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Understanding and Mitigating Corrosion in Pipelines: A Comprehensive Study for Mechanical Engineers

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Abstract: Corrosion in pipelines is one of the serious challenges in the field of mechanical engineering, particularly with regards to oil and gas, water distribution, and other chemical processes. This article addresses an in-depth effect of corrosion mechanisms, factors influencing corrosion rates, and the effect of corrosion on pipeline integrity. Additionally, the paper will explore advanced methods for detecting, preventing, and mitigating corrosion in pipelines. The study is supported by real-world case studies illustrating the consequences of pipeline failures due to corrosion and emphasizes the importance of regular maintenance and innovative material selection. The findings are intended to guide mechanical engineers in designing more durable and corrosion-resistant pipeline systems. This comprehensive study examines corrosion mechanisms, factors influencing corrosion rates, and advanced methods for detecting, preventing, and mitigating corrosion in pipelines, with real-world case studies underscoring the importance of regular maintenance and innovative material selection for mechanical engineers.

Introduction

The transportation of oil, gas, and chemicals relies heavily on pipeline infrastructure, making a significant contribution to the economy. Nevertheless, one of the primary challenges faced by these pipelines is corrosion ([21]). Corrosion is a natural process in which metals degrade due to electrochemical reactions with the environment. Without proper engineering and preventive maintenance, corrosion can lead to leaks and ruptures in pipelines, resulting in costly incidents and environmental damage ([14]).

Pipeline integrity can be harmed by various degrees of corrosion mechanisms, for instance, chemical corrosion, electrochemical corrosion, and microbial corrosion ([19], p. 6-10). Chemical corrosion occurs when metals directly interact with their surrounding environment, leading to degradation ([5]). Electrochemical corrosion involves the flow of electric current between different areas on a metal surface caused by differences in electrical potential ([5]). Microbial corrosion is accelerated by microorganisms that deteriorate pipeline materials ([5]).

Corrosion rates are influenced by factors such as environmental conditions (including soil composition and moisture levels), material properties (including alloy composition and surface finish), and operating parameters like temperature and pressure ([15]).

The impact of corrosion on pipeline integrity is substantial, often resulting in leaks, ruptures, and potentially catastrophic failures. Utilizing advanced methods for detecting corrosion, such as non-destructive testing techniques and remote monitoring technologies, can help identify potential issues early on ([15]).

It is crucial to prevent and mitigate corrosion in pipelines to ensure their longevity. Coating and lining solutions offer a protective barrier between the pipeline material and its environment ([1]). Cathodic protection systems assist in preventing corrosive reactions through the application of outer electrical current to disrupt the original flow of electrons which seem to cause corrosion ([1]).

Real-world case studies underscore the importance of regular maintenance practices in preventing costly failures due to corrosion. Innovative material selection plays a critical role in enhancing pipeline integrity and longevity ([26]).

In conclusion, understanding the mechanisms of corrosion in pipelines is essential for their safe operation. By implementing preventive maintenance strategies, utilizing advanced detection methods, and selecting appropriate materials, the impact of corrosion on pipeline integrity can be minimized. Ongoing research into innovative technologies will continue to foster improvements in pipeline safety and reliability for years to come ([27]).

2. Corrosion Mechanisms

2.1. Chemical Corrosion

Chemical corrosion has been a serious danger poses in the oil and gas sector, especially within petroleum refineries, where it can lead to severe breakdowns and costly disruptions in operations. Naphthenic acid (NA) stands out as one of the most corrosive substances found in crude oil, capable of causing various types of corrosion within refinery equipment ([3]). Due to its aliphatic structure and terminal carboxylic acid group, NA can create shallow or deep pits within units like vacuum and atmospheric distillation columns ([3]). Furthermore, NA can result in metal thinning, uniform etching on stainless steel surfaces, as well as grooves and marks on transmission lines and heating tubes ([3]). These examples underscore the diverse ways in which chemical corrosion can manifest in refinery machinery due to specific corrosive elements present in the environment.

To counteract chemical corrosion effectively, refineries depend on customized chemical inhibitors and scavengers tailored to address fluid properties, operational conditions, flow rates, and product variations ([36], pp. 11-15). These inhibitors are strategically introduced into the process at crucial points through dispersion or distribution systems to ensure accurate dosages are maintained ([36], pp. 11-15). By implementing these mitigation measures based on monitoring data, refineries can proactively combat the detrimental effects of chemical corrosion on their equipment.

Furthermore, water chemistry plays a vital role in CO2-induced corrosion within pipelines by influencing speciation from simple to complex

Figure 1: Above are of the instances of oil refineries menaces occurred being corroded. a. The G. Eagle Refinery, b. R. Refinery, c.C. Refinery. (source: reference [3])

Unit	Temperature (ºC)	Corrosion Type	Primarily effect
Desalter	50	Contained pitting oxidization.	Salt
Atmospheric Cleansing	371	Located pitting erosion, and flow-fitted localized corrosion	Sulfur, Naphthenic acid, HCl
Vacuum Distillation	400	Localized pitting corrosion	Sulfur, Naphthenic acid, HCl
Catalytic cracking	600	Inter-granular corrosion, SCC, erosion-corrosion	
Hydrotreater	670	SCC, Hydrogen embrittlement, Pitting	H_2S, Ammonium salts, polythionic acid
Sour water stripper	245	Localized pitting corrosion, erosion-corrosion	H_2S, flow velocity, chloride

Table 1: A brief description of Refinery Units fitted with Corrosion Status.

(Source: reference [3])

Constituent	Chemical type
Hydro-carbons:	
Paraffinic (Alkanes)	Plain chain; split restraint
Naphthenic	Alkyl cyclopentanes; alkyl cyclohexanes
Aroma entity	Alkyl benzenes; aroma naphthenic fluorenes; polynuclear aromas
Melted vapors	Nitrogen (N_2); carbon dioxide (CO_2)
Sulfur composites	Elemental sulfur (S_8), (H_2S)sub-ref-a, mercaptans; Disulfides raw sulfides, polysulfides; sulfones thiophenes & hydrogen sulfide benzothiophenes;
Natural nitrogen mixtures	Pyridine, quinoline
Natural oxygen composites	Carboxylic acids (including naphthenic acids)sub-ref-b, alcohols, phenolssub-ref-b, aldehydes, ketones, esters, ethers, oxyacids
Biological metallic mixes	Porphyrins
Colloidal particles	Asphaltenes; resins; paraffin waxes
Surfactants	Sulfonic acids, sulfonates, sodium napthenates
Metals	Vanadium, nickelsub-ref-c, ironsub-ref-c, aluminum, sodium, potassium, calcium, copper
Water (S &Wsub-ref-d or BS & Wsub-ref-d)sub-ref-e	Fresh or saline
Solids	Sandy soil, dirty surface, silt, soil, mud, corroded products (metallic element, oxides, sulfides, salts)

Table 2: Crude oil constituents. (Source: reference [3])

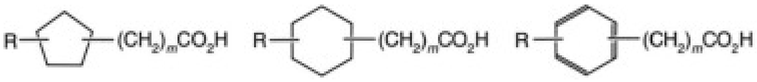
Key	Structure
Acyclic Z = 0	
Moncyclic Z = −2	
Bicyclic Z = −4	
Tricyclic Z = −6	

Table 3: These are some typical examples of aromatic as well as non-aromatic napthenic acids and their constituent structures [3])

Figure 2: Resultant effect of naphthenic acid being corroded (NA),. (Source: reference [3])

Corrosion Form	Refinery Unit	Remarks
It may be in deeper, Shallow, large and often round pits	The vacuum from the within contains atmosphere and purification columns that is shell, wall shell, bubble caps and trays	This may take place owing to the boil and reduction of NA on metal sub-surface and it may occur mainly in liquid that is mixed vapor streams
The metal may be thin and sometimes uniform.	It contains stainless steel coupled with the shell of the empty cleansing column	

