



Review Article

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Global Impact of Corrosion: Occurrence, Cost and Mitigation

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Abstract

In atmospheric conditions, most of the metals and alloys are unstable and prone to corrosion. The corrosion potentially affects industrial equipment, reduce the shelf life of the infrastructure assets and the quality of the environment. Therefore, it is essential to control the corrosion to save considerable expenses in materials, equipment, and structure. This review article provides a brief overview and impact of corrosion, recent incidence related to corrosion, incurred cost, and mitigation methods of corrosion.

Keywords: Corrosion; Effect of corrosion; Corrosion-related incidence; Corrosion cost; Mitigation

Concepts of Corrosion

According to ISO 8044 standard, corrosion can be defined as the deterioration of the metals by the physicochemical interaction between metals and its environment or technical system, of which these form a part [1]. From a realistic point of view, corrosion can be observed as “the chemical reversion of refined metal to its most stable energy state” [2]. Theoretically, corrosion is considered a confined electrochemical oxidation and reduction reaction that takes place on the metal surface. The electrochemical corrosion process consists of an anode, cathode, and aqueous solution, or electrolyte having positively and negatively charged ions that possess some conductivity. Typically, upon dissolution of metals, the electrons have been transferred to another position on the surface that results in gradual deterioration and consequent failure of the host metal.

Corrosions are of many kinds, but they can be subdivided into two main types, internal and external. External corrosion is

regarded as the corrosive effect of high temperature, high humidity, high salt, and highly acidic environments on the metallic part of the alloy [3]. On the contrary, internal corrosion is associated with stored or transported gases or liquids [4]. Continuous exposure of the metal to fluids can cause this type of corrosion either in anaerobic or aerobic conditions [5]. Water is believed to be the most common liquid that has contact with extremely corroded metallic planes. At the same time, oil, despite being not corrosive, contains hydrocarbon phases, most of which are complex emulsions containing oxygen, water, and other dissolved corrosive gases.

The petroleum production operations suffer from different types of corrosion involving several mechanisms. The four broad groups of electrochemical, chemical, biological, and mechanically assisted corrosions are presented in Table 1, and briefly discuss their cause and affected areas to shed some light on the effects of corrosion on oil and gas production in petrochemical industries (Table 1).

Table 1: Different corrosive environments.

Nature of Corrosion	Type of Corrosion	Cause of Corrosion	Affected Areas/Materials
Electrochemical corrosion	Galvanic corrosion	Difference in electrode potentials.	Metal with more negative potential.
	Crevice corrosion	Metal within narrow clearances being devoid of oxygen.	Crevices.
	Pitting corrosion	Chloride ions.	Passive metals.
	Stray current corrosion	Extraneous DC from electrified mining operations.	Underground pipelines.

Chemical corrosion	Oxygen corrosion	Depolarization and electron acceptance capability of O_2 .	Drill pipes.
	Sour corrosion	H_2S working as an acid in H_2O .	Deep wells.
	Sweet corrosion	CO_2 producing H_2CO_3 in H_2O .	Transmission pipelines, main down-hole tubing.
	Concentrated brines corrosion	Dense halide brines of Ca, Zn and Mg.	Stainless steels.
	Strong acids corrosion	HCl, HF, etc., pumped into the wells to increase permeability.	Deep wells.
Biological corrosion	Microbiologically Induced corrosion	Organic acids, CO_2 , H_2S produced by fungi and bacteria.	Underground pipelines.
Mechanically assisted corrosion	Cavitation	Gas bubbles' implosion on metal surfaces.	High-speed blade propellers and pumps.
	Erosion	Cutting action of high-velocity abrasive particles.	Drill pipes.
	Erosion corrosion	Removal of a protective film of corrosion products by erosion.	Propellers, impellers, pumps, valves.
	Corrosion fatigue	Alternating stresses in a corrosive environment.	Drill ships, drilling and production rigs, and platforms.
	Sulfide stress corrosion	Dispersion of molecular H_2 into the metals' matrices.	Valve trim, preventer hard parts and tool joints.
	Chloride stress cracking	Tensile stress in the presence of O_2 , Cl- and high temperature.	Stainless steels, pipe-wells, and tubing bundles.
	Stress corrosion cracking	Corrosive environment and non-cyclic tensile stress.	Bridge cables, landing gear on aircraft.

Effects of Corrosion

The effects of corrosion shade our daily life both by direct and indirect means. It is straightforward in the sense that corrosion has an impact on the useful service lives of our possessions, and indirect, in which producers and suppliers of goods and services incur corrosion costs, which they pass onto the consumers. At home, corrosion can easily be recognized on metal tools, automobile body panels, charcoal grills, and outdoor furniture. Painting is one of the significant preventative maintenances that safeguards such items from corrosion. Corrosion protection is built into all major household appliances such as furnaces, dryers, washers, ranges, and water heaters [6].

How corrosion affects us from home to work is of much more severe consequence. The corrosion of steel reinforcing bars in concrete can occur without being noticed. It can cause the failure of a section of highway, damage to buildings, bridges, parking structures, and the collapse of electrical towers, etc., resulting in significant economic loss and jeopardizing public safety. Corrosion that occurs in major industrial plants, such as chemical processing plants or electrical power plants, is perhaps the most dangerous of all. Such type of corrosion could result in plant shutdowns. Some corrosion consequences are economical and result in the following:

- Replacing the corroded equipment
- Taking preventive measures, such as painting
- Equipment shut down due to corrosion failure

- Overdesigning to allow for corrosion
- Efficiency loss
- Damage of equipment adjacent to one in which corrosion failure occurs.

Some consequences are social and can cause the following issues:

- Health, for instance, an escaping product from corroded equipment or corrosion product itself can cause pollution
- Safety, as an example, sudden failure can cause an explosion, fire, release of a toxic product, and/or construction collapse
- Unpleasant appearance of the corroded materials to the eye
- Depletion of natural resources, including the metals and fuels used to manufacture them.

Corrosion Related Accidents

The circumstances can much exaggerate corrosion damage. Throughout history, many corrosion accidents have gone unnoticed