Corrosion education as a tool for the survival of natural gas industry

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PRELIMINARY COMMUNICATION

Corrosion has been identified as the major problem to the pipeline industry. It single-handedly contributes to over 50% failure of global pipeline system and also cost the industry trillions of dollars annually on prevention and correction. However, as knowledge in corrosion science and engineering advances, the basic knowledge decreases. This work is prepared to study natural gas pipeline corrosion from cradle to grave. The paper identifies the types of corrosion, their causes, initiation processes within the pipeline, and the consequences of the resulted corrosion on the industry and environment as well as the means to prevent this major problem in the industry. Finally, this study is able to recommend both predictive and corrective measures in handling the problem. Conclusively, this article is very valuable to both the researchers and the people in the industry since it is able to successfully present adequate basic background on corrosion for those with little knowledge on this subject and also gives the research trend to the experts in the field.

Key words: natural gas, pipeline, corrosions, environmental implication, prevention

1. Introduction

Environmental awareness on the impacts of a failure along oil and gas pipeline on the ecosystem is increasing daily due to the implications on the four environmental matrices (air, water, land and vegetation) and the human health. Pipelines are the long metallic carbon alloyed structures used in petroleum, chemical, textile and many other industries to transport fluid during processes and to storage tanks. It is operated at a very high pressure and varying temperatures while the tube size employed is a function of fluid volume to be transported and the distance.

Transportation pipeline is an essential part of the infrastructure of modern society; it is a low-cost, safe mode of long distance transportation of petroleum products[28] frequently used for the transportation of large quantities of hydrocarbons under high pressure (Figures 1a and 1b). Over 3.5 million kilometres (2.2 million miles) of pipelines carry natural gas and other hazardous materials in USA, while the whole households in Australia, Canada and other industrialized countries are supplied gas for cooking and electricity generation through several kilometres of pipeline network systems.

Due to the nature of the conveyed cargo, pipelines are usually constructed with material of special characteristics and properties such as tensile strength, stiffness (elastic modulus), toughness (fracture resistance), hardness (wear resistance) and fatigue resistance. Commonly used materials are the stainless steel and the Monel. Stainless steel is the most frequently used corrosion resistant material in the industry with chromium content higher than 12% for oxidizing condi-

Fig. 1a. A suspended Alaska oil pipeline
Sl. 1a. Uzdignuti naftovod na Aljaski

Fig. 1b. An onshore natural gas pipeline
Sl.1b. Kopneni plinovod

Fig. 2. Image of Lagos Pipeline Explosion of December 2006
Source: African Shirt (2006)
Sl. 2. Slika eksplozije cjevovoda u Lagosu, prosinca 2006.
Izvor: African Shirt (2006)

tions while nickel is added to improve the corrosion resistance in non-oxidizing environments. Monel, the classical nickel-copper alloy with the metals in the ratio 2:1 is the most commonly used alloy after stainless steels. It has good mechanical properties up to 500 °C. It is more expensive than stainless steel, has good resistance to dilute mineral acids and can be used in reducing conditions where the stainless steel would be unsuitable.

In recent times however, considerable public and regulatory attention has been focused on the potential danger of pipeline failures due to past experiences in many countries. The spate of accidents in the industry resulting in oil spill and gas leak has attracted a significant level of awareness in safety and loss prevention.

A case study of a typical offshore platform in the North Sea, UK, showed that the amount of gas present in a 150 km long and 0.4 m diameter pipeline at 100 bars could be as much as 637 000 kg.[39] This represents an enormous source of energy release, which in the event of Full Bore Rupture (FBR) poses the risks of general and extreme fire exposure to all personnel in open platform areas and also undermines platform safety while the Piper Alpha disaster in the North Sea of July 6th, 1988 clearly demonstrated the catastrophic consequence of this type of failure when 165 of the 226 on board died, majority (109) from smoke inhalation.[13] It was estimated that the energy released during this tragedy was equal to 1/5th of the UK energy consumption at the period. Lagos State of Nigeria's oil pipeline explosion of December 2006 (Figure

Table 1. Some Global Major Pipeline Accidents

Date	Location	Nature of Accident	Damage Caused
05-05-09	Rockville, USA	Natural gas pipeline explosion.	Homes were evacuated in a one-mile area of explosion.
16-05-08	Ijegun, Lagos, Nigeria.	A bulldozer accidentally struck an oil pipeline which eventually exploded.	100 deaths. 15 homes and 20 vehicles burnt.
01-11-07	Carmichael, USA	Propane pipeline explosion.	2 deaths, 5 injured.
26-12-06	Lagos, Nigeria.	A vandalized oil pipeline exploded	Over 500 deaths.
30-07-04	Ghislenghien, Belgium	Explosion of a major natural gas pipeline.	23 killed, 122 injured.
2003	Chongqing, China	A gas well blew out releasing toxic sour gas cloud to the environment.	243 deaths.
02-07-03	Wilmington, Delaware	Excavation damage to natural gas distribution line resulting in explosion and fire.	
21-10-00	Colombia	Pipeline explosion.	43 deaths.
19-08-00	Carlsbad, New Mexico USA	Natural gas pipeline ruptured due to severe internal corrosion and exploded.	12 members of the same family killed.
10-06-99	Bellingham, Washington	A gasoline pipeline ruptured. 250,000 gallons of gasoline escaped into a creek and resulted into fire.	3 deaths, 8 injured, over $45 million property damages.
08-08-96	Lively, Texas, USA	Liquid natural gas burst due to inadequate corrosion protection.	2 men killed.
21-11-96	San Juan PR	Liquid natural gas line explosion due to employee's negligence in responding to leak.	33 people killed.
09-11-93	Nam Khe Village, East of Hanoi.	A 9-year-old boy lit a match while scooping fuel from broken underground pipe leading to explosion	45 deaths.
001-03-98	Ecuador	Pipeline explosion and fire at Ecuador's largest oil pipeline.	11 deaths, 80 injured.
18-10-98	Jesse Village Delta, Nigeria	Oil pipeline explosion while villagers were scooping fuel from a ruptured pipeline.	Over 2000 deaths.
04-06-89	Ufa, Russia	Sparks from two passing trains detonated gas leaking from an LPG pipeline	645 deaths.
03-06-89	Russia	Liquefied natural gas Pipeline explosion	575 deaths
23-06-89	Eastern Pakistan	Gas Pipeline ruptured and exploded.	12 killed; hundreds injured.
03-10-89	Gulf of Mexico	Submerged Gas pipeline exploded.	11 deaths.
28-10-93	Las Tejeria, Venezuela	Telephone crew laying fiber optic cable ruptured natural gas pipeline beneath highway leading to explosion	36 deaths.
1982	Amoco field, Canada	A high profile blowout releasing sour gas for 67 days to environment.	2 human and hundreds of cattle death.

