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Corrosion and Erosion and their Effect on Pipe Failures: An Introduction to Design, Methodologies, and Requirements Utilized by Forensic Engineers

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INTRODUCTION

This paper provides foundational knowledge and practical insight into the mechanisms of corrosion and erosion, with the aim of raising awareness among forensic engineers, insurance adjusters, and related professionals. By understanding the fundamental principles, common types, investigators can more accurately identify contributing factors in equipment failures, assess liability, and determine root causes. For adjusters and insurers, this information is intended to enhance the evaluation of damage claims, support more informed decision-making, and promote better risk assessment. This serves as an educational tool to bridge the gap between technical metallurgy and real-world insurance and forensic investigations.

Halliwell has investigated numerous cases involving pipe failures, which represent a significant portion of industrial loss claims and forensic engineering assessments. Piping systems are essential components of industrial infrastructure, and their failure can lead to severe operational downtime, safety incidents, environmental exposure, and considerable financial liability. Given the complexity and potential consequences of these failures, each case demands a rigorous technical evaluation to accurately identify root causes, determine liability, and provide clear and defensible conclusions to support insurance assessments and legal proceedings following peer reviewed standards that included ASME B31.3, 2022; and API RP 579-1/ASME FFS-1, 2021, to name a few. One such case study, analyzed and documented by Halliwell, is presented later in this report.

The underlying mechanisms of corrosion and erosion discussed in this document are equally applicable to other pressure-retaining equipment such as storage tanks, pressure vessels, and transport tankers (API 653, 2020; ASME Section VIII, Div. 1, 2021).[1,2] Halliwell's expertise extends to failures across these systems, where wall thinning, pitting, and other forms of degradation have played a central role in significant industrial losses. These findings reinforce the critical need for integrating robust corrosion mitigation and inspection strategies, such as risk-based inspection (RBI), non-destructive testing (NDT), and cathodic protection, into the design, fabrication, and lifecycle management of such equipment (NACE SP0102, 2021; ISO 55000, 2014).[3,4] These considerations carry substantial implications for engineering standards, insurance underwriting, and regulatory compliance frameworks.

In evaluating these matters, it is important to first focus on the nature of corrosion and erosion, understanding these phenomena and their potential impacts on the design and construction of pipes, vessels, tanks, and other critical infrastructure. Effective mitigation strategies are critical for implementation during the design phase to prevent or reduce the effects of these processes. Mitigation strategies can include, but are not limited to, material selection, protective coatings, and proper design to withstand corrosion and erosion. Additionally, relevant industrial codes and standards are the basis to guide these efforts and ensure compliance with industry's best practices.

Pipes are essential components in industrial systems, serving as the primary means for transporting fluids, gases, and solids (in slurry form) in various processes. They are widely used in industries such as oil and gas, chemical processing, power generation, water treatment, and manufacturing. The selection, design, and installation of piping systems play a crucial role in ensuring operational efficiency, safety, and regulatory compliance.

The design of industrial piping systems involves multiple factors, including material selection, pressure and temperature considerations, flow rate requirements, and environmental conditions. Engineers must also adhere to industry standards such as ASME B31.3 (Process Piping), API, and ASTM specifications to ensure durability and reliability.[5]

Piping systems are fundamental to industrial infrastructure, enabling the safe and efficient transportation of liquids, gases, and solids across various applications. The design of these systems must account for operational requirements, safety considerations, material selection, and compliance with industry standards. Different industries have unique demands that influence piping design, ranging from consideration of high-temperature and high-pressure environments to the conveyance in the piping of corrosive and hazardous substances.

Investigating the integrity of pipes is crucial to prevent catastrophic failures and resulting costly damages, and maintenance costs should be an operational consideration in the design process to ensure that costs to maintain the system are not prohibitive for the intended use and associated lifecycle of the piping system. To avoid these high costs, it is essential to understand the fundamental factors that affect the performance and durability of pipes during operation and service. Proactive monitoring, maintenance, and proper design considerations based on these factors can significantly extend the lifespan of piping systems, reduce the risk of failures, and ultimately minimize both operational and financial risks associated with pipe damage and loss of integrity.

Each industry has unique requirements that dictate the selection, design, and installation of piping systems. Engineers must consider factors such as material compatibility, pressure and temperature limits, environmental conditions, flexibility and thermal stress, and regulatory standards to ensure safe and efficient operations. By adhering to industry-specific guidelines, industrial piping systems can achieve longevity, reliability, and compliance with safety regulations. Each industry has its own standard and regulations, but in general the design can be followed by fundamentals.

CODES AND STANDARDS IN PIPING

The fundamental principles of piping systems in industrial applications, covering their definition, classification, design considerations, and key factors influencing their performance are further detailed specific to the industrial process. These codes and standards specifically discussed are commonly used in many industries to have a common ground for design considerations, analysis, maintenance, and inspection.