Corrosion Form	Refinery Unit	Remarks
Trenches, striations, and deeper confined attack	In transmission lines and heating tubes (furnace)	Serious NA corrosion may occur across the bends, elbows, tees, and pumps when there is disruption in the flow.
overall corrosion	Carbon steel trays and bubble caps	This may also be witnessed through the unusual change of acid and non-acidic crudes in the refinery

Table 4: the following are sorts of corroded units being used at various refinery units because of naphthenic acid. (Source: reference [3])

Grade	Yield Stress	Extreme Tensile	Charpy Higher-Shelf	Strain Solidifying
Empty Cell	(MPa)	Strength (MPa)	Energy (ft-Ib)	Coefficient
X52	411	508	32	0.0832
X65	483	625	122	0.0881
X70	525	601	70	0.0856

Table 5: Automated and breakage materials assigned used in offshore and pipeline projects. (Source: reference [2])

CO_2	Solluble carbon dioxide
H_2CO_3	Carbon acid
HCO3-	Bicarbonat ion
CO32-	Carbonate ion
H^+	Hydrogen ion
OH^-	Hydro-oxide ion
Fe^{2+}	Iron ion
Cl^-	Chloride ion
Na^+	Sodium ion
K^+	Potassium
Ca^{2+}	Calcium ion
Mg^{2+}	Magnesium ion
Ba^{2+}	Barium ion
Sr^{2+}	Strontium ion
CH_3COOH (HAc)	Acetic acid
CH_3COO^- (Ac^-)	Acetate ion
HSO4-	Bisulphate ion
SO42-	Sulphate ion

Table 6: Other unique organisms obtainable in oilfield brines (source: reference [9])

Empty Cell	Response	Balance constant
Dissoluble of carbon dioxide	$CO_2(g) \Leftrightarrow CO_2$	Ksol=CCO2/PCO2
Aquatic separation	H2O⇔Kb,waKf,waH++OH-	Kwa=CH+COH-
Carbon dioxide hydration	CO2+H2O⇔Kb,hyKf,hvH2CO3	Khy=CH2CO3/CCO2
Carbon acid separation	H2CO3⇔Kb,caKf,caH++HCO3-	Kca=CH+CHCO3-/CH2CO3
Bicarbonate anion dissociation	HCO3-⇔Kb,biKf,biH++CO32-	Kbi=CH+CCO32-/CHCO3-
Acetic acid dissociation	HAc⇔Kb,acKf,acH++Ac-	KHAc=CH+CAc-/CHAc
Hydrogen sulphate anion dissociation	HSO4-⇔Kb,HSO4-Kf,HSO4-H++SO42-	KHSO4-=CH+CSO42-/CHSO4-

Table 7: Again these are some chemical activity typical found in oil/gas field brines and as wel as their reaction constants (source: reference [9])

2.2. Electrochemical Corrosion

Electrochemical corrosion often sets a serious danger to the status and quality of pipelines especially in the domain of oil and gas where exposure to corrosive elements is common. As stated in [1], internal pipeline corrosion can arise from various factors including temperature fluctuations, corrosive gases like CO2 and H2S, water composition, flow velocity, and microbial activity. The synergistic interactions of these elements can hasten the deterioration of pipeline materials, potentially leading to disastrous failures if left unattended. Sweet corrosion, characterized by the acidic environment created by CO2 and water, accounts for a significant portion of pipeline failures.

In addition to sweet corrosion, sour corrosion induced by H2S presence further complicates the corrosion process. According to [20], H2S influences corrosivity potential by impacting pH levels and corrosion product formation. The combined effect of H2S and CO2 on corrosion rates necessitates careful consideration during material selection for pipelines operating in hydrocarbon production settings.

The mechanisms driving electrochemical corrosion involve intricate interactions between pipeline materials and their surrounding environments. As emphasized in [25], factors such as pH levels, temperature variations, and dissolved gases play pivotal roles in determining the speed and scope of corrosion. The dissolution of corrosive gases produced by CO2 and H2S can lead to the creation of less protective compounds on metal surfaces, hastening the degradation process.

A detail analysis of these electrochemical project is vital for implementing effective preventive measures against pipeline corrosion. Techniques like cathodic protection systems highlighted in [14] can aid in mitigating the effects of electrochemical deterioration by actively preventing corrosive reactions at vulnerable points along the pipeline. Furthermore, coating and lining solutions as discussed in [21] provide additional protection against external factors contributing to electrochemical corrosion.

Moreover, as underscored in various references ([2], [20]), thorough studies on material characteristics, environmental conditions, and operational parameters are crucial for evaluating and managing risks associated with electrochemical corrosion effectively. By integrating advanced methods for detecting corrosion such as non-destructive testing techniques ([2]), operators can proactively monitor pipeline integrity and pinpoint potential areas of concern before they escalate into critical challenges.

In summary, a comprehensive grasp of electrochemical corrosion mechanisms is imperative for safeguarding pipeline infrastructure against premature deterioration and ensuring sustained operational reliability. By combining advanced detection methods with proactive maintenance strategies, operators can adeptly manage risks linked to electrochemical deterioration while bolstering the overall integrity of their pipelines.

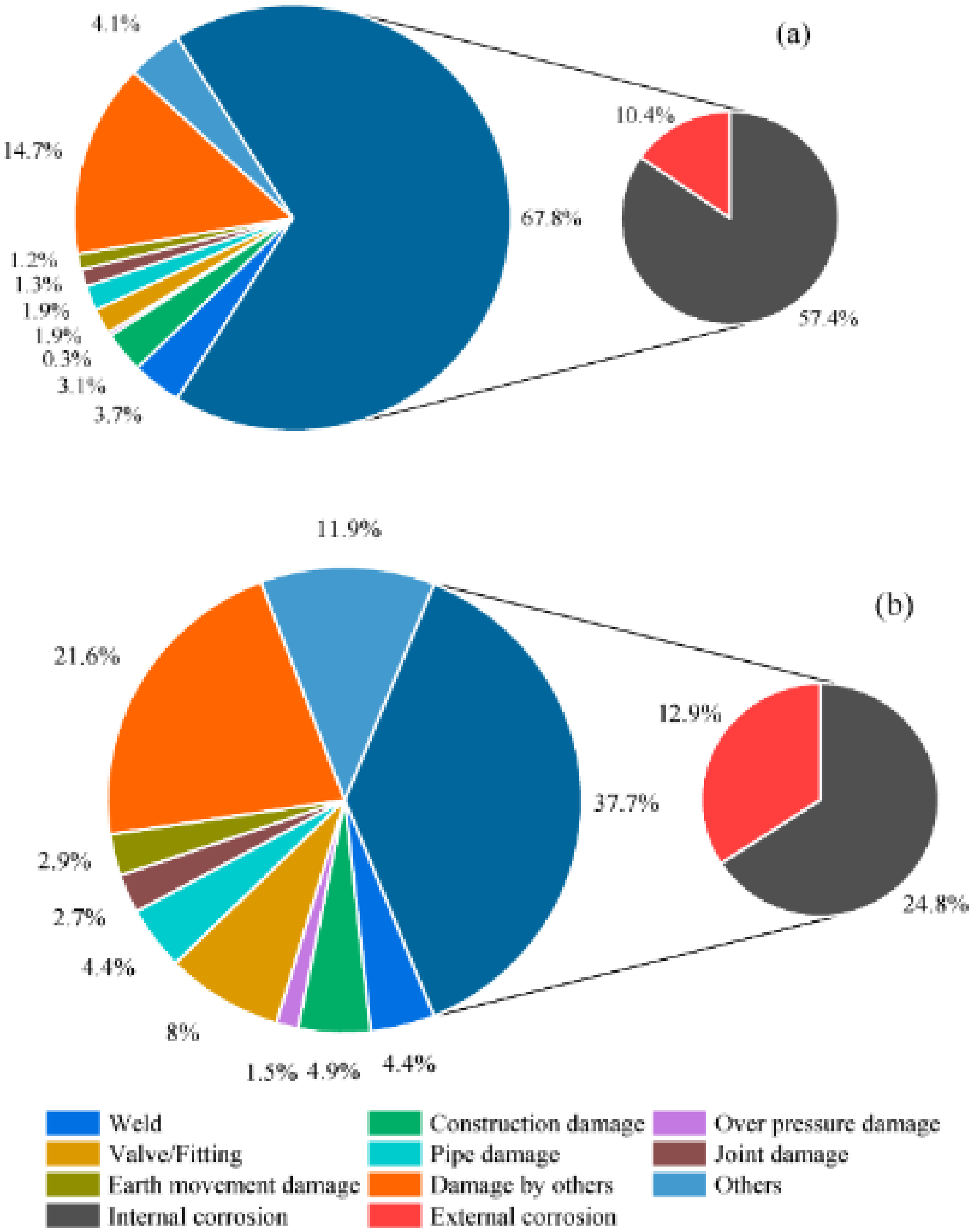


Figure 3: As presented above, are various incidents occurred to numerous pipelines from 1990-2005. for crude oil: there are:(3826 incidents) for natural gas piplines leakage there are (411 incidents). [25])