2) also resulted in the death of over 500 people, and the Jesse fire incident lead to cremation of over 2000 people in 1998.[54]

Pipeline failure which may be due to many reasons broadly classified as sabotage, equipment failure, and human error[3] is a global occurrence and is characterized by damages of different magnitude (Table 1). Corrosion has been identified to be responsible for over 50% of pipeline failure in the industrialized countries (Table 2).

Corrosion is the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties.[24] The process involves electrolytic action whereby the substances which increase the concentration of hydrogen ions (H^+) such as acids and acid salts stimulate it while those substances that increase hydroxyl ion (OH^-) inhibit it. Pipeline corrosions could be broadly classified as internal and external corrosions. While the environmental conditions around the pipeline are responsible for the external corrosion,[43,35,79] the internal corrosion is mainly caused by the fluid flowing through the pipeline and the pipe's geometry. Corrosion may also be caused or facilitated by the activities of microorganisms living within or on the pipe wall.[67,70]

Despite the global understanding that corrosion is a strong enemy to the survival of oil and gas industry, there is not yet enough education on combating this problem hence, the importance of this manuscript. This work is developed to shed more light on corrosion and its significance to gas industry. It covers the corrosion process, the types and mechanisms of corrosion, the factors influencing corrosion, the impacts of pipeline failure due to corrosion on the four environmental matrices. Finally, the paper makes recommendations to bridge the knowledge gap. This study is a valuable tool for those new to corrosion science and engineering, the researchers and the field personnel.

2. Chemistry and electrochemistry of corossion

For metallic materials, the corrosion process is either a chemical or electrochemical process.[72] Electrochemical process involves the transfer of electrons from one chemical species to another. Metal atoms characteristically lose or give up electrons through oxidation reaction (Equation 1) which takes place at the anode[48] or reduction reaction (Equation 2) taking place at the cathode.[49]

$$M \rightarrow M + ne^-$$
$$Fe \rightarrow Fe^{2+} + 2e^- \quad (1)$$
$$Al \rightarrow Al^{3+} + 3e^-$$

Most metals undergo corrosion in acid solutions that have high concentration of hydrogen ions (H^+) which reduces evolving of hydrogen gas, H_2 through reduction process (Equation 2)

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

For an acid solution having dissolved oxygen, reduction according to equation (3) may occur[44] whereas, for a neutral or basic aqueous solution in which oxygen is dissolved, reduction according to Equation 4 is mostly favored.[91]

$$O_2 + 4H^+ 4e^- \rightarrow 2H_2O \quad (3)$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4(OH^-) \quad (4)$$

For multivalent ions, reduction may occur by decreasing its valence state through acceptance of an electron (Equation 5) or by totally reducing itself from an ionic state to a neutral metallic state (Equation 6). Two or more of the reduction processes may occur simultaneously.

$$Mn^+ + e^- \rightarrow M^{(n-1)+} \quad (5)$$

$$Mn^+ + ne^- \rightarrow M \quad (6)$$

However, corrosion by chemical reaction does not involve electron transfer. In this case, the metal is attacked by a diluted acid (e.g HCl) to evolve hydrogen gas (equation 7).

$$Fe + 2HCl \rightarrow FeCl_2 + H_2 \quad (7)$$

2.1 Internal Corrosion of a Gas Pipeline

Corrosion of the internal wall of a gas pipeline occurs when the pipe wall is exposed to water and contaminants

Table 2. Summary of pipeline failure incidents by cause in developed countries

Cause	Contribution (%)			
	USA[a]		Canada[b]	Russia[c]
	Liquid Pipeline	Gas Pipeline	Gas Pipeline	Gas Pipeline
Corrosion	19.26	41.25	57	31
Natural forces	-	-	12	
Defective Weld	8.61	-	15	
Incorrect operation	3.28	-		5
Defective pipe	4.51	-	8	12
Outside damage	23.36	28.75	4	23
Malfunction of equipment	9.02	11.25		
Construction defects				29
Others	31.97	18.75	4	

*Source: [a] DOT (2005); [b] Cribb (2003); [c] Mokrousov (2008) in the gas such as oxygen (O_2), dihydrogen sulphide (H_2S), carbon-dioxide (CO_2) or chloride ion (Cl^-). The nature and extent of the corrosion damage are functions of the concentration and particular combination of these various corrosive agents within the pipeline.[40,42]

In gas transmission lines, internal corrosion usually signifies the presence of significant partial pressures of CO_2 and/or H_2S in the line. On a weight percentage or weight fraction basis, O_2 is more dissolved to ordinary steels than either CO_2 or H_2S.[84] Although, the probability of having appreciable concentrations of O_2 inside a gas transmission line is apparently quite low, a small partial pressure of O_2 can produce surprisingly high (higher) internal corrosion rates in steel pipes than that containing liquid water.

3. Types of corrosion

According to Roberge[72], corrosion can be generally classified into three major categories while the corrosion through microbial activities could be the fourth group. The first group belongs to those that can be readily identified by visual examination; this includes uniform corrosion, localized corrosion and galvanic corrosion. The second group is for those requiring further examination for identification which includes erosion corrosion, cavitations corrosion, fretting corrosion (these three are classified under velocity corrosion), intergranular corrosion and dealloyed corrosion while the third group are those that can only be confirmed through the use of a microscope which involve cracking form of corrosion and high-temperature corrosion. Another form apart from these three general groups is the hydrogen ion induced corrosion.[31,23]

3.1 Pitting and Crevice Corrosions

Crevice and pitting corrosions are related because they both require stagnant water, Cl^- and O_2 or CO_2; and the mechanism of corrosion is very similar for both. They are confined to a point or small area that develops in highly localized areas on the metal surface.[75,60] This results in the development of cavities or "holes" that may range from deep cavities of small diameters to relatively shallow depressions in the material (Figures 3 and 4).