OIL AND GAS INDUSTRY

In the oil and gas sector, piping systems are used for upstream extraction, midstream transportation, and downstream refining. These pipes must withstand operating pressures, operating temperatures, and corrosive environments which sometimes can be extreme. Common materials include carbon steel, stainless steel, and corrosion-resistant alloys. Design considerations focus on API (American Petroleum Institute),[6,7] such as 570, 574, 579, and ASME (American Society of Mechanical Engineers) such as B31.1, B31.4 standards to ensure structural integrity and safety.[8, 9]

CHEMICAL PROCESSING INDUSTRY

Chemical plants require piping systems that can handle aggressive chemicals, high pressures, and extreme temperatures. Corrosion-resistant materials like stainless steel, Hastelloy, and PTFE-lined pipes are commonly used. The design must comply with ASME B31.3 (Process Piping) and ANSI standards to ensure the safe transport of hazardous substances without leaks or contamination.[5]

POWER GENERATION INDUSTRY

Power plants, including fossil fuel, nuclear and renewable energy facilities, rely on piping for steam, water, and fuel transport. High-pressure and high-temperature conditions demand the use of alloys such as P91 steel. Boiler feedwater, steam piping, and cooling water systems[10,11,12] must adhere to ASME B31.1 (Power Piping) and ASTM G14 standards for efficiency and safety.[8,9]

WATER TREATMENT AND DISTRIBUTION

Water treatment plants use piping systems for raw water intake, filtration, chemical dosing, and distribution. Common materials associated with these piping and distribution systems include PVC, ductile iron, and stainless steel, chosen for their corrosion resistance and durability. Standards such as AWWA (American Water Works Association), AWWA C200, and NSF/ANSI, NSF/ANSI 60, govern the design and material selection for potable water and wastewater applications.[10,11]

PHARMACEUTICAL AND FOOD INDUSTRIES

In pharmaceutical and food processing industries, hygiene and contamination control are critical to avoiding product recall and liability. Stainless steel (304L, 316L) is commonly used due to its non-reactive properties and ease of cleaning. Piping systems must comply with FDA, cGMP (Current Good Manufacturing Practice), and ASME BPE[12] (Bioprocessing Equipment) standards to maintain product purity and safety, and they should be designed to withstand regular dosing or cleaning of the piping.

HVAC AND BUILDING SERVICES

Piping in heating, ventilation, and air conditioning (HVAC) systems are used for chilled water, hot water, and refrigerants. Materials such as copper, aluminum, PEX, and galvanized steel are selected based on efficiency and longevity. The design follows ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) such as 55, and 189.1 standards to optimize energy use and performance.[13]

For each industry, specific standards are used, and a number of these codes and standards are provided. Table 1 contains a comprehensive list of codes and standards used for the design, verification, validation, inspection, and maintenance of piping systems across various industries. These standards and codes are summarized in **Table 1**.

Type	Standard Series	Code	Description
Design Codes and Standards	ASME B31 Series	ASME B31.1	Power Piping (used in power plant)
		ASME B31.3	Process Piping (used in chemical, oil & gas, and refineries)
		ASME B31.4	Pipeline Transportation Systems for Liquids and Slurries
		ASME B31.8	Gas Transmission and Distribution Piping Systems
		ASME B31.9	Building Services Piping
		ASME BPE	Bioprocessing Equipment (for Pharmaceutical and food industries)
	API (American Petroleum Institute)	API 570	Piping Inspection Code (maintenance, inspection, repair)
		API 579	Fitness-for-Service (FFS) Evaluation
		API 1104	Welding of Pipelines and Related Facilities
		API 6D	Pipeline Valves
	ASTM (American Society for Testing and Materials)	ASTM A106	Standard Specification forSeamless Crbon Steel Pipe
		ASTM A312	Standard Specification for Stainless Steel Pipe
		ASTM A53	Standard Specification for Pipe, Steel, Black and Hot-Dipped, Zinc-Coated
	ISO (International Organization for Standardization)	ISO 3183	Petroleum and natural gas industries – Steel pipe for pipelines
		ISO 14692	Reinforced Thermosetting Resin (RTR) Piping Systems
	AWWA (American Water Works Association)	AWWA C200	Steel Water Pipe
		AWWA C900	Polyvinyl Cholride (PVC) Pressure Pipe
Verification and Validation Standards	ASME (American Society of Mechanical Engineers)	ASME BPVC Section VI	Pressure Vessel Code (applies to piping under pressure)
		ASME B31 G	Assessment of Corroded Pipelines
	ISO (International Organization for Standardization)	ISO 9001	Quality Management Systems (for validation processes)
Inspection and Maintenance Standards	API (American Petroleum Institute)	API-579-1/ ASME FFS-1	Fitness-for-service Evaluation (used to assess structural integrity)
	IEC (International Electrotechnical Commission)	IEC 61511	Functional Safety for the Process Industry Sector (related to pipeline safety systems)
	API (American Petroleum Institute)	API 570	Piping Inspection Code (for in-service inspection, repair, and alteration)
		API 574	Inspection Practices for Piping System Components
		API 580	Risk-Based Inspection (RBI) methodology
		API 581	Risk-Based Inspection Technology
Welding and Fabrication Standards	ASME (American Society of Mechanical Engineers)	ASME PCC-2	Repair of Pressure Equipment and Piping
	ISO (International Organization for Standardization)	ISO 24817	Composite Repairs for Pipework
	ASME (American Society of Mechanical Engineers)	ASME Section IX	Welding and Brazing Qualifications
	API (American Petroleum Institute)	API 1104	Welding of Pipelines and Related Facilities
	AWS (American Welding society)	AWS D1.1	Structural Welding Code for Steel
	ISO (International Organization for Standardization)	ISO 15614	Specification and Qualification of Welding Procedures
Non-Destructive Testing (NDT) Standards	ASME (American Society of Mechanical Engineers)	ASME Section V	NDT Methods (Radiography, Ultrasonic Testing, Magnetic Particle Testing, etc.)
	API (American Petroleum Institute)	API RP 677	Welding Inspection and Metallurgy
	ISO (International Organization for Standardization)	ISO 9712	Qualification of NDT Personnel

Table 1 – The industrial standard and codes for piping systems

CORROSION AND EROSION

Erosion and corrosion are among the leading causes of pipe failure across various industries, and the rate of erosion and corrosion is highly influenced by the operating environment, the application of loads, internal and external pressures, and, most importantly, the characteristics of the fluid transported within the pipes.