Chemical	CaO	MgO	K_2O	Na_2O
composition	0.92	1.54	2.17	0.60

Table 8: Dissoluble chemical property of soil sample (wt.%). (Source: reference [42])

Chemical	$CaCl_2 \cdot 2H_2O$	$MgSO_4 \cdot 7H_2O$	KCl	$NaHCO_3$
composition	0.036	0.190	0.069	0.540

Table 9: the natural mixture in tempered soil solutions (g/L). (Source: reference [42])

2.3. Bacterial Rust

Micro-biologically Influenced Corrosion (MIC) asserts an essential risk to the status, safety, and dependability of pipelines, as emphasized in [13] p. 21-25. This form of corrosion is mainly attributed to sulfate-reducing bacteria (SRB), which may lead to local can result in pitting corrosion over time. The colonies of bacteria formed within pipelines generate substances that corrode the metal, making it challenging to prevent, detect, and mitigate the corrosion effectively. Monitoring various pipeline properties is essential for addressing these tasks.

Understanding the mechanisms underlying MIC is crucial for effectively combating its adverse effects. As highlighted in [4], biofilms play a key role in initiating pitting corrosion by compromising the protective layer on certain materials. Additionally, aerobic bacteria present in biofilms can create an anaerobic environment conducive to the growth of anaerobes like SRP and NRP. Grasping these mechanisms is critical for devising successful strategies to manage MIC.

Detecting and preventing MIC entails monitoring the physical, chemical, and biological aspects of pipelines. [24] p. 46-50 outlines different techniques for detecting internal corrosion in gas pipelines, such as visually inspecting the pipeline's interior, measuring the thickness of the pipe cover, and to assess corrosion probes, and to use in-line examination tools. By employing these methods, pipeline operators can identify areas of pitting or metal loss early on and implement appropriate measures to prevent further damage.

Prevention of MIC involves regulating the quality of gas entering the pipeline and regularly analyzing gas samples for corrosive impurities and signs of corrosion products. Through the implementation of corrosion-mitigation strategies and monitoring microbial activity on pipe walls, operators can effectively manage the risks associated with internal corrosion ([24] p. 46-50). Furthermore, maintaining suitable operating conditions for pipelines is essential to keep internal corrosion in check.

In conclusion, Microbiologically Influenced Corrosion poses a significant danger to pipeline integrity due to sulfate-reducing bacteria's actions. Understanding the mechanisms behind MIC and implementing efficient detection and prevention measures are vital for ensuring the long-term safety and reliability of pipelines. By actively monitoring the physical, chemical, and biological features of pipelines and taking proactive steps to mitigate corrosive elements, operators can reduce the impact of MIC on pipeline integrity (as mentioned in [13] p. 21-25 & [24] p. 46-50).

Ref.	Publication year	Research focus
Spark et al.[12]	2020	This study focused on soil factors that caused MIC as a result of buried movable water pipelines. They include essential soil features, bacteria, as well as biochemical systems.
Wasim et al.[17]	2018	The focus here is on soil factors in relation to corrosive activity of metal pipes. In this case, soil resistivity, pH as well as moisture position, temperature, in addition to numerous aeration, particle content, presence of bacteria and other soil type.
Lee and Schwab[18]	2005	This paper addressed factors in connection with drinking water distribution techniques deficiency in the third-world countries. Thus, pipeline corrosion, insufficient disinfection substance, minimal water power, epileptic service, massive leaks, unbalanced water pricing, and excessive water usage.
Imran et al.[19]	2006	This critical review was mainly on the impact of rationing water generation sources on the water quality and water allocation criteria. Similarly, it explains guide for the source water blends to prevent corrosion.
Emerson and De Vet[20]	2015	This study in on Iron-oxidizing bacteria. This instance, often cause corrosion in water allocation within pipelines.
Bachmann and Edyvean[21]	2005	Again, this research addressed the major causes, outcome and affirming biofoul in portable water systems to avoid potential corrosion.
McDougall et al.[22]	2001	The main discussion of this paper is recent developments towards perceiving the role of biofilms on copper corrosive facilities that affect consumption water.
Percival[23]	1998	The microbial biofilms and long-term approach should be dealt with directly on pipe covers is the focus of this study which seeks to cause severe issues affecting consumption water systems, that is corrosive and bacterial build-up.

Table 10: As presented above, are brief studies on the causes of corrosive effect in subsurface metal pipelines. (Source: reference [26])

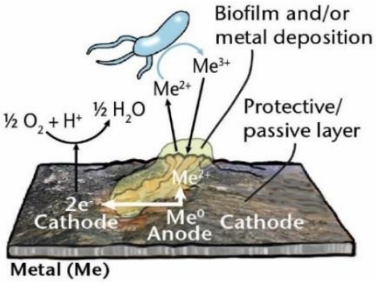
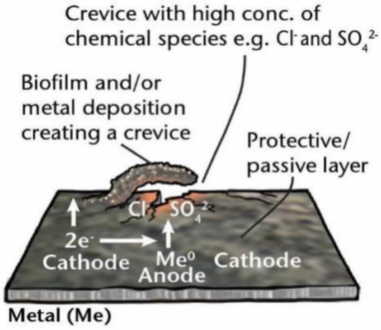
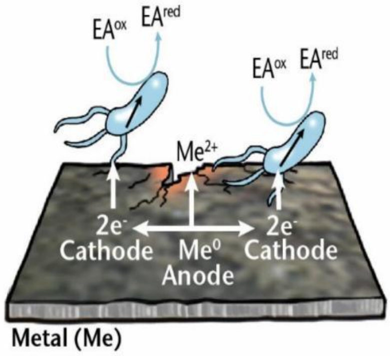
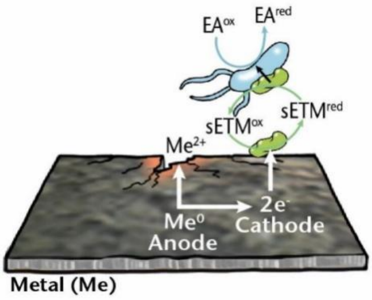
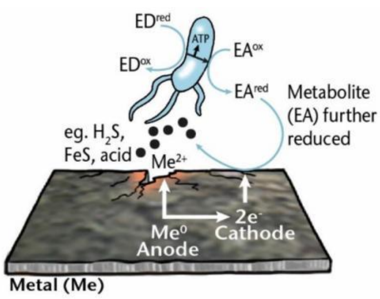
<table>
<tr><th>MIC mechanisms</th><th>Description</th><th>Diagram</th></tr>
<tr><td>Beneath deposit corrosion, oxygen gradient corrosion</td><td>A type of “localized corrosion associated with, and taking place under, or immediately around, a deposit of corrosion products or other substance” (ISO 2020), for instance, biofilm or metal accumulation by metal-oxidizing bacteria which seems to be found in a uneven provision.</td><td>
</td></tr>
<tr><td>Crevice corrosion</td><td>A type of “localized corrosion associated with, and taking place in, or immediately around, a narrow aperture or clearance formed between the metal surface and another surface (metallic or non-metallic).” (ISO 8044)The composition of chloride and other unfamiliar anions in the hole increases corrosion.</td><td>
</td></tr>
<tr><td>Direct EMIC</td><td>Metal corroding can also be achieved through extracellular electron movement by living organisms directly as a result of contact with the metal subsurface, while the electron may consume the surface of be cell enzymes.</td><td>
</td></tr>
<tr><td>Indirect EMIC</td><td>Corrosion of metals on the other hand has been increased by dissoluble electron transfer mediators which will release it from biological elements in connection with electrons received from the metallic elemen for metabolism.</td><td>
</td></tr>
<tr><td>Metabolite MIC (MMIC)</td><td>Corrosive elements lost directly or otherwise by metabolic elements obtained by microorganisms all in aerobic and anaerobic situation.</td><td>
</td></tr>
</table>