Pitting corrosion is frequently observed in a CO_2 and H_2S oil and gas fields. It is very difficult to detect, predict or designed against at the plant designed stage. Through its gradual formation, the products from the corrosion

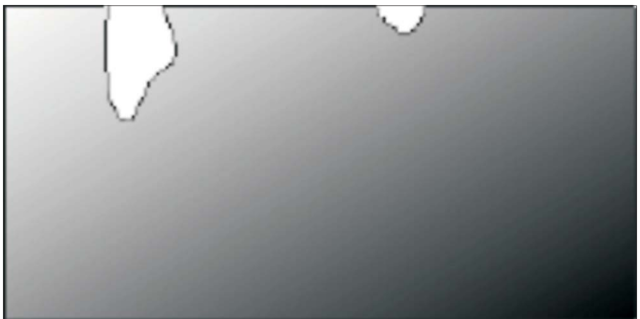


Fig. 3. The image of a metal attacked by pitting corrosions.
Sl. 3. Slika metala napadnutog točkastom korozijom

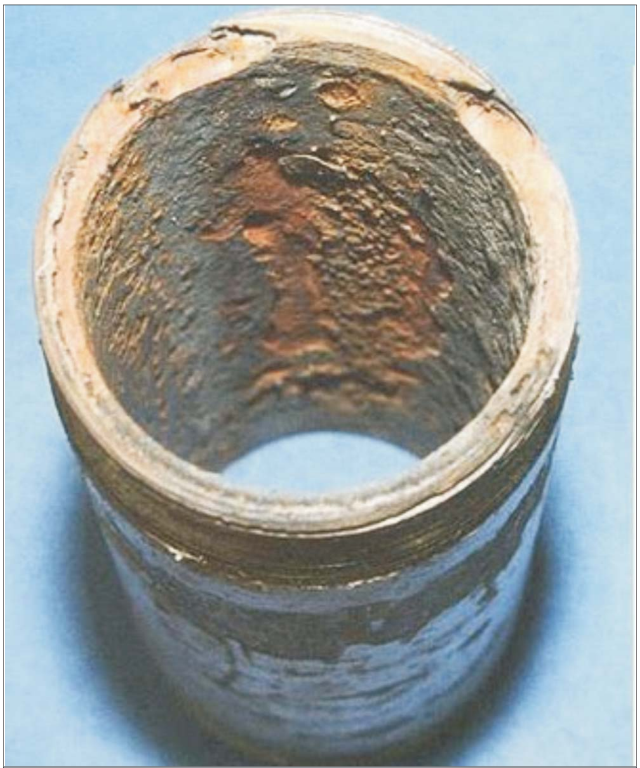


Fig. 4. Image of a metal attacked by crevice corrosions
Sl. 4. Slika metala napadnutog pukotinskom korozijom

cover the cavities, hence, making the small narrow pit unnoticed. However, this small pit is capable of collapsing the whole pipeline structure.

Crevice corrosion is formed by contact with adjacent piece of the same or another metal with a non-metallic material. When this occurs, the intensity of attack is usually more severe than on surrounding areas of the same surface.[1,30] It is mostly formed under a shielded area such as under gaskets, washers, insulation material, fastener heads, surface deposits, disbonded coatings, threads, lap joints and clamps.

Chloride ions and operating temperature influence pitting formation, thus, offshore pipelines are more prone to this corrosion type since sea water contains sodium chloride which could be produced with wet gas from the reservoir. Stagnant fluid (inside the tubing) can also easily initiate pitting corrosion and crevice attacks, especially, if particles settle out of the fluid (liquid). Stainless steel Type 304 can be attacked by pitting corrosion inside the sea at 10 °C even, at low chloride level, while Type 316 which is more resistant to pitting can easily be attacked by crevices at a slightly increased temperature.

3.2 Stress-corrosion cracking (SCC)

This corrosion (Figure 5) can be accelerated by residual internal stress in the metal or external applied stress. Residual stresses are produced by deformation during fabrication, by unequal cooling from high temperature and by internal structural arrangements involving volume change.

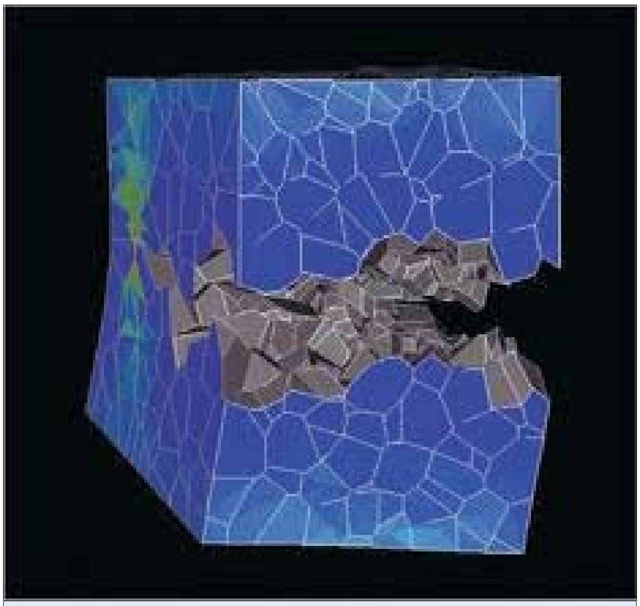


Fig. 5. A three-dimensional model reproducing stress corrosion crack shapes
Source: Itakura et al (2005)
Sl. 5. Trodimenzionalni model prikazuje pukotinsku koroziju pod naprezanjem
Izvor: Itakura et al (2005)

Fig. 6. The “Horseshoe” type erosion-corrosion damage in a copper pipeline.
Sl. 6. "Potkovičasti" tip erozijsko korozijskog oštećenja u bakarnom cjevovodu

The steel pipeline is composed of many crystals of about 0.05 mm[27,12] whose temperature is always kept high to prevent hydrate formation and/or the liquefaction of some other components during operation. This may generate irradiation inside the steel especially at a high temperature, thus, subjecting the material to tensile stress in a corrosive environment. This problem increases at pH≥8 but decreases at pH≤6.[20] When SCC occurs, its intricate crack shape follows the interface between these grains in a zigzag manner. There can be multiple cracks in the pipeline, thus, making the study of SCC progression in a pipelength very crucial for the pipe’s safety assessment.