Pipes in industrial applications are subjected to harsh operating conditions, making them vulnerable to corrosion and erosion, which can significantly impact their integrity, performance, and lifespan. Understanding these degradation mechanisms is essential for material selection, design improvements, and maintenance strategies.

CORROSION IN PIPING SYSTEMS

Corrosion is the chemical or electrochemical reaction between the pipe material and its environment, leading to material degradation.[14] There are several types of corrosion in a pipe:

Uniform Corrosion:

It is imperative for insurance companies and adjusters to understand this type of corrosion, as it is a common cause and origin of failure across many industries. Additionally, it is important to verify whether any mitigation strategies are required to prevent such issues during the service life of pipes and equipment.

The type of corrosion known as uniform or general corrosion occurs evenly across the entire pipe surface, leading to a gradual and consistent reduction in wall thickness. It does not create concentrated weak points, but instead results in a uniform thinning of the pipe material. Although this reduces the risk of sudden, localized failures, it can still compromise the overall structural integrity of the pipe by uniformly increasing stress levels over time. If the corrosion progresses unchecked, the pipe may eventually become too thin to withstand internal pressure, leading to leaks or catastrophic failure. This form of corrosion is particularly common in carbon steel when exposed to atmospheric conditions, moisture, or aqueous environments containing dissolved oxygen, chlorides, or acidic compounds. Industries that rely on water transport, oil and gas pipelines, and chemical processing systems frequently encounter uniform corrosion. This corrosion can be mitigated through protective coatings, inhibitors, or cathodic protection.[15]

Pitting Corrosion:

Pitting corrosion is a highly localized form of attack that results in the formation of small holes or pits on the pipe surface.[15] This type of corrosion is particularly dangerous because it can lead to sudden and unexpected failures, even when the overall material loss is minimal. It is commonly observed in stainless steel and other alloys exposed to aggressive environments containing chlorides (e.g., seawater, brines) or sulfides. Pitting corrosion can occur in HVAC systems, underground piping, storage tanks, and stainless steel components exposed to marine or chemical environments. Due to its localized nature, pitting corrosion significantly increases stress concentration around the pit edges, leading to elevated local stress levels and higher stress intensity. This, in turn, reduces the intrinsic fracture toughness of the pipe material, making it more susceptible to failure under mechanical or cyclic loading. If left unchecked, pits can act as initiation sites for crack formation and propagation, potentially leading to through-wall penetration or catastrophic failure in a circumferential, radial or axial direction.

The severity of pitting corrosion is influenced by several factors, including the electrochemical potential of the material, where stainless steel is particularly vulnerable when its passive film breaks down. The presence of aggressive ions such as chloride, bromide, and sulfide significantly accelerates pitting. Additionally, higher operating temperatures and lower pH levels promote pit formation, while oxygen concentration influences passivation and the breakdown of protective oxide layers.[16]

To prevent and mitigate pitting corrosion, selecting higher-grade stainless steel (e.g., duplex stainless steel, super austenitic stainless steel, or titanium) is essential. Other protective measures include the application of corrosion-resistant coatings, the use of corrosion inhibitors, and cathodic protection, especially in subsea applications.

Pitting corrosion is particularly problematic because it often occurs in hidden or difficult-to-inspect areas, such as under deposits or at weld seams. Therefore, proactive maintenance and continuous monitoring are essential to ensuring the long-term reliability of piping systems in aggressive environments.[17]

Additionally, pitting is also observed in piping systems in which the flow becomes stagnant for periods of time and is normally more prevalent in the lower section of the pipes.

Crevice Corrosion:[15,16]

Crevice corrosion typically occurs in narrow gaps, joints, or shielded areas where stagnant fluids become aggressive. These confined spaces limit oxygen diffusion, leading to the breakdown of the passive protective film on metal surfaces, making them more susceptible to localized attacks. Forensic engineers often encounter crevice corrosion in bolted or gasketed connections, lap joints, and under deposits or seals, particularly in stainless steel components exposed to stagnant moisture or chloride-rich environments.

The severity of crevice corrosion is influenced by factors such as chloride concentration, pH levels, oxygen availability, and material composition. Stainless steels and aluminum alloys are particularly vulnerable in chloride-rich environments due to the breakdown of their passive oxide layer. To mitigate this kind of corrosion, one needs to consider proper design considerations, such as proper drainage configuration, material selection, protective coatings and sealants, and cathodic protection (e.g. In subsea applications, cathodic protection systems can help mitigate crevice corrosion).

Galvanic Corrosion:[15,16]

This type of corrosion, known as galvanic corrosion, occurs when two dissimilar metals are in direct contact in the presence of a conductive fluid (electrolyte). In this electrochemical reaction, the more active metal (anode) corrodes at an accelerated rate, while the more noble metal (cathode) remains protected. Forensic engineers typically observe galvanic corrosion at interfaces between dissimilar metals—such as steel and copper or aluminum and stainless steel—especially in marine environments, HVAC systems, plumbing assemblies, and electrical enclosures where moisture is present. The rate and severity of galvanic corrosion depend on factors such as the electrochemical potential difference between the metals, the conductivity of the electrolyte, temperature, and exposure time. As mentioned in the previous corrosion types, preventing galvanic corrosion requires proper material selection (i.e., using similar metals in contact with each other), insulation to separate dissimilar metals, the use of cathodic protection (i.e., employing sacrificial anodes or impressed current systems), and effective environmental control and monitoring of the corrosion conditions by ensuring that cathodic protection systems are active.