Table 11: Brief explanation of the basic mechanisms related to MIC of metals. (source: reference [4])

Engineering/Design Information	Operational Information
The item size and the major dimensions. Corrosive allowance	The period of installation / authorization
The type of material and the manufacturer, in this sense, the manufacturer should be suitable in terms of the materials and channel of processing fluids and conditions.	Functional problems – solids concentration, flow limitation, expected outages
Fabrication procedure, connecting e.g. welding methods, weld strength. affirmation and observation, heat remedy; use of flanged joining (crevice formation)	Fluid features and chemical concentration; which include sample tracing and means of sample accummulation and preserving field and analytical procedures employed.
Design label; engineering images, procedures, flow diagram	Field changes to real design; managing the change of records
System operating window (temperature, inflow and outflow)	The real operating window (temperature,and in-flow should be maintained within range)
Pipeline raising profile This may be the results of several any flow modelling that was conducted Inputs and outputs; systems and circuits	Actual procedure inputs and outputs Microbiological observation data,which include sample locations, sampling and improvement methods, field and lab procedures used.
Corrosive elements and real danger assessment plan should be found	Corrosion observation results from coupons and probes
To identify dead legs, no-flow entities	Leakage/failure and fixing history
List of proposed corrosion observation areas	Corrosion reduction – actual activities, chemical management, pigging, flushing, etc.
First identification of corrosive mitigation should be made	The need to inspect and maintain accurate recourds and also of integrity evaluation records.
Means of initial commission and experimentation; hydrostatic test records, procedures, actual test media used	Procedure upsets, emergency shut down records-Test

Table 12: Execution and engineering information that can prevent the potential danger the MIC appraisal. (source: reference [4])

3. Factors Influencing Corrosion Rates

3.1. Environmental Conditions

Environmental factors have a profound impact on the corrosion rates experienced by pipelines. As indicated in [9], the composition of the water surrounding pipelines can greatly influence the corrosion mechanisms at play. The presence of various dissolved species, including carbon dioxide, bicarbonate ion, chloride ion, and others, can lead to intricate corrosion processes. In a situation where the density of melted salts is high, the resolution may become non-ideal, exacerbating the corrosion even further.

Furthermore, as highlighted in [19] p. 11-15, fluctuations in oxygen levels, moisture content, and soil composition along the pipeline's route can act as concentration cells that accelerate corrosion. The quality of coatings applied along the pipeline is crucial in shielding against environmental factors that hasten corrosion. If coatings become disbonded, not only does this expose the steel to corrosive elements but it also hinders cathodic protection currents.

Additionally, external elements such as temperature variations, humidity levels, and overall environmental conditions can contribute to the deterioration of pipelines. Population density and incidents of mechanical damage also factor into assessing defect risk and determining maintenance strategies for pipelines.

Moreover, according to [31], environmental aspects like H2S concentration, humidity levels, temperature fluctuations, and pH changes are critical for monitoring and mitigating corrosion in sewage pipelines. These factors can impact microbial corrosion rates and affect biochemical processes that contribute to pipeline deterioration.

Lastly, as noted in [7], chloride ions found in soil moisture, humidity levels, and resistivity can fuel corrosion propagation within gas pipelines. The presence of chloride ions boosts bacteria activity within electrochemical cells and speeds up surface oxidation processes.

In conclusion, a comprehensive understanding of the environmental conditions surrounding pipelines is essential for effectively managing corrosion rates. Variables such as water chemistry, soil composition, temperature shifts, and humidity levels all significantly influence the extent of corrosion damage. By considering these environmental factors and implementing suitable mitigation measures like coatings and cathodic protection systems (as detailed in other parts of this document), pipeline operators can bolster the integrity and longevity of their infrastructure. See also [5].

Indicator type	Indicator description	Impact of using degradation models
Lagging indicant	Pipeline leakage	Reactive solution to past incidents
Spills	Data usage for model activity and substantiation	
Corrosion-related failures	Historical information for purification degradation models	
Functional integrity problems	This will help to identify areas susceptible to degradation	
Regulative fines and penalties	Costly consequences of integrity failures	
Reputation damage	Long-term impact on stakeholder trust	

Table 13: Some major lagging indicators of pipeline status. (source: reference [5])

Indicator type	Indicator description	Impact of using degradation models
Leading indicators	Impact and consequence on environment	Resultant impacts on ecosystems and public awareness
CP system status	Early indicators of possible corrosion issues	
Flow rate and pressure	Identifies abnormal flow patterns and pressure drops	
Temperature state and thermal gradient	Detection of overheating in the system and temperature-aligned stresses	
Pipeline coating integrity	Early detection of coating damage	

Indicator type	Indicator description	Impact of using degradation models
	or degradation	
Soil and groundwater monitoring	Tracks soil corrosivity and potential leaks	
Review of information (e.g., ILI, MFL, visual inspections)	Integration of inspection results into potential models	
External factors (e.g., weather, seismic activity)	Include external factors which influence pipeline position	
Maintenance , support and repair history	Enhances maintenance periods according to the historical data	

Table 14: Leading signs of pipeline state. (source: reference [5])

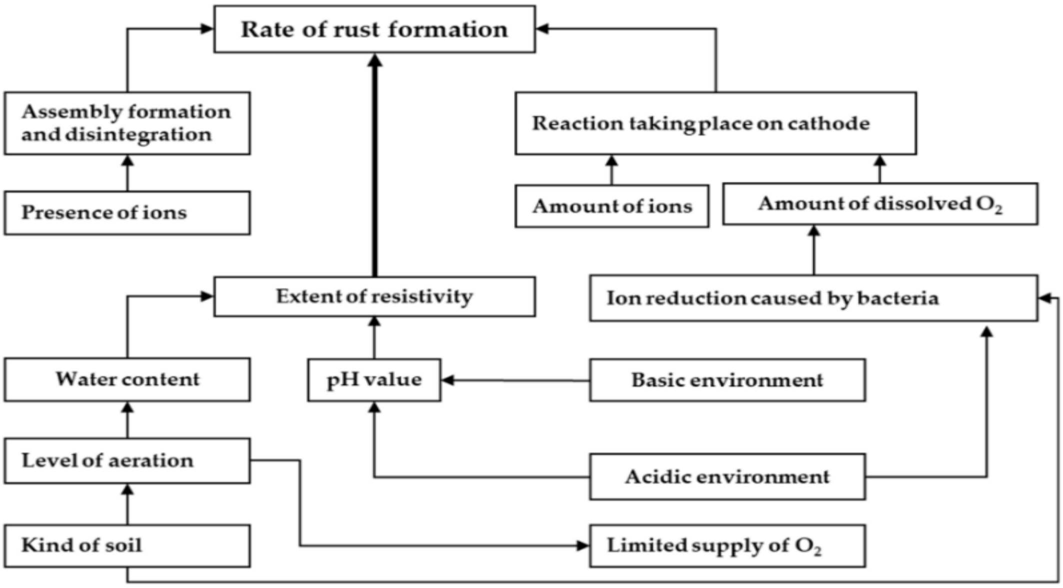


Figure 4: Relationships between corrosion-provoking conditions. (source: reference [7])