Fig. 7. Cavitation of a nickel alloy pump impeller blade exposed to a hydrochloric acid medium.
Source: CHCMT (2009)
Sl. 7. Kavitacija lopatice miješala pumpe od slitine nikla izložene klorovodičnoj kiselini
Izvor: CHCMT (2009)

3.3 Erosion, Cavitations and Fretting Corrosions

These corrosions occur as a result of high velocity flow of fluid inside the pipe. The industries transporting slurries and other particle-laden liquids in pipes through offshore and marine technologies spend millions of pounds every year to repair material damage from erosion-corrosion damages.[41] In a survey, erosion–corrosion (Figure 6) was rated in the top five most prevalent forms of corrosion damage in the oil and gas industry.[68]

Erosion is the destruction of a metal by abrasion or attrition caused by the relative motion/flow of liquid or gas (with or without suspended solids in the pipe) against the metal surface. For this corrosion type, there is a constant bombardment of particles on the wall surface.[72] This gradually removes the surface protective film or the metal oxide from the metal surface, thus, exposing the surface to corrosion from the fluid properties. Factors such as turbulence, cavitations, impingement or galvanic effects can add to the severity of erosion-corrosion attack which eventually leads to rapid failure.

Cavitation corrosion (Figure 7) is caused by the collapse of bubbles formed at areas of low pressure in the pipeline.[72] The fluid traveling at a very high speed will experience a drop in pressure at a point of discontinuity in the flow path. This will lead to the formation of gas or vapor bubbles (transient voids or vacuum bubbles) in the stream which implode upon hitting the metal surface and produce a shock wave sufficiently strong enough to remove the protective films. Corrosion is then greatly accelerated at this mechanically damaged surface.

Fretting (Figure 8) is the corrosion damage experienced at rough contact surfaces. It is induced by repeatedly moving a load across a surface at a relatively high veloc-

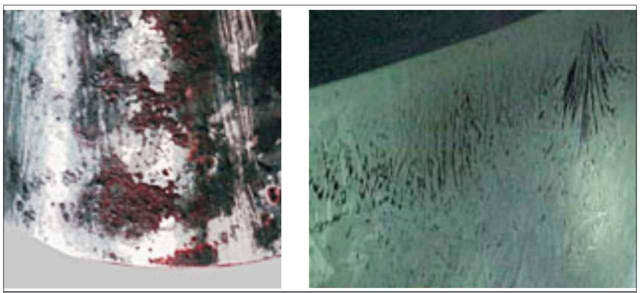


Fig. 8. Fretting corrosion
Source: ILZRO (2009)
Sl. 8. Korozija uslijed trenja
Izvor: ILZRO (2009)

ity.[62] Contact surfaces exposed to vibration during transportation are exposed to the risk of fretting corrosion. Damage occurs at the interface of two highly loaded surfaces which are not designed to move against each other. The protective film on the metal surfaces is removed by the rubbing action and exposes fresh, active metal to the corrosive action of the atmosphere. This problem is experienced in the oil and gas pipelines as the motion of the fluid inside the tube causes a lot of vibration due to the contact of the weight of the fluid with the inner surface of the tubing.

3.4 Uniform corrosion of carbon steel

Uniform corrosion (Figure 9) is the least damaging form of corrosion in that it is predictable if the corrosion rate is known. This is a corrosion process exhibiting uniform thinning that proceeds without appreciable localized attack and commonly occurs on metal surfaces having homogenous chemical composition and microstructure.

As corrosion occurs uniformly over the entire surface of the metal component, it can be practically controlled by cathodic protection, use of coatings or paints, or simply by specifying a corrosion allowance.

4. Factors influencing gas pipeline corrosion

Corrosion of gas pipeline materials is primarily influenced by some factors that are readily available during its transportation within the system. These factors include the gas pH, present oxidizing agent(s), the system temperature, the fluid velocity, the pipe wall's shear stress, the size of available particles, the fluid composition and the fluid viscosity amongst others.

4.1 pH

The corrosion rate of most metals is affected by pH[94] and hydrocarbon pipelines are susceptible to corrosion–induced stress and stress corrosion cracking at high pH.[20,80] Also, pH promotes the galvanic corrosion in metals and alloys.[85] For pH related corrosions, the corrosion rate of acid-soluble metals such as iron is controlled by the rate of transport of oxidizers (usually dissolved oxygen) to the metal surface whereas the amphoteric metals such as aluminum and zinc dissolve rapidly in either acidic or basic solutions. However, corrosion of noble metals such as gold or platinum is not appreciably affected by pH.

4.2 Oxidizing agents

Oxidizing agents are often powerful accelerators of corrosion. In their study based on monoethanolamine (MEA) system, Veawab and Aroonwilas[88] indicated bicarbonate ion (HCO_3^-) and water (H_2O) as primary oxidizing agents while Stack et al[83] revealed oxygen as a contributor to erosion-corrosion in aqueous slurries. In many cases, the oxidizing power of a solution is its most important single property in promoting corrosion. When oxygen is involved, there is a rapid reaction between the O_2 and the polarizing layer of atomic hydrogen absorbed on the oxide layer and this reaction rapidly removes the polarizing layer.

Fig. 9. Uniform corrosion of structural steel
Source: KSC (2009)
Sl. 9. Jednolika korozija konstrukcijskog čelika
Izvor: ILZRO (2009)

4.3 Temperature

Like most other chemical reactions, corrosion rate increases with temperature since ionic mobility increases with temperature, thus, leading to conductance increases.[87,50,32,15] The process temperature and pressure govern the solubility of the corrosive species in the fluid. These species include oxygen, carbon-dioxide (or hydrogen sulfide in case of sour field), chlorides and acetic acid amongst others. From the rule of thumb, reaction rate doubles between the temperature rises of 20 °F to 50 °F (6.6 °C - 10°C). This linear increase stops along the line partly due to a change in the oxide film covering the surface. Temperature also has secondary effects through the influence on the solubility of air (O_2), which is the most common oxidizing substance influencing corrosion.

4.4 Fluid Velocity

The fluid velocity plays a great role in corrosion rate.[74,4,82,5] When the velocity is very high, the impact of the particles present in the fluid upon the inner wall of the pipe tends to remove the protective oxide layer and some of the metals under it causing erosion and thus lead to erosion-corrosion with time. Also, when H_2O is involved, water velocities of 30 to 40 ft per second (9.1 - 12.2 m/s) initiate corrosion since increase in the relative movement between a corrosive solution and a metallic surface frequently accelerate corrosion.