Galvanic corrosion is commonly observed in marine environments, piping systems, heat exchangers, and structural applications where different metals are used together. Proper material selection and engineering design are crucial to minimizing its effects.

Erosion-Corrosion:[15,16]

This type of corrosion results from the synergistic effect of mechanical wear and chemical corrosion. It often occurs in high-velocity fluid systems containing suspended solids. This phenomenon is commonly observed in areas with elbows, bends, and pipe reducers, where turbulent flow and increased shear stress accelerate material degradation. The removal of the protective corrosion layer that forms expose virgin, unaffected surfaces to corrosion exacerbating the Erosion-Corrosion

process. Forensic engineers commonly identify erosion-corrosion in piping systems, elbows, pump impellers, and valve components where high-velocity fluids—often containing suspended solids or entrained air—cause accelerated material loss, particularly in water treatment plants, power stations, and industrial process lines. It can be mitigated by proper material selection, design optimization, control of flow parameters, and use of protective coating.

Stress Corrosion Cracking (SCC):[14,16]

Stress Corrosion Cracking (SCC) occurs when a combination of tensile stress and a corrosive environment leads to crack initiation and propagation, ultimately resulting in material failure. This phenomenon arises from the synergistic effects of chemical attack and mechanical loading, where the metal experiences continuous stress in the presence of corrosive species. SCC is influenced by several key factors, including tensile stress from applied loads such as bending, tension, torsion, or internal/external pressure, as well as residual stresses induced by welding, cold working, or improper heat treatment. The corrosive environment also plays a crucial role in triggering SCC, depending on the material. For example, chloride-induced SCC affects stainless steels, particularly in marine, desalination, and chemical processing environments, while hydrogen-induced SCC occurs in high-pressure hydrogen environments, commonly seen in refining and energy industries. Carbonate or ammonia-induced SCC impacts carbon steels and copper alloys in industrial applications. Additionally, SCC becomes more severe at elevated temperatures, where corrosion kinetics and crack propagation rates increase.

SCC is commonly observed in buried gas pipelines, especially in high-pressure environments, as well as in boilers and heat exchangers due to the combination of high temperatures and aggressive fluids that cause stress corrosion in stainless steel, copper alloys, and other materials. It is also frequently encountered in offshore and subsea structures, where chloride-rich seawater and dynamic loading promote SCC, making it a critical concern in oil and gas production. To minimize the risk of SCC, stress reduction and the use of higher safety margins are essential. The two most important factors in mitigating this type of corrosion are proper material selection and environmental control. Materials such as duplex stainless steels, titanium, and nickel-based alloys are more resistant to SCC and are preferred in aggressive environments. Additionally, reducing exposure to SCC-promoting agents, such as chlorides, hydrogen sulfide, and ammonia, through pH control, deoxygenation, and corrosion inhibitors, can significantly enhance resistance.

SCC is a significant failure mode occurring in the energy sector, particularly in subsea oil and gas applications, where pipes and equipment are continuously exposed to extreme environmental conditions and mechanical stresses. Preventing SCC requires a combination of engineering design, material selection, and proactive maintenance strategies to ensure long-term system integrity and reliability.

Microbiologically Influenced Corrosion (MIC):[16,18]

Microbiologically influenced corrosion (MIC) is caused by bacteria, such as sulfate-reducing bacteria (SRB), and leads to localized pitting and severe metal loss. This type of corrosion is particularly common in water and oil pipelines, where the bacteria thrive in anaerobic conditions and fluids are stagnant. MIC can significantly accelerate the degradation of materials, making it a serious concern in industries that rely on pipeline systems. To mitigate and manage Microbiologically Influenced Corrosion (MIC), several methods are recommended, such as the use of biocides, appropriate material selection, cathodic protection, and proper surface treatment.

EROSION IN PIPING SYSTEMS

Erosion is the mechanical removal of material from the pipe surface caused by high-velocity fluids, suspended particles, or turbulent flow.[19] This process can be exacerbated by corrosion, leading to a phenomenon known as erosion-corrosion, where the combined effects of mechanical wear and chemical attack accelerate material degradation. Several factors can influence the rate of erosion, including flow velocity, where higher speeds increase the risk of erosion; fluid composition, as slurries, sand-laden fluids, and steam can all accelerate erosion; pipe geometry, with bends, elbows, tees, and reducers experiencing higher wear due to turbulence; and material hardness, where softer materials tend to erode faster than harder alloys.[20] There are several types of erosion that can occur in a pipe:

Solid Particle Erosion:

This type of erosion occurs when solid particles, such as sand, rust or debris, strike the pipe wall. It is particularly common in oil and gas pipelines, especially in multiphase flow, where the presence of gas, liquid, and solid particles increases the likelihood of material degradation.[21]

Liquid Droplet Erosion (LDE):

This type of erosion occurs when high-speed liquid droplets impact the pipe wall. It is common in steam piping and gas pipelines that carry condensates, where the rapid movement of droplets contributes to material wear and degradation.[22] Forensic engineers often encounter liquid droplet erosion (LDE) in high-speed turbine blades, compressor components, and steam piping where high-velocity liquid droplets repeatedly impact metal surfaces, leading to surface fatigue and material loss, particularly in power generation and aerospace applications.