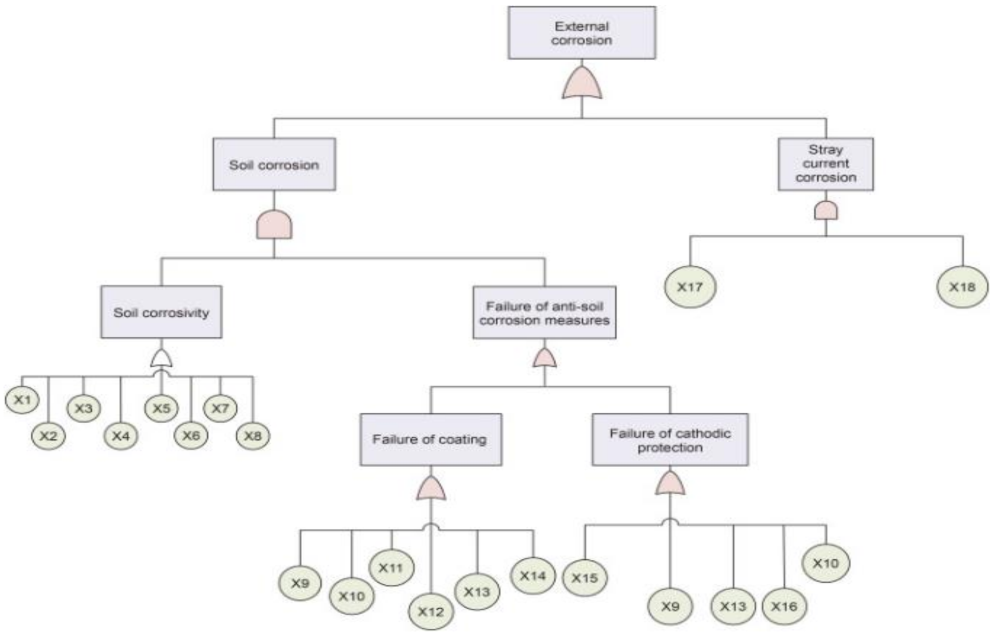


Figure 5: Fault tree diagram. (source: reference [43])

Symbol	Description	Symbol	Description
X_1	pH value	X_{10}	Construction quality issues
X_2	Resistence	X_{11}	Service time of the pipe
X_3	Moist soil	X_{12}	Coating quality issues
X_4	Redox possibility	X_{13}	Insufficient inspection frequency
X_5	Salinity of soil	X_{14}	Improper selection of coating
X_6	Texture of soil	X_{15}	Line failure
X_7	Free corrosive elements	X_{16}	Part failure
X_8	Chloride composition	X_{17}	Stray current
X_9	Third party actions	X_{18}	Failure of stray current protective measures

Table 15: Basic events of FT. (source: reference [43])

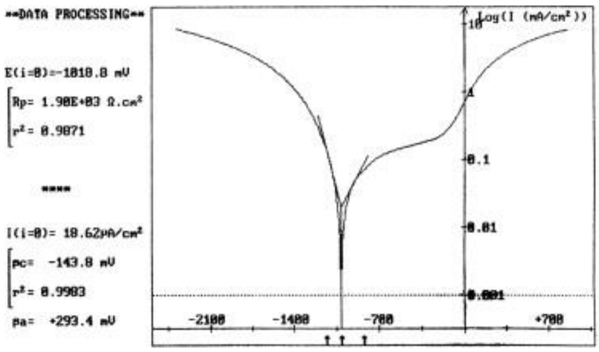


Figure 6: Tafel plot typical of pipe borne in the water stage drew from the crude oil. (source: reference [8])

Material	i_{corr} (µA/cm²)	N_{EQ}	*EW*	*D* (g/cm³)	Corrosion position	
Empty Cell	Emp. Cell	Emp. Cell	Emp. Cell	Emp. Cell	mpy	mm/year
Pipeline	18.62	0.03630	27.55	07.68	08.616	0.2184

Table 16: Corrosive possibility of pipe bornes under study. (source: reference [8])

3.2. Material Properties

The susceptibility of pipelines to corrosion in challenging environments, such as offshore systems, is heavily influenced by the properties of the materials used. Literature ([2]) emphasizes the impact of both microstructural and alloying elements on the integrity of steel pipelines. Various material microstructures, thus, baintic steel, pearlitic steel, spheroidized steel, martensitic steel, and numerous, have shown different corrosion rates (Katiyar et al., 2019). This underscores the significance of considering material composition when evaluating corrosion vulnerability.

When it comes to subsea pipelines, material selection is crucial for ensuring operational efficiency and longevity. The classification and numbering systems of steels are based on their chemical composition, which dictates their performance in corrosive settings ([16]). While carbon steel is commonly utilized for subsea pipelines, highly corrosive environments may require the use of corrosion-resistant alloys with superior resistance. The selection process involves assessing corrosion rates and comparing mechanical and corrosion resistance properties to identify the most appropriate material for a specific project.

Additionally, various empirical, probabilistic, and semi-empirical types were to addres the dissemination rate of corrosion effects in complex microenvironments ([2]). These models take into account aspects related to microstructure and natural conditions to evaluate the probability of pipeline failure. This will lead to the combination of semi-empiricalconstituents with Monte Carlo simulations which offers a risk-founded instrument for selecting suitable materials and managing pipeline integrity in corrosive environments.

The interplay between environmental factors and material properties can either exacerbate or alleviate a pipeline's susceptibility to corrosion ([26]). Other factors like composition, air quality, moisture content, temperature fluctuations, and bacterial activity can impact the corrosion process. Furthermore, older or lower-quality pipes lacking protective coatings may be more prone to corrosion due to manufacturing flaws or inherent material characteristics ([41]).

In conclusion, comprehending how material properties influence corrosion rates is vital for choosing appropriate materials for pipeline construction. By taking into consideration microstructural elements, alloying elements, and environmental factors during material selection processes, pipeline operators can mitigate corrosion risks and ensure the long-term integrity of their assets.

Model	Application	Source
Southwell’s linear model: d(t)=0.076+0.038t	Steel structure	(sub-ref-Schumacher, 1979)
Southwell’s bi-linear model: d(t)={0.09t0≤t<1.46y0.76+0.038t1.46≤t<16y	Steel structure	(sub-ref-Schumacher, 1979)
Melchers-Southwell’s nonlinear model: d(t)=0.84t0.823	Marine structure	(sub-ref-Melchers, 1999)
Melcher’s power law model: d(t)=0.1207t0.6257	Marine structure	(sub-ref-Melchers, 1999)
Melcher’s tri-linear model: d(t)={0.170t0≤t<y0.152+0.0186t1≤t<8y−0.364+0.083t8≤t<16y	Marine steel structure	(sub-ref-Melchers, 2008; sub-ref-Melchers, 1999)
Yamamoto-Ikegami’s nonlinear model: d(t)=C1(t−T0−Tt)C2	Ship structure	(sub-ref-Yamamoto and Ikegami, 1998)
Paik’s nonlinear model: d(t)=C1(t−Tc)C2	Ship structure	(sub-ref-Paik et al., 2004)
Paik & Kim’s model: dC=αβ(Yeβ)α−1exp[−(Yeβ)α] α=0.0020Ye3−0.0994Ye2+1.5604Ye−6.0025 β=0.0004Ye3−0.0248Ye2+0.4793Ye−2.3812	Ship structure	(sub-ref-Paik and Kim, 2012)
Soares and Garbatov’s model: d(t)=d∞[1−e(t−TcTt)]	Ship structure	(sub-ref-Soares and Garbatov, 1999)
Mohd & Kee's model: fc=αβ(Yeβ)α−1exp[−(Yeβ)α]	Subsea/offshore structure	(sub-ref-Mohd and Kee, 2013)