4.5 Wall shear stress

Wall shear stress is one of the parameters that highly influence hydrodynamically induced corrosion such as erosion corrosion.[9,14,10] Turbulent flow is frequently used in the gas industry to transport fluids in order to increase the transportation efficiency at a minimized cost. Particles and other geometrical changes in the flow give rise to higher shear stress though abrasion leading to drag (skin friction) which eventually induces corrosion of the inner wall by wearing off the protective coatings.

4.6 Particle size

The size of the particle traveling with a conveyed fluid inside a pipeline network plays a significant role in initiating internal corrosion of the pipeline.[36,61] Erosion and cavitation corrosions are among the identified corrosion types that could be initiated by the particle size distributions. Niu and Cheng[51] and Xu et al[92] established that particles are capable of initiating erosion-corrosion by using sand and Nano-Particle-Reinforced Ni Matrix Composite Alloying Layer respectively while Obanijesu et al[58] established the capability of hydrate clathrates from hydrate formation in gas pipeline to initiate the erosion, cavitation, galvanic and electrolytic corrosions depending on the formation stage, the point of contact, the gas velocity and composition. It is explained that, as the particles, traveling at sonic or supersonic velocity hit the pipe inner wall, the pipe's surface is gradually chipped off thus, exposing it to a corrosion type based on the governing mechanism.

4.7 Chemical Composition and Concentration

The gas composition and concentration play significant roles in the corrosion rate of the transporting pipeline. While Zhao et al[94], established that ion concentrations of a conveyed fluid aids Stress Corrosion Cracking (SCC), various relationships between corrosion rates of pipes and the composition and concentration have been established by other researchers.[18,21,36,76,45]

The influence of pH and concentration on corrosion rate is best understood through electrochemical reaction. At any considered pH, the pipe corrosion rate increases with concentration of the fluid's non metallic components.[94] This is so as the corrosion behaviour of metallic alloys is governed by a partially protective surface film, with the corrosion reactions occurring predominantly at the breaks or imperfections of the partially protective film. The implication is that the fraction of film free surface increases with decreasing bulk pH and with increasing fluid non metallic ion concentration. This is consistent with the known tendency of non metallic ions to cause film breakdown and the known instability of the metallic hydroxides in solutions with pH less than 10.5. While the stannates, AZ91D (a Die casting magnesium alloy known as the alternative to zinc and aluminium because of its high-purity and excellent corrosion resistance) is appreciated in the industry due to its properties (Tables 3 and 4) and ability to reduce corrosion rates of a coated pipeline by behaving as a barrier to prevent the non metallic ions' attack and hence, decreases

Table 3. Typical room temperature mechanical properties of AZ91 castings

Property	AZ91A,B,D		AZ91C,E	
	F Temper	F Temper	T4 Temper	T6 Temper
Tensile strength , MPa (10^3 psi)	230 (33)	165 (24)	275 (40)	275 (40)
Tensile yield strength, MPa (10^3 psi)	150 (22)	97 (14)	90 (13)	145 (21)
Elongation in 50 mm (2in) %	3	2.5	15	6
Comprehensive yield strength at 0.2% offset, MPa (10^3 psi)	165 (24)	97 (14)	90 (13)	130 (19)
Ultimate bearing strength, MPa (10^3 psi)	-	415 (60)	415 (60)	515 (75)
Bearing yield strength, MPa (10^3 psi)	-	275 (40)	305 (44)	360 (52)
Hardness, HB	63	60	55	70
Hardness, HRE	75	66	62	77
Charpy V-notch impact strength, J (ft.lbf)	2.7 (2.0)	0.79 (0.58)	4.1 (3.0)	1.4 (1.0)

Table 4. Typical tensile properties of AZ91C-T6 sand castings at elevated temperatures

Testing temperature		Tensile strength		Yield strength		Elongation
°C	°F	MPa	10^3 psi	MPa	10^3 psi	In 50mm %
149	300	185	27	97	14	40
204	400	115	27	83	12	40

the susceptibility of the alloys to corrosion, increasing stannate concentration was found to have an adverse effect on the corrosion resistance.[21]

4.8 The Fluid Viscosity

This has been an area where people have not been looking into as there is no recent literature available, the most probably recent being Ricciardiello and Roitti.[71] However, the science can easily be used to support this claim.

Viscosity is the resistance of a liquid to shear forces and hence to flow.[57] This is a quantity expressing the magnitude of internal friction in a fluid, as measured by the force per unit area resisting uniform flow. Thus, the higher the viscosity, the lower the mobility and higher the time of surface interaction between the fluid's properties and the pipe inner surface to facilitating corrosion initiation.

5. Consequences of pipeline failure on the industry

The present global drive is mostly through the energy sector of which gas plays the significant role.[25] The industrialized countries presently generate and supply electricity through the gas to homes and industries. This hydrocarbon and its products such as methane, ethane and propane amongst others are transported through pipeline networks which upon corrosion, could leak or rupture and the conveyed fluid escaping into the immediate environments. The major impacts of these accidents on the pipeline industry can be classified into economic, safety and environmental consequences.

5.1 The Economic Impacts

The economic impact of gas pipeline corrosion on the industry includes the cost implication of construction and repair of a pipeline unit. About $694 100/km is required to construct a new pipeline[86] and considering damage along a 778 900 km pipeline (total major pipe-length in USA in 2009), the cost of repair is roughly $541bn. A study conducted by Battelle[7] in 1995 put the annual cost of corrosion on US economy at $300bn with 1% ($3bn) coming from oil and gas pipelines alone while a later study conducted by Thompson and Vieth[86] put the new annual cost on corrosion from the same country at $276bn (representing 3% of annual GDP) with $8.6bn coming from oil and gas transmission pipelines. Considering this economic trend, the cost implication of corrosion on USA alone has increase from $3bn to $8.6bn within a short period of 8 yrs (1995-2003). Since 2003 however, various new gas fields have been discovered and exploited within the same country, thus, increasing the number of existing pipelines for petroleum and its products. Globally likewise, the related increase in the number of pipeline has resulted from increased demand of the gas. This has increased both the on-shore and off-shore transboundary pipelines from the gas rich countries to those lacking the hydrocarbon. These pipelines have been generally subjected to conditions favoring various corrosion accidents which increase daily (Table 5).