Cavitation Erosion:

Cavitation erosion is a type of damage caused by the formation and collapse of vapor bubbles fluid. This phenomenon occurs when the pressure within the fluid drops below its vapor pressure, causing the fluid to vaporize and form bubbles. When these bubbles move to regions of higher pressure, they collapse violently, generating intense shockwaves and localized high temperatures. This process leads to rapid pitting, surface degradation, and erosion of the material, often resulting in significant damage over time. Cavitation is particularly common in areas of fluid systems where pressure fluctuations occur, such as near control valves and pump suction pipes, where the rapid changes in pressure can create conditions conducive to bubble formation. The resulting damage can compromise the integrity of piping systems and equipment, leading to costly repairs and downtime.[16] Forensic engineers typically observe cavitation erosion in pump impellers, hydraulic turbines, valves, and pipe bends where rapid pressure changes in fluids cause vapor bubble formation and collapse, leading to localized surface damage, pitting, and material loss—commonly in water handling and hydraulic systems.

IMPACT OF CORROSION AND EROSION ON PIPE CONFIGURATION AND STRESS LEVELS[23,24,25,26,27,28]

One of the key strategies for mitigating and preventing the effects of corrosion and erosion in piping systems is to reduce stress levels and stress intensity during operation. Corrosion and erosion can weaken the pipe material, leading to localized stress concentrations that increase the likelihood of structural failure. Therefore, it is crucial to analyze stress distribution under various loading conditions, including bending, tension, torsion, and internal or external pressure. By understanding these stress factors, engineers can implement design modifications, material selection, and protective measures to enhance piping durability and reliability. Additionally, maintaining an adequate safety margin is essential to account for long-term material degradation and unforeseen operational stresses, ensuring the continued integrity and performance of the piping system.

By properly designing piping systems to prevent corrosion and erosion, industries can achieve substantial cost savings across multiple areas, particularly in insurance placement and damage repair costs. Corrosion, if left unchecked, can lead to premature pipe failure, which often results in expensive repairs, replacements, and costly downtimes. However, with effective design strategies, such as the selection of corrosion-resistant materials, the use of protective coatings, and the implementation of cathodic protection systems, companies can significantly extend the life of their piping infrastructure. This not only minimizes the frequency of pipe replacements, but also reduces the operational disruptions caused by unforeseen failures. All of which can reduce the cost of insurance coverage, as they act to lower the frequency and severity of insurance claims.

In addition to reducing repair costs, preventive measures can help decrease the costs associated with insurance premiums with the use of risk-based assessments performed as part of insurance underwriting to evaluate for the frequency and potential for system failure. Systems prone to corrosion and frequent damage are considered higher risk, resulting in higher premiums. By mitigating the risk of pipe failures through design and maintenance strategies, companies can reduce their risk profile, thereby lowering insurance costs.

Moreover, avoiding corrosion-related failures reduces the potential for significant environmental damage, which can be both costly to address and detrimental to a company's reputation. In industries such as oil and gas, water treatment, power generation, and chemical manufacturing, the integrity of piping systems is crucial to the safety of the environment and the efficiency of operations. Failure in these sectors can result in catastrophic consequences, including hazardous material leaks, safety violations, and environmental contamination, which may lead to regulatory fines and extensive legal costs.

By proactively addressing corrosion and erosion, companies not only enhance the reliability of their operations, but can also minimize the likelihood of legal disputes arising from equipment failure. This creates a more stable financial environment by reducing the costs associated with liability claims, lawsuits, and compliance penalties. Ultimately, a well-designed, corrosion-resistant piping system leads to better long-term financial health, ensuring companies remain competitive by keeping maintenance and operational costs under control.

CASE STUDY: THE IMPACT OF CORROSION AND EROSION ON PIPE INTEGRITY

In this section, we examine a case study that illustrates how corrosion and erosion can severely undermine the integrity of a piping system, even when the original design incorporates a fair margin of safety. In heavy industrial facilities, piping systems are critical to operational efficiency and safety. Therefore, accounting for material degradation over time is essential in the design phase.

Proper estimation of wall thickness reduction due to corrosion and erosion must be factored into the design criteria to maintain structural integrity throughout the system's service life. Failure to do so can lead to premature pipe failure, posing risks to both personnel and equipment.

This case study analyzes a carbon steel pipe with an outside diameter of 20 inches and an initial wall thickness of 0.375 inches. The pipe operates under an internal pressure of 145 psi (1 MPa). The material used is carbon steel with a yield strength of 36 ksi.

Figure 1 presents a cross-section of the pipe, showcasing the geometric and material properties that form the basis of the stress analysis. By evaluating the hoop stress in the pipe wall and modeling progressive wall thinning due to corrosion and erosion, we highlight the critical need for robust design strategies, suitable material selection, and continuous monitoring.

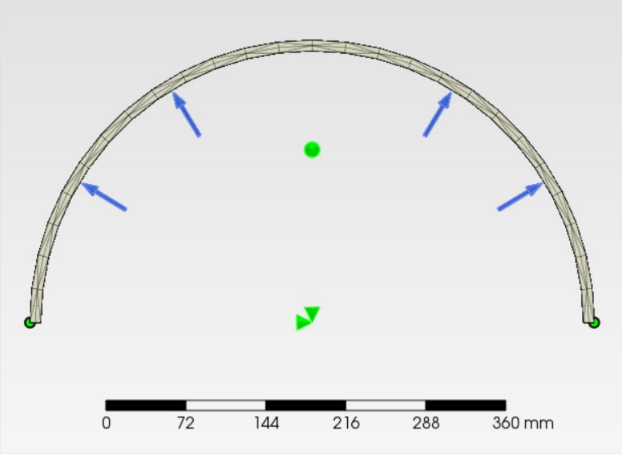


Figure 1 – Half symmetry pipe cross section under internal pressure. Image created by Alireza Shirani (Halliwell) in FreeCAD and PrePomax in March 2025. For illustration and education purposes. All rights reserved.