Model	Application	Source
α=−0.02287Ye2+0.61835Ye−0.94398 β=0.001347Ye2+0.004688Ye+0.292059		
Generic linear model: d(t)=d0+cdT L(t)=L0+clT	Pipeline structures	(sub-ref-Witek, 2018)
Ossai's model: Dmax(t)={0.12t0.771forlow0.2687t0.7408formoderate0.3887t0.7879forhigh0.6508t0.8657forsevere0.695t0.7689foralldata	Pipeline structures	(sub-ref-Ossai et al., 2015)

Table 17: Empirical semi-empirical corrosion addressing models similar to marine/offshore systems. (Source: reference [2])

3.3. Operating Parameters

Operational factors have a unique in determining the corrosion rates experienced by pipelines. Various elements such as flow characteristics, pressure levels, temperature variations, and fluid compositions can significantly impact the corrosion mechanisms that affect pipeline integrity ([8]). A research study investigating internal corrosion in subsea oil pipelines revealed that the flow pattern, influenced by the polyphase which controls the these substances; crude oil, water, and gas, can affect the distribution of corrosive elements throughout the pipeline ([8]). The presence of different phases within the pipeline can result in distinct flow patterns like stratified flow, where liquids and gas segregate from each other, potentially leading to water accumulation on the pipeline's bottom surface ([8]).

Moreover, to clearly perceive the uniqueness of gas passing through the pipeline and monitoring operational conditions are essential aspects in mitigating corrosion risks. An examination of a natural gas pipeline rupture and fire incident emphasized that effective monitoring of gas quality and operational conditions could have identified potential corrosion issues within the pipeline ([24] p. 51-55). Normal sampling and synthesis of liquids and solids obtained from the line could have provided insights into the corrosive contaminants present in the system ([24] p. 51-55). in the same instance, it is essential to implement an inner corrosion effect according to comprehensive monitoring protocols is crucial for detecting and mitigating internal corrosion in pipelines ([24] p. 56-60).

Furthermore, operational parameters such as the frequency of corrosion monitoring can also influence the detection and management of corrosion in pipelines. A new pipeline corrosion monitoring technique utilizing piezoelectric active sensing showcased how testing operating conditions at different intervals enabled tracking of corrosion states over time ([6]). Through regular corrosion assessments and monitoring changes in operational conditions, operators can gain valuable insights into the progression of corrosion within their pipelines.

In summary, taking into account operational parameters like flow patterns, gas quality surveillance, and corrosion testing schedules is crucial for effectively managing and alleviating corrosion in pipelines. By incorporating these elements into maintenance practices and risk-based maintenance strategies, operators can enhance their ability to detect early signs of corrosion and implement timely preventative measures to uphold pipeline integrity.

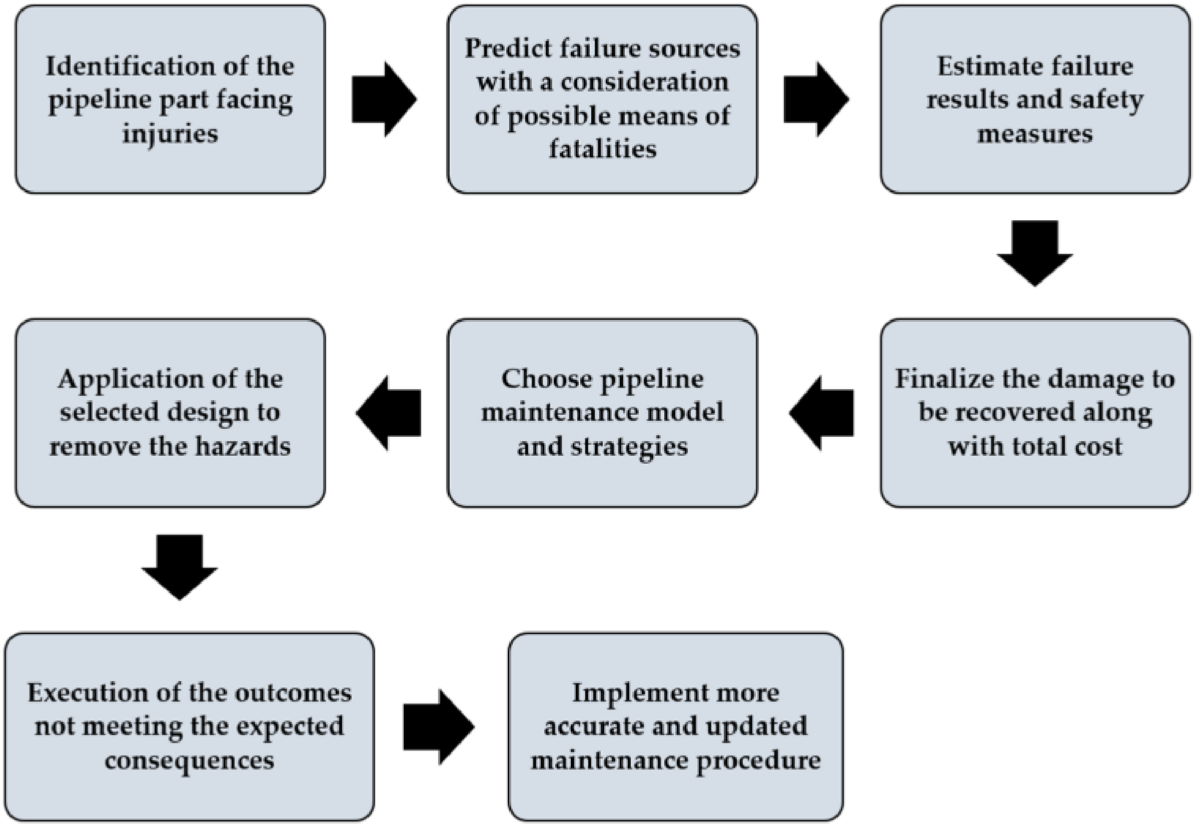


Figure 7: A pipeline system maintenance optimization framework. (source: reference [7])

Policy	Evaluation Criteria	Judgement Criteria	Merits	Demerits	Pipeline Uniformity
Corrective maintenance policy	absolute failure	Information about failure	Appropriate terms in relation to cost	Improved downtime	Unsuitable for the pipelines
Protection management policy	Prior periods, including age and service	Experts' opinion, industrial and historical practice, latest repair	Minimizing the occurrence and to be effective in terms of reduction in manufacturing loss	Decisions are mostly subject based and no proper evaluation to ascertain their condition.	Not suitable for serious results of pipelines.
Predictive Maintenance/Condition-based Maintenance policy	Condition-based assessment	To examine and evaluate the situation	Pipeline assessment in real-time	Excessive cost of pipeline inspection and other unforeseen instances in the process and other decisions with regards to the assessment	Appropriate for pipelines
Proactive	Observing	The need to	Evaluation of	Variability	Most popular

Policy	Evaluation Criteria	Judgement Criteria	Merits	Demerits	Pipeline Uniformity
Maintenance/Risk-Based Maintenance Policies	the danger failure and condition	evaluates and inspect the Assessment of situation, risk, and need-based repair approach	pipelines in real-time reduces the likelihood of dangerous events and the various effects of the actual events	and uncertainty in inspection data logical presumptions and decision-maker assessments are subjective	policy for pipeline infrastructure

Table 18: Examination of the above principles for maintenance from a proposed pipeline perspective. (source: reference [7])

Operating Conditions	OC1	OC2	OC3	OC4	OC5	OC6	OC7	OC8	OC9
Corrosion time (h)	0 h	5 h	10 h	15 h	20 h	25 h	30 h	35 h	40 h

Table 19: Testing operating conditions. (source: reference [6])

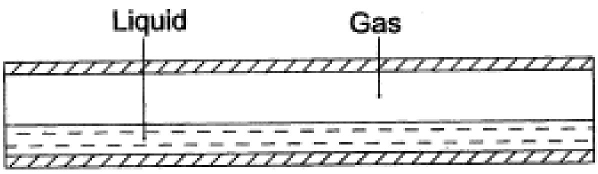


Figure 8: Gas-liquid stratified flow in horizontal pipeline. (source: reference [8])

Liquid flow rate (Q_l) (m^3/s)	Gas flow rate (Q_g) (m^3/s)	Liquid velocity (U_{sl}) (m/s)	Gas velocity (U_{sg}) (m/s)	Flow pattern
4.7918×10^{-3}	0.1445	0.0420	1.2675	Stratified flow

Table 20: additional results of U sl and U sg with assumed flow approach. (source: reference [8])

4. Impact of Corrosion on Pipeline Integrity

Pipeline corrosion is one of dangerous menace to the status of the transportation system, with the potential for catastrophic consequences on the surrounding environment and population. According to data cited in [1], internal corrosion is responsible for 70% of pipeline distractions in the domain of oil and gas, underscoring the critical need to understand and address this issue. Components like temperature water chemistry, fluctuations, flow velocity variations, corrosive gases and microbial influences can all contribute to the onset of corrosion within pipelines.