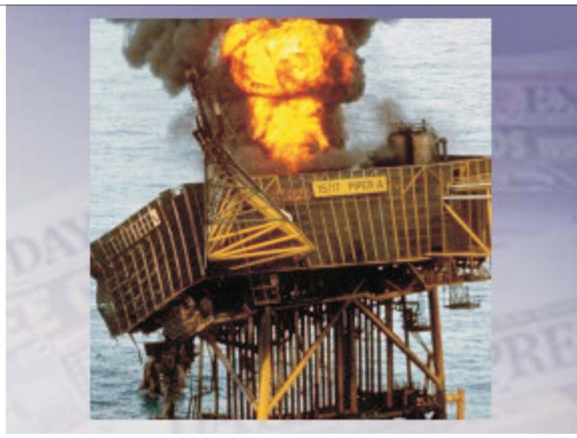
5.2 Safety Consequences

The failure along the pipe-length could subject the pipeline operators working at the platform as well as the community to severe safety risks which are predominantly death. Notably is the Bellingham, Wash pipeline accident of June 10, 1999 where 946 thousand liters (250 000 gallons) of gasoline from a ruptured, large transmission pipeline spilled into a nearby creek, accidentally ignited, and led to the deaths of three young individuals, eight injuries, and over $45 million in property damages.[66] Experience from the Piper Alpha offshore accident of 6th July 1988 at North Sea (Figure 10) where the failure of the primary propane condensate pump led to an explosion can never be forgotten in gas industry. Within 20 minutes of the failure, the gas risers (pipes between 61.0 and 91.4 cm (24 and 36 inches)) in diameter on the platform carrying gas at 137.0 bar (2 000 lbf/in.^{2})burst and created inferno. 167 out of the 226 personnel died with

Table 5. Some global pipeline accidents due to corrosion and consequences

Date	Location	Nature of Accident	Damage Caused
03-02-09	Shah Oilfield, Al Gharbia, UAE	A pipeline from the 50,000 barrel per day oilfield got leaking due to corrosion and released H_2S gas to the environment before explosion.	3 killed by inhaling high concentration of H_2S gas, 1 injured.
19-08-00	Carlsbad, New Mexico, USA	A 30-in diameter natural gas pipeline ruptured due to severe internal corrosion (pitting) and exploded.	12 members of the same family killed, 3 vehicles bumt and 2 nearby steel suspended bridges damaged. Property and other damages and losses totaled $998,296
08-08-96	Lively, Texas, USA	An 8-in diameter LPG pipeline transporting liquid butane burst due to inadequate corrosion protection.	2 men killed, 25 families evacuated, damages cost over $217,000.
04-03-65	Louisiana, Tennessee, USA	Gas transmission pipeline exploded from stress corrosion cracking	17 killed

A: Before the fire / Prije požara



B: During burning / Tijekom gorenja

C: Final platform stage / Finalni prikaz platforme

D: Memorial status / Memorijalni spomenik

Fig. 10. The North Sea Piper Alpha accident of 6th July, 1988
Sl. 10. Piper Alpha incident u Sjevernom moru na dan 6. srpnja 1988.

109 from smoke inhalation.[13] The fire was visible up to 137 km (85 miles) away and the heat felt at 1,6 km (1 mile) away. Almost the whole production platform was melted to sea level. This accident is still regarded till today as the global worst offshore accident ever.

The resulting explosions from variously related pipeline accidents have also been devastation. Over 2000 people were burnt to death in the Jesse fire accident of 1998 in Nigeria (Obanijesu et al, 2006) while a similar occurrence claimed over 250 lives at Alagbado pipeline fire incidence of 2006 in Nigeria (Fig. 2).

5.3 Environmental

The environmental threats posed by a gas pipeline failure depend on the quality and quantity of gas released, operating pressure, failure mode and the immediate environment. There could be damage and debris throw due to stored energy released by the failure (severe for gas), vapour cloud explosion, release of toxic gases (e.g. H_2S), asphyxiation and thermal radiation.

Many of the existing and proposed pipelines are routed through critical wildlife and wild lands. An example is the US $2.23 billion worth 3 056-kilometres-long Bolivia-Brazil pipeline. The 20 year contract pipeline is expected to transport 8 million m^3 for the first 7 years and 16 million m^3 for the remaining 13 years.[65] However, the pipe-length runs through the Amazon River Basin which contains the world's largest tropical forest and almost half of the planet's terrestrial biodiversity. This is the largest basin in the world and is about 6 751 km (4 195 miles) long and 7 044 km^2 (2 720 square miles) in area. Specifically, the river basin includes 15 000 tributaries and sub-tributaries, four of which are in excess of 1 609 km (1 000 miles) long.[78] Any failure from such pipelines will result in release of toxic gas or fire which in addition to affecting the community living could add to the destruction of the tropical ecosystems, loss of species and specimens, degradation of soil, water, air and destruction of basic infrastructures. Most importantly, it could add to the extinction of this wildlife.

Also, the toxic gases release from gas pipeline accidents could lead to human death amongst several other hazards. In 1982, a high-profile blow out at an Amoco well in Western Canada spewed sour-gas cloud for 67 days, killing two workers and hundreds of cattle. In 2003 also, 243 people were killed by inhalation of the toxic gas released from a blown out gas well near the city of Chongqing in Central China that clouded the environment. Hydrogen disulfide is a corrosive material that is frequently associated with pipeline failure. The gas can combine with other chemicals in a pipeline to produce microbial reduced corrosion (tiny cracks that are not detectable with the naked eye but can leak deadly quantities of gas). H_2S as an enhancer of internal corrosion due to its ability to corrode steel naturally exists in many gas fields especially in Asian countries such as India, China, Pakistan, etc. Noteworthy is the Shah natural gas deposit that is located beneath Shah Oilfield in India. This gas field contains up to 30% H_2S. Similar fields with such high sour gas are Bah, Asab and the offshore Hail fields (all in India). The gas is heavier than air[59] and can travel along the ground to easily cause respiratory failure and brain damage even at low concentration. The threshold for human tolerance to this gas is very low. It is estimated to be less than 20 ppm[16] and the fatality of the gas as a killer has been recorded to be high worldwide.

Marine lives are not spared from the effect of failure along such pipelines. Natural gas boils at -162 °C and its release into waterbody will result in formation of hydrates.[56] This causes problems ranging from behavioural nature (e.g., fish excitement, increased activity, and scattering in the water) to chronic poisoning depending on the quantity of the gas and the total period of exposure.[63,64] Dissolution of component is also eminent which will affect the pH of the sea water for the contact period and adversely affect the sea foods' quality.