Finite Element Analysis (FEA) was performed on this pipe, and the resulting von Mises stress distribution is shown in **Figure 2**. The maximum von Mises stress (mainly hoop stress) in the pipe is approximately 3,916 psi (27 MPa), which closely matches the theoretical hoop stress calculations for this pristine pipe, as demonstrated in **Figure 3**.

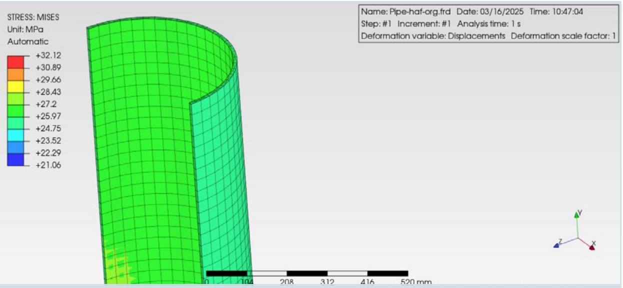
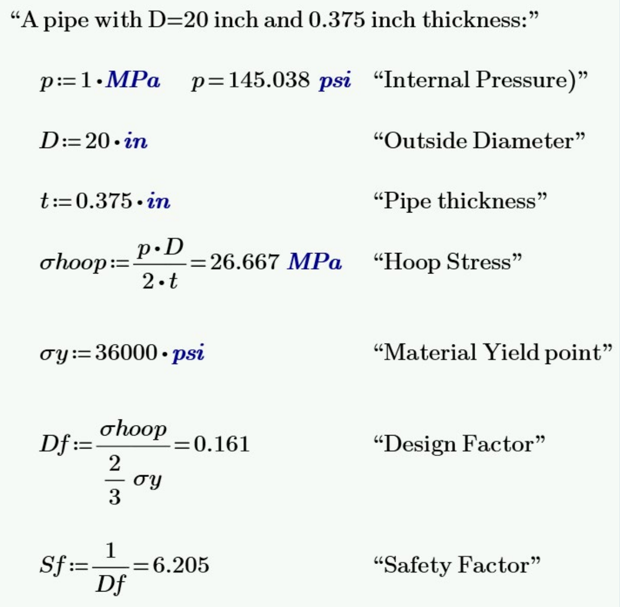


Figure 2 – Von Mises stress distribution in the pipe. Image created by Alireza Shirani (Halliwell) in PrePomax in March 2025. For illustration and education purposes. All rights reserved.



"A pipe with D=20 inch and 0.375 inch thickness:"

$p := 1 \cdot MPa$ $\quad p = 145.038\ psi$ "Internal Pressure)"

$D := 20 \cdot in$ "Outside Diameter"

$t := 0.375 \cdot in$ "Pipe thickness"

$\sigma hoop := \frac{p \cdot D}{2 \cdot t} = 26.667\ MPa$ "Hoop Stress"

$\sigma y := 36000 \cdot psi$ "Material Yield point"

$Df := \frac{\sigma hoop}{\frac{2}{3}\ \sigma y} = 0.161$ "Design Factor"

$Sf := \frac{1}{Df} = 6.205$ "Safety Factor"

Figure 3 – Mathematical calculation of pipe stress distribution. Image created by Alireza Shirani (Halliwell) in MathCad in March 2025. For illustration and education purposes. All rights reserved.

Both the hand calculations and finite element analysis (FEA) show consistency in results, confirming a large safety factor of 6.2.

However, this result could be misleading, as the effects of corrosion or erosion can significantly alter the stress distribution. A localized reduction in pipe thickness around the circumference, such as a 3-inch imperfection (**Figure 4**), can lead to a substantial increase in stress. In this analysis, it is assumed that corrosion has reduced the pipe thickness in a small region to approximately 0.060 inches, as illustrated in **Figure 4**.

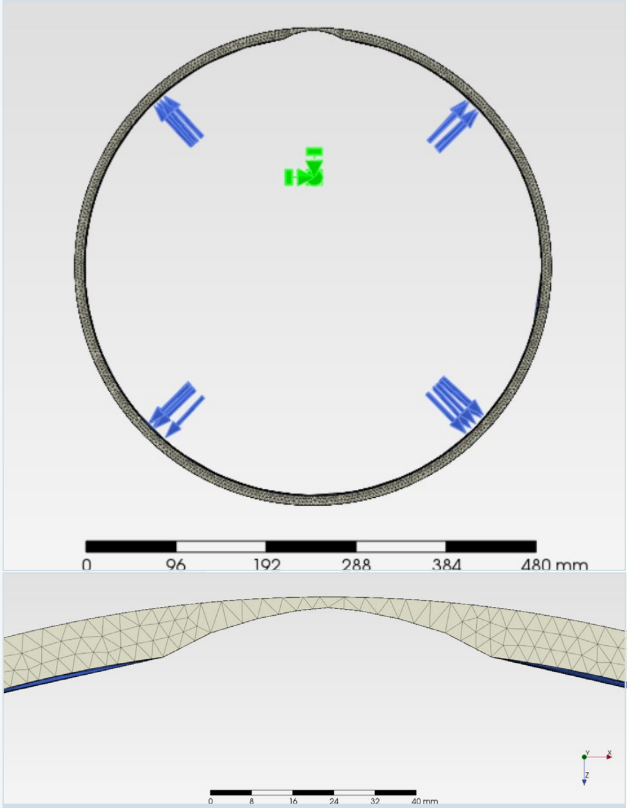


Figure 4 – Corrosion related thickness imperfection of the same pipe. Image created by Alireza Shirani (Halliwell) in FreeCAD and PrePoMax in March 2025. For illustration and education purposes. All rights reserved.

