–239, 2018.

[14] Qiuping Ma, Guiyun Tian, Yanli Zeng, Rui Li, Huadong Song, Zhen Wang, Bin Gao, and Kun Zeng. Pipeline in-line inspection method, instrumentation and data management. *Sensors*, 21(11):3862, 2021.

[15] Xiangming Sun, Jayendran Srinivasan, Robert G. Kelly, and Ravindra Duddu. Numerical investigation of critical electrochemical factors for localized corrosion using a multi-species reactive transport model, 2020.

[16] F. D. A. Aarão Reis. Effects of porosity in a model of corrosion and passive layer growth, 2017.

[17] Zaharah A. Bukhsh, Nils Jansen, and Hajo Molegraaf. A maintenance planning framework using online and offline deep reinforcement learning, 2023.

[18] Weimin Zhao, Timing Zhang, Yonglin Wang, Jianhua Qiao, and Zerui Wang. Corrosion failure mechanism of associated gas transmission pipeline. *Materials*, 11(10):1935, 2018.

[19] Kevin Leung. First principles, explicit interface studies of oxygen vacancy and chloride in alumina films for corrosion applications, 2021.

[20] Quinn Campbell. Voltage-dependent first-principles simulation of insertion of chloride ions into al/al$_2$o$_3$ interfaces using the quantum continuum approximation, 2023.

[21] V. N. Chuvil'deev, A. V. Nokhrin, C. V. Likhnitskii, A. A. Murashov, N. V. Melekhin, K. A. Rubtsova, A. M. Bakmetyev, P. V. Tryaev, R. A. Vlasov, N. Yu. Tabachkova, and A. I. Malkin. Effect of annealing on the hot salt corrosion resistance of the fine-grained titanium alpha-alloy ti-2.5al-2.6zr obtained via cold rotary swaging, 2024.

[22] Open.

[23] Mona Taghavikish, Naba Kumar Dutta, and Namita Roy Choudhury. Emerging corrosion inhibitors for interfacial coating. *Coatings*, 7(12):217, 2017.

[24] Lekan Taofeek Popoola. Organic green corrosion inhibitors (ogcis): a critical review. *Corrosion Reviews*, 37(2):71–102, 2019.

[25] Ahmed A Al-Amiery, Wan Nor Roslam Wan Isahak, and Waleed Khalid Al-Azzawi. Corrosion inhibitors: natural and synthetic organic inhibitors. *Lubricants*, 11(4):174, 2023.

[26] Abu Naser Sarker, Ronald D. Haynes, and Michael Robertson. Moving mesh simulations of pitting corrosion, 2023.

[27] Siavash Jafarzadeh, Ziguang Chen, and Florin Bobaru. Computational modeling of pitting corrosion. *Corrosion reviews*, 37(5):419–439, 2019.

[28] Mojtaba Mokhtari, Xintong Wang, and Jorgen Amdahl. Numerical analysis of pit-to-crack transition under corrosion fatigue using a stochastic pit generation algorithm, 2023.

[29] Assia Boumahdaf and Michel Broniatowski. A recursive algorithm for a pipeline maintenance scheduling problem, 2016.

[30] Chandrabhan Verma, Eno E Ebenso, MA Quraishi, and Chaudhery Mustansar Hussain. Recent developments in sustainable corrosion inhibitors: design, performance and industrial scale applications. *Materials Advances*, 2(12):3806–3850, 2021.

[31] Klodian Xhanari, Matjaž Finšgar, Maša Knez Hrnčič, Uroš Maver, Željko Knez, and Bujar Seiti. Green corrosion inhibitors for aluminium and its alloys: a review. *RSC advances*, 7(44):27299–27330, 2017.

[32] Chiara Gattinoni and Angelos Michaelides. Understanding corrosion inhibition with van der waals dft methods: the case of benzotriazole, 2015.

[33] Jaime Valls Miro, Nalika Ulapane, Lei Shi, Dave Hunt, and Michael Behrens. Robotic pipeline wall thickness evaluation for dense nondestructive testing inspection. *Journal of Field Robotics*, 35(8):1293–1310, 2018.

[34] Anne-Laure Fougères, John P. Nolan, and Holger Rootzén. Models for dependent extremes using stable mixtures, 2007.

[35] Munehiro Nishida, Taisei Matsumoto, Hiroya Koga, Terukazu Kosako, and Yutaka Kadoya. Evaluation of surface roughness of metal films using plasmonic fano resonance in attenuated total reflection, 2019.

Disclaimer:

SurveyX is an AI-powered system designed to automate the generation of surveys. While it aims to produce high-quality, coherent, and comprehensive surveys with accurate citations, the final output is derived from the AI's synthesis of pre-processed materials, which may contain limitations or inaccuracies. As such, the generated content should not be used for academic publication or formal submissions and must be independently reviewed and verified. The developers of SurveyX do not assume responsibility for any errors or consequences arising from the use of the generated surveys.