6. Existing and proposed solutions to gas pipeline corrosion problems

Leak-free and error-free operation is the objective of every pipeline owner.[28] Since this is not realistic, there is then a need to put both preventive and corrective management schemes in place in order to minimize pipeline corrosion through timely investment in research and development in various universities. The following areas should be considered in the various researches so as to promote safe mode operational options.

There is a need for effective corrosion monitoring in the gas pipeline, especially, the internal corrosion which is apparently significantly more difficult than monitoring of external corrosion.[84] One method that may yield valuable information concerning the general internal condition of a line is to periodically run scraper pigs through the lines. The inner wall of the pipes should be cleaned, scrubbed and scrapped with pigs for preventive and maintenance purposes as well as to improve the flow of the hydrocarbons. Pigging is the process of driving a metallic scrapper through the pipeline by the flowing fluid trailing spring-loaded rakes to scrape wax off the internal walls.[19] The present most common method which involves the use of magnetic flux for pipeline leakage is done by magnetizing the pipe wall to read the metal loss through sensors. However, this method requires magnetic saturation of the pipe wall thus, making it difficult to inspect small diameter or thick wall pipelines hence, a need for improvement. To solve this problem, Gloria et al[17] developed an internal corrosion sensor based on a direct magnetic response from a small wall area. Extensive studies along this field should be encouraged with improvements on the shortcomings while the detected damaged areas should be immediately replaced.

For political, financial and other reasons, many countries do not allow free access to information on the rate at which hydrocarbon pipeline inspection is carried out. This action is always detrimental because in many instances, the resulting problems would have been detected and avoided through research and development long time before their escalation. Evaluating the quantity and composition of material that is removed from the line by the scraper may be useful in evaluating whether or not significant internal corrosion has been occurring in the line. Subsequently, this information may assist to predict when the line should be replaced.

Failure to properly dehydrate the gas in the gathering system prior to its transportation through the distribution system will lead to internal corrosion.[81,90] This is so as the gas temperature will drop below its water dew point at a distance along the pipe and the liquid water will condense within the line. The condensed water that is produced will then tend to accumulate in the low points along the line to initiate crevice or pitting corrosion, hence the need to properly dehydrate the gas before its transportation. This can be achieved by passing the gas through a properly designed absorber packed with triethylene glycol (TEG) before the transportation. Some vital factors to be considered at the design stage as recommended by Bahadori and Vuthaluru[6] include correct estimation of the column size, properly determined TEG concentration and its circulatory rate within the column, its purity level and the required number of trays. For maximally effective operation, the dehydration can be selectively carried out by passing the gas through a series of the absorber. Other available dehydration methods include the use of liquid desiccants, solid desiccants, calcium chloride, refrigerant, membrane permeation and supersonic dehydration. However, for any method to be applicable, proper considerations must be given to the gas pressure, temperature and composition.[29] The overall advantages include high heating value, low risk of hydrate deposition and high gas velocity during transportation.

The alloy type, material strength and toughness play great roles in pipeline properties during equipment selection.[52] The American Society for Testing and Material (ASTM) standards should be consulted and the higher alloyed metal such as ASTM G48 should be used to convey the fluid to prevent pitting and crevice corrosion.[40] Care must also be taken as austenitinic stainless steel can also be attacked by stress corrosion cracking when exposed to fluid containing chloride at the temperature above 60 °C. Materials with known resistance to the pipe's immediate environment should be properly selected while the chloride concentration, operating temperature and the fluid pH should be maximally controlled.[94,93]

Large diameter pipelines transporting natural gas require high strength, low alloy steels with substantial quantities of molybdenum. Ravi et al[69] discovered in a study that steels with molybdenum as an alloy are more resistant to sulphide stress corrosion (SSC), hydrogen induced blister cracking (HIBC) and hydrogen embrittlement (HE) as well as having the minimum corrosion rate from sour gas compared to those steels with nickel, copper and chromium as alloys. For pipe toughness which is also a required material property, studies should be carried out mixing various alloys/metals with

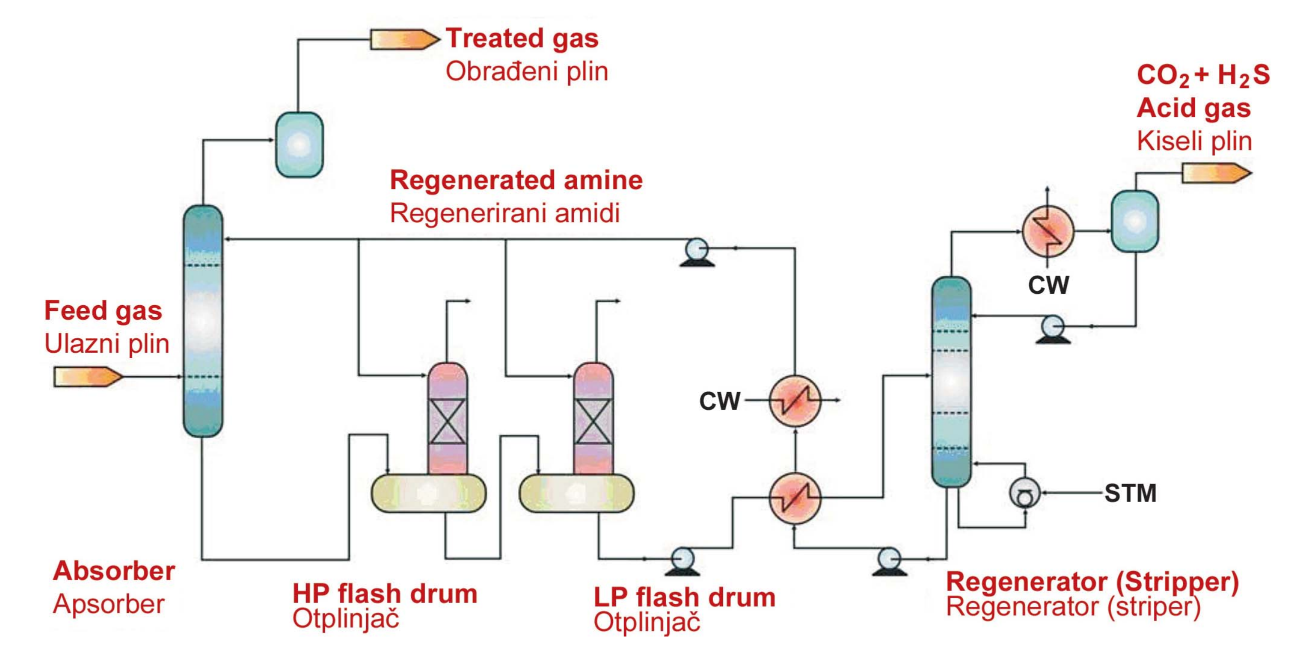


Fig. 11. A typical gas sweetening process plant for acid gas removal from raw natural gas stream.
Sl. 11. Tipično procesno postrojenje za čišćenje zemnog plina od kiselih komponenata

the molybdenum at different concentrations to get the best and most cost effective ratio.