Finite element analysis (FEA) was performed on the corroded pipe under an internal pressure of 145 psi (1 MPa). The resulting von Mises stress distribution and axial deformation are shown in Figures 5 and 6, respectively.

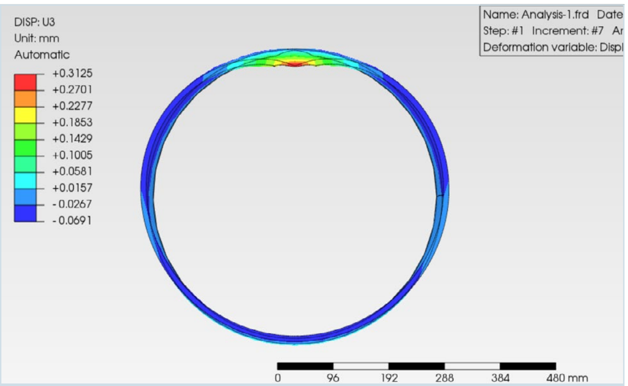


Figure 5 – Deformation of the pipe in axial (U3) configuration. Image created by Alireza Shirani (Halliwell) in PrePoMax in March 2025. For illustration and education purposes. All rights reserved.

An elastic-plastic analysis was performed in this section, as the presence of geometric imperfections caused the stresses to exceed the material's yield strength. The von Mises stress at the thinned section reaches 268 MPa (38,900 psi), well beyond the yield strength of 36,000 psi and approaching the material's ultimate tensile strength. As shown in **Figure 5**, the maximum radial displacement exceeds 0.31 inches (8 mm), surpassing the remaining pipe thickness at that section. Displacement results and von Mises stress results shown in Figure 6 clearly indicate that under an internal pressure of 145 psi (1 MPa), the pipe is on the verge of collapse and rupture. This highlights the significant impact of thickness reduction due to corrosion, demonstrating that even under the same internal pressure, a corroded pipe experiences drastically higher stress and deformation. Additionally, it is important to note that the mechanical and material properties of a corroded section, such as intrinsic fracture toughness, are lower than those of a new, pristine pipe, further increasing the risk of failure.

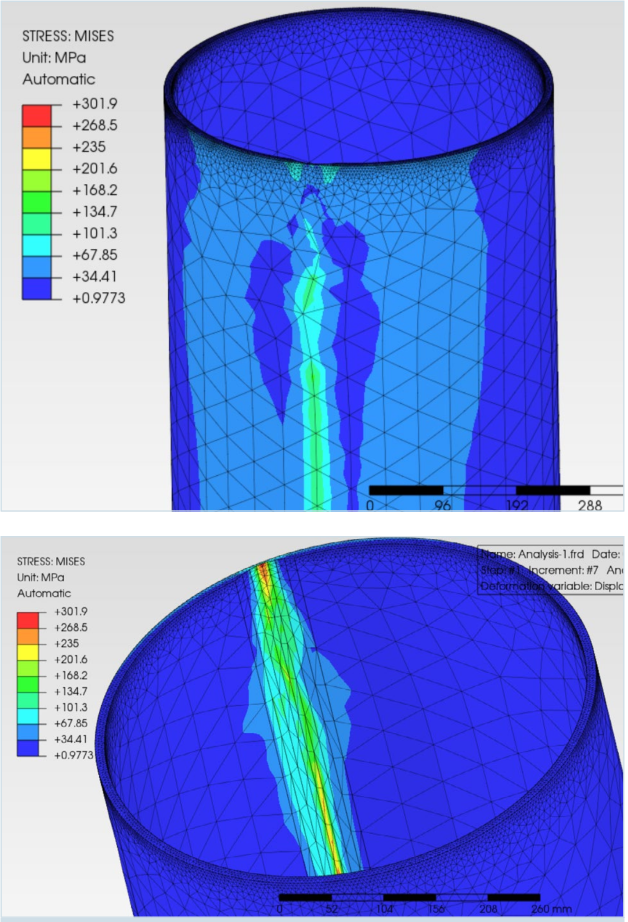
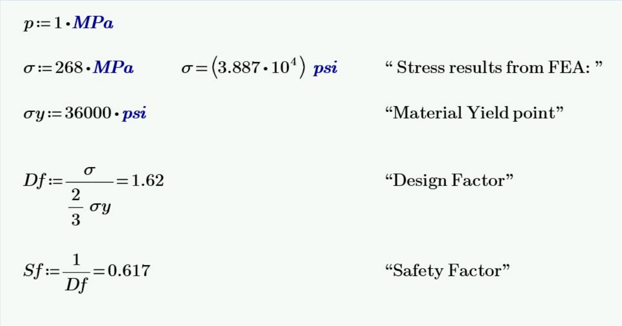


Figure 6 – von Mises stress of pipe with imperfection in thickness. Image created by Alireza Shirani (Halliwell) in PrePoMax in March 2025. For illustration and education purposes. All rights reserved.