The impact of corrosion on pipeline integrity can be devastating, as illustrated by a case study referenced in [24] p. 56-60 where internal corrosion resulted in a rupture and fire close to Carlsbad, New Mexico. The absence of a robust internal corrosion control program and monitoring systems led to significant damage to the pipeline. Additionally, as highlighted in [3], the substantial costs associated with corrosion in refineries demonstrate how different types of corrosion can disrupt operations and lead to catastrophic failures.

External corrosion presents another critical challenge for pipelines, as discussed in [12]. Environmental factors such as soil composition, water content, and atmospheric conditions can hasten the deterioration of steel pipelines through processes like galvanic and atmospheric corrosion. Understanding these mechanisms is essential to implement effective preventive practices.

Addressing the impact of corrosion on pipeline integrity necessitates proactive steps such as utilizing coating and lining solutions mentioned in [24] p. 56-60, employing cathodic protection systems as detailed in [24] p. 56-60, and adopting advanced non-destructive testing techniques outlined in [3]. By incorporating these strategies, operators can identify and resolve corrosion problems concerning the domain to avert serious dangers.

In conclusion, managing the impact of corrosion on pipeline integrity is a multifaceted challenge that demands a comprehensive approach to mitigation. By grasping the various mechanisms of corrosion, implementing preventative measures, and conducting regular maintenance inspections as emphasized in [23], operators can ensure the safe operation of pipelines and guard against potential failures with devastating repercussions. Upholding consistent maintenance practices is essential for preserving pipeline integrity effectively.

5. Conclusion

In summary, the battle against pipeline corrosion is an ongoing challenge that demands a multifaceted approach to affirm the safety, efficiency, and reliability of pipeline operations. The integrity of pipeline infrastructure is paramount for the welfare of communities, the environment, and the economy ([18]). A thorough understanding of various corrosion other executions chemical corrosion, electrochemical corrosion, and microbial corrosion, is crucial for implementing effective mitigation strategies ([38]). Environmental conditions, material properties, and operating parameters are key factors influencing corrosion rates and determining the extent of corrosion damage ([5]).

The significance of corrosion on pipeline integrity cannot be overstated. Corrosion can result in structural defects that jeopardize the safety and functionality of pipelines ([40]). Cutting-edge methods for detecting corrosion, including non-destructive testing techniques and remote monitoring technologies, are essential for identifying potential issues before they escalate ([29]). Implementing corrosion prevention and mitigation strategies through coating and lining solutions, as well as cathodic protection systems, are essential components of a comprehensive corrosion management plan ([25]).

Practical problems may provide useful insights as well as to address the challenges and progresses associated with implementing corrosion prevention technologies ([17]). Regular maintenance is critical for prolonging the lifespan of pipelines and reducing the risks linked to corrosion-induced failures ([12]. Innovative material selection plays a vital role in enhancing pipeline resistance to corrosive environments and improving longevity ([10]).

To tackle the complexities linked to pipeline corrosion effectively, it is crucial to continue investing in research, embracing innovative technologies, and adhering to regulatory standards. By collaborating to develop proactive management strategies and implementing best practices in corrosion prevention and mitigation, stakeholders can mitigate the impacts of corrosion on pipeline infrastructure. The future of pipeline integrity hinges on industry collaboration, advancements in materials science and technology, and a commitment to safeguarding critical assets for generations to come.

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References

1. H. U. Khalid, M. C. Ismail and N. Nosbi. "Permeation Damage of Polymer Liner in Oil and Gas Pipelines: A Review". Oct 2020. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7601364/
2. S. Adumene, F. Khan, S. Adedigba, S. Zendehboudi and H. Shiri. "Offshore pipeline integrity assessment considering material and parametric uncertainty". Sep 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S266714332100055X
3. Aisha H. Al-Moubaraki and I. B. Obot. "Corrosion challenges in petroleum refinery operations: Sources, mechanisms, mitigation, and future outlook". Dec 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1319610321001757
4. J. Knisz, R. Eckert, L. M. Gieg, A. Koerdt, J. S. Lee, E. R. Silva, T. L. Skovhus, B. A. A. Stepec and S. A. Wade. "Microbiologically influenced corrosion-more than just microorganisms". Jul 2023. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10479746/
5. M. Hussain, T. Zhang, R. Dwight and I. Jamil. "Energy pipeline degradation condition assessment using predictive analytics - challenges, issues, and future directions". Sep 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2667143324000064
6. D. Yang, X. Zhang, T. Zhou, T. Wang and J. Li. "A Novel Pipeline Corrosion Monitoring Method Based on Piezoelectric Active Sensing and CNN". Jan 2023. [Online]. Available: https://www.mdpi.com/1424-8220/23/2/855
7. T. Ahmed, Y. Mahmood, N. Yodo and Y. Huang. "Weather-Related Combined Effect on Failure Propagation and Maintenance Procedures towards Sustainable Gas Pipeline Infrastructure". Jan 2024. [Online]. Available: https://www.mdpi.com/2071-1050/16/13/5789
8. M.N. Ilman and Kusmono. "Analysis of internal corrosion in subsea oil pipeline". Apr 2014. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2213290213000503
9. [9] S. Nesic. "Key issues related to modelling of internal corrosion of oil and gas pipelines - A review". Dec 2007. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0010938X07001539
10. I. Malashin, V. Tynchenko, V. Nelyub, A. Borodulin, A. Gantimurov, Nikolay V. Krysko, Nikita A. Shchipakov, Denis M. Kozlov, Andrey G. Kusyy, D. Martysyuk and A. Galinovsky. "Deep Learning Approach for Pitting Corrosion Detection in Gas Pipelines". Jan 2024. [Online]. Available: https://www.mdpi.com/1424-8220/24/11/3563
11. M. Nnoka, T. A. Jack and J. Szpunar. "Effects of different microstructural parameters on the corrosion and cracking resistance of pipeline steels: A review". May 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1350630724001110
12. "Pipeline Safety Stakeholder Communications". May 2024. [Online]. Available: https://primis.phmsa.dot.gov/comm/FactSheets/FSCorrosion.htm
13. B. Lowe, M. Gloven and Dr. Ted Anderson. "coursesbrochure". Nov 2022. [Online]. Available: https://www.clarion.org/catalog/coursesbrochure.pdf
14. MATCOR. "Pipeline Corrosion - All You Need to Know". Feb 2020. [Online]. Available: https://matcor.com/pipeline-corrosion/
15. M. Wasim and Milos B. Djukic. "External corrosion of oil and gas pipelines: A review of failure mechanisms and predictive preventions". Apr 2022. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S1875510022000580
16. H. El-Mogi. "Design of Submarine Pipeline With Respect to Corrosion and Material Selection". Dec 2016. [Online]. Available:

https://uis.brage.unit.no/uis-xmlui/handle/11250/2438600

17. "ASM Handbook Volume 13C: Corrosion: Environments and Industries - ASM International". Jul 2024. [Online]. Available: https://www.asminternational.org/asm-handbook-volume-13c-corrosion-environments-and-industries/results/-/journal_content/56/05145G/PUBLICATION/
18. admin. "The Vital Role of Corrosion Management in Preserving Pipeline Integrity". Mar 2024. [Online]. Available: https://g3soilworks.com/2024/03/20/the-vital-role-of-corrosion-management-in-preserving-pipeline-integrity/
19. Michael Baker Jr., Inc. and Raymond R. Fessler, Ph.D... "Pipeline Corrosion FINAL REPORT". Nov 2008. [Online]. Available: https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/docs/technical-resources/pipeline/gas-transmission-integrity-management/65341/finalreportpipelinecorrosion.pdf
20. B. Kermani, John W. Martin and Khlefa A. Esaklul. "Materials Design Strategy: Effects of H2S/CO2 Corrosion on Materials Selection". Mar 2006. [Online]. Available: https://onepetro.org/NACECORR/proceedings/CORR06/All-CORR06/NACE-06121/118069
21. S. Prabhu. "An Intro to Pipeline Corrosion and Protection Methods". Jul 2024. [Online]. Available:https://www.corrosionpedia.com/an-intro-to-pipeline-corrosion-and-coatings/2/1383
22. Wood. "Electronic Corrosion Engineer - Realistic Corrosion Assessments Calibrated to Real Field Data [Free Trial]". Aug 2024. [Online]. Available: https://www.woodplc.com/solutions/expertise/ece-corrosion-and-materials-selection
23. Richard B. Eckert and Dr. Kathy Buckingham. "Investigating Pipeline Corrosion Failures". (Accessed Aug 18, 2024). [Online]. Available: https://inspectioneering.com/journal/2017-08-23/6801/investigating-pipeline-corrosion-failures
24. [24] N. T. S. Board. "Natural Gas Pipeline Rupture and Fire Near Carlsbad, New Mexico August 19, 2000". Feb 2003. [Online]. Available: https://www.ntsb.gov/investigations/AccidentReports/Reports/PAR0301.pdf
25. M. Vakili, P. Koutnik and J. Kohout. "Addressing Hydrogen Sulfide Corrosion in Oil and Gas Industries: A Sustainable Perspective". Jan 2024. [Online]. Available: https://www.mdpi.com/2071-1050/16/4/1661
26. Hassan M. Hussein Farh, M. E. A. B. Seghier, R. Taiwo and T. Zayed. "Analysis and ranking of corrosion causes for water pipelines: a critical review". Sep 2023. [Online]. Available: https://www.nature.com/articles/s41545-023-00275-5
27. D. Jayasinghe. "Internal Corrosion of Pipelines Carrying Crude Oil". Jul 2024. [Online]. Available: https://www.corrosionpedia.com/internal-corrosion-of-pipelines-carrying-crude-oil/2/7282
28. M. Achour, C. Johlman and D. Blumer. "Understanding the Corrosion Inhibitor Partitioning in Oil and Gas Pipelines". Nov 2008. [Online]. Available: https://onepetro.org/SPEADIP/proceedings/08ADIP/All-08ADIP/SPE-117942-MS/145507
29. U. Sarwar, A. A. Mokhtar, M. Muhammad, R. K. Wassan, A. A. Soomro, M. A. Wassan and S. Ka. "Enhancing pipeline integrity: a comprehensive review of deep learning-enabled finite element analysis for stress corrosion cracking prediction". (Accessed Aug 18, 2024). [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/19942060.2024.2302906
30. R. Scott Lillard, H. Cong, K. Garrity, D. Wagner. "Understanding and Mitigating the Threat of AC Induced Corrosion on Buried Pipelines". Jun 2021. [Online]. Available:

https://rosap.ntl.bts.gov/view/dot/56145/dot_56145_DS1.pdf

31. S. Foorginezhad, M. Mohseni-Dargah, K. Firoozirad, V. Aryai, A. Razmjou, R. Abbassi, V. Garaniya, A. Beheshti and M. Asadnia. "Recent Advances in Sensing and Assessment of Corrosion in Sewage Pipelines". Mar 2021. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0957582020317262
32. J. Kaatz. "Pipeline Integrity Management: Pipeline Corrosion Detection and Prevention". Apr 2024. [Online]. Available: https://www.woodwayenergy.com/pipeline-integrity-management-corrosion-detection-prevention/
33. S. Turcott and S. Mathura. "Water Corrosion Case Studies". (Accessed Aug 18, 2024). [Online]. Available: https://www.linkedin.com/posts/shane-turcott-3a2ab51b_sanya-really-glad-you-enjoyed-and-found-activity-7132719853966151680-RuU3
34. G. T. Kim, H. S. Hwang, S. L. Oh and B. M. Kim. "Case Studies Of Corrosion Failures In Oil Refineries". Mar 2010. [Online]. Available: https://onepetro.org/NACECORR/proceedings/CORR10/All-CORR10/NACE-10354/128842
35. Z. Riaz. "All You Should Know About Internal Pipeline Corrosion". Oct 2022. [Online]. Available: https://www.linedpipesystems.com/all-you-should-know-about-internal-pipeline-corrosion/
36. "The Corrosion Monitoring and Mitigation Handbook Creating a Balanced and Effective Program for Downstream Processes". Jun 2020. [Online]. Available: https://www.sentry-equip.com/SentryEquipment/media/SentryEquipment/Resources/Marketing%20Materials/The-Corrosion-Monitoring-Handbook.pdf
37. R. Osthus. "Effects of Pitting Corrosion in Chemical Processing Plants". Feb 2022. [Online]. Available: https://coldspray.com/effects-of-pitting-corrosion-in-chemical-plants/
38. "CO2 Corrosion Mitigation in Hydrocarbon Pipelines". Mar 2024. [Online]. Available: https://inspenet.com/en/articulo/corrosion-by-co2-hydrocarbon-pipes/
39. H. Conrad. "Combating corrosion: Researchers fight underwater deformation with enhanced metals". Jan 2021. [Online]. Available: https://engineering.tamu.edu/news/2021/01/combating-corrosion-researchers-fight-underwater-deformation-with-enhanced-metals.html
40. M. S. "A Closer Look: Investigating Corrosion Mechanisms Under Pipe Supports". Apr 2024. [Online]. Available: https://medium.com/@corrosafeofficial/a-closer-look-investigating-corrosion-mechanisms-under-pipe-supports-8f2e8561d1f4
41. fastacservice.com. "Understanding Underground Natural Gas Pipe Corrosion: A Plumber's Insight". Feb 2024. [Online]. Available: https://www.fastacservice.com/2024/02/understanding-underground-natural-gas-pipe-corrosion-a-plumbers-insight/
42. Y. Hou, D. Lei, S. Li, W. Yang and C. Li. "Experimental Investigation on Corrosion Effect on Mechanical Properties of Buried Metal Pipes". Jan 2016. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.1155/2016/5808372
43. Y. Li, X. He and J. Shuai. "Risk analysis and maintenance decision making of natural gas pipelines with external corrosion based on Bayesian network". Jun 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1995822621000649

44. Y. Sung, H. Jeon, D. Kim, M. Kim, J. Choi, H. R. Jo, J. Oh, O. Lee and H. G. Lim. "Internal pipe corrosion assessment method in water distribution system using ultrasound and convolutional neural networks". Jul 2024. [Online]. Available: https://www.nature.com/articles/s41545-024-00358-x

45. Z.B. Wang, L. Pang and Y.G. Zheng. "A review on under-deposit corrosion of pipelines in oil and gas fields: Testing methods, corrosion mechanisms and mitigation strategies". Sep 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2667266922000482

46. "Pipeline Safety: Pipeline Integrity Management in High Consequence Areas (Gas Transmission Pipelines)". Dec 2003. [Online]. Available: https://www.federalregister.gov/documents/2003/12/15/03-30280/pipeline-safety-pipeline-integrity-management-in-high-consequence-areas-gas-transmission-pipelines