Again, the system's pH should be closely monitored and any unfavourable pH value should quickly be controlled. Studies should be carried out to know the effective transport pH comfortable for each available type of piping material. Reducing the concentration of the acid gases such as chloride, sulfides and carbon-dioxide in the gas transmission stream by gas sweetening processes (Figure 11) will effectively reduce the internal corrosion of the pipeline. Pitting and crevice corrosion can be prevented in offshore fields by keeping the chloride level below 150 ppm and maintaining the operating temperature of less than 10 °C. Since ambient temperature at onshore is definitely more than 10 °C, full-scaled studies should be carried out on such prevention and in both cases, stagnancy of fluid should be prevented.

Though, acids promote corrosion generally, however, chromic acid and its salts inhibit it by producing a polarizing or damping effect which prevents the solution of metal and the separation of hydrogen.[72] So, studies should be conducted on the possibility of introducing chromic salts into pipeline alloy, this may assist in improving on the material's shelf-life.

Furthermore, all the existing pipeline design models are faulty as none up to date considers corrosion factor. Since all the factors influencing corrosion are present during the gas transportation to interact, corrosion rate is more rapid and complex to predict. Very robust corrosion predictive models should be developed to consider all the factors and their activities during the transport both in the presence and absence of inhibitors. Furthermore, means should be considered to lump such model(s) into the existing pipeline design models and this must be considered during initial pipeline design stage. To assist in this, the existing corrosion models could be improved upon to factor in the missing information such as the effect of the inhibitors.

NS (2005) developed equation[53] (8) as a basic corrosion model to predict the annual corrosion rate of a gas pipeline using CO_2 as the corrosion agent. Obanijesu[55] applied the same model to predict the corrosion rate of a gas pipeline with H_2S as the corroding agent and its thermodynamic properties as the main focus.

$$C_{rt} = K_t \cdot f_i \cdot \frac{S^{0.146+0.0324 \log f_i}}{19} \cdot f(pH)t, \ \frac{mm}{yr} \qquad (8)$$

Though, the two solutions from the works were able to give fair predictions, they however correctly varied some physical data, (e.g. temperature and pressure) while some parameters were taken to be constant over a few kilometres to reduce the iteration of measurement, some of which could be costly. Also, the results presented were calculated without full consideration given to corrosion inhibitors (like the introduction of glycol). Models should be developed using these models as basis. Where gases such as CO_2, H_2S, O_3, and other organic and inorganic gases are present in the same stream, these two models could be modified to accommodate the contributions of each agent to corrosion rate of the pipeline. Where inhibitors are present (which is common in pipeline systems) their effects must be evaluated separately.

All existing corrosion studies have clearly shown that allowing H_2S to pass through a gas pipeline is 'poisonous' to the transport equipment, and the higher the quantity allowed to pass through the equipment, the higher the corrosion rate. It is therefore recommended that H_2S should be maximally removed from the raw sour natural gas before transporting it through a pipeline network.

This could be done by installing effective treatment plant between the producing field and the transportation facility.

All employees exposed to work in an H_2S environment should go through essential training and employ all required tools, equipment and protective systems to ensure safety since most accidents happen due to failure to adhere to these procedures. Immediate response and instant arrival of Accident Response Planning Unit (ARPU) personnel to such point of accident should be considered. For this to work perfectly, all personnel must be well trained and equipped with necessary materials. Inventory of the available materials should be regularly taken (probably quarterly) for immediate replacement. Since offshore problem is being considered, the ARPU must also be equipped with helicopters in case of multiple accidents at a time. To ensure effectiveness, various types of insurance schemes should be considered for each of the ARPU personnel.

To minimize gas pipeline internal corrosion as a result of microbial activities, on-line systems should be developed to monitor bacteria activities in the pipeline.[77,22,89] Also, water soluble inhibitors should be developed to minimize the microbial influenced corrosion on pipelines.[46] However, the use of de-ionized water should be considered.

It has been established that cavitations and erosion corrosions result from the wearing off of a protective scale or coating on the metal surface due to the collision of the particles with the pipe's wall leading to the significantly lowered velocity, thus, causing abrasive wear and that thermal treatment has no effect on erosive wear. The use of harder materials of construction and change in velocity can be employed to prevent or minimize these corrosion types. Selection of alloys with greater corrosion resistance and/or higher strength is also essential. Erosion corrosion can also be controlled by the use of harder alloys with flame-sprayed (or welded) hard facings. Flamed-sprayed technique is a thermal spraying coating process in which a material is sprayed on another material's surface by electrical (plasma or arc) or chemical means (combustion flame) based on the operating temperature and the material type.[38] Coating material (surface deposit) is fed in powder or wire form, heated to a molten or semi-molten state and accelerated towards substrates in the form of micrometer-size particles and the resulting coatings made by the accumulation of numerous sprayed particles.[34,8,37] The coating quality, which increases with the particle velocities, is determined by its porosity, oxide content, macro and micro-hardness, bond strength and surface roughness.

Finally, alterations in fluid velocity and changes in flow patterns can also reduce the effects of erosion corrosion on the gas pipeline. This can be done by re-designing the system to reduce the flow velocity, turbulence, cavitation or impingement of the environment.

7. CONCLUSION

The fate of natural gas is between its being resourceful energy and disaster related to its exploration and production. However, since both considerably affect man and environment, there is dire a need to maximize the advantage therein and minimize the associated failures.

This review study has effectively considered the corrosion mechanisms along the gas pipeline and established that failures along the pipe-length often lead to gross loss of lives, properties and even, economic loss with unimaginable environmental consequences. The study has further showed that the causes of these failures are better prevented than corrected. Finally, the study shows that the best possible means of achieving these is the full commitment of the pipeline operators to investing in research and development to develop various relevant scientific models and management schemes.

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