The same pipe, with imperfections and non-uniform thickness, has a safety factor of 0.617 when applying the API-prescribed 2/3 safety factor. As shown in **Figure 7**, this value is significantly less than 1, indicating that the pipe is structurally inadequate and at high risk of failure.



$p := 1 \cdot MPa$

$\sigma := 268 \cdot MPa$ $\sigma = (3.887 \cdot 10^4)\ psi$ " Stress results from FEA: "

$\sigma y := 36000 \cdot psi$ "Material Yield point"

$Df := \dfrac{\sigma}{\frac{2}{3}\sigma y} = 1.62$ "Design Factor"

$Sf := \dfrac{1}{Df} = 0.617$ "Safety Factor"

Figure 7 – Mathematical calculation of pipe stress distribution. Image created by Alireza Shirani (Halliwell) in MathCad in March 2025. For illustration and education purposes. All rights reserved.

The Stress Intensity Factor (SIF) in a thin-walled pipe depends on the crack type and location. Common cases include axial and circumferential cracks. The general formula[16] is:

$K = Fa\ \sigma\ (\pi\ a)^{0.5}$

where:

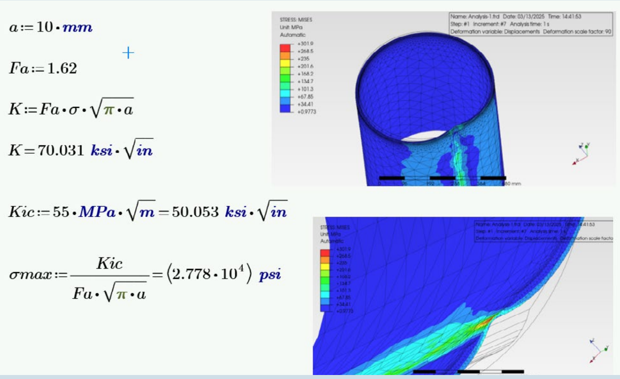
- **K = Stress Intensity Factor (MPa√m or psi√in)**
- **F_a = Geometry correction factor (dimensionless, depends on crack shape and pipe geometry)**
- **σ = Applied stress (MPa or psi)**
- **a = Crack depth (m or in)**

For a pipe with OD = 20 inch, and wall thickness of 0.060 inch, the ratio of OD/t = 333.3 for thin wall pipe,

$F_a = 0.33+0.07\ (OD/t)^{0.5}$

which yield to, $F_a = 1.61$.

With this value, the calculated stress intensity factor is 78.9 ksi√in. For a corroded pipe, the intrinsic fracture toughness (K_{ic}) of carbon steel is typically around 50 ksi√in, which is lower than that of a pristine pipe. This clearly indicates that if a crack exists, it will propagate. As shown in the calculations below, with a K_{ic} of 50 ksi√in, the maximum allowable stress cannot exceed 27,700 psi, as it is shown in **Figure 8**. This demonstrates that even under an internal pressure of 145 psi, the pipe would fail immediately upon the initiation of a small crack.



$a := 10 \cdot mm$

$Fa := 1.62$

$K := Fa \cdot \sigma \cdot \sqrt{\pi \cdot a}$

$K = 70.031\ ksi \cdot \sqrt{in}$

$Kic := 55 \cdot MPa \cdot \sqrt{m} = 50.053\ ksi \cdot \sqrt{in}$

$\sigma max := \dfrac{Kic}{Fa \cdot \sqrt{\pi \cdot a}} = (2.778 \cdot 10^4)\ psi$

Figure 8 – Stress Intensity calculation of 20-inch OD pipe. Image created by Alireza Shirani (Halliwell) in MathCad in March 2025. For illustration and education purposes. All rights reserved

Note: **Figures 1 through 8** were created by Alireza Shirani (Halliwell) using general purpose software of PrePoMax,[29] FreeCAD,[30] and MathCad.[31] For illustration/educational purposes. All rights reserved.

CONCLUSION

Understanding pipe failure modes is essential for ensuring the reliability and safety of piping systems across various industries. The analysis of different failure mechanisms—such as corrosion, mechanical damage, fatigue, and environmental factors—highlights the importance of proactive maintenance, material selection, and proper installation practices. By identifying early warning signs and implementing effective mitigation strategies, the risk of failures can be significantly reduced, thereby enhancing operational efficiency and safety.

Moreover, the cost and time associated with pipe replacement and maintenance play a crucial role in decision-making. Unexpected failures often lead to expensive emergency repairs, production downtime, and potential legal liabilities, all of which can have significant financial implications. Proper maintenance planning helps minimize these costs and ensures timely interventions, reducing the need for extensive replacements. From an insurance perspective, frequent failures and high maintenance costs can lead to increased premiums, as insurers assess risks based on historical failure rates and repair expenses. Conversely, a well-maintained piping system can lower insurance costs by demonstrating reduced risk exposure.

A systematic approach to monitoring, inspection, and failure analysis not only extends the service life of piping systems, but also minimizes financial burdens and operational disruptions. When failures due to corrosion and erosion occur, they often result in insurance claims related to property damage, business interruption, or environmental contamination. In these instances, forensic engineers play a crucial role in determining the root cause, differentiating between natural wear, design deficiencies, and negligence, and providing insurers and legal professionals with impartial, technical assessments. Investing in preventive measures ultimately leads to more cost-effective and reliable infrastructure, benefiting both operators and insurers alike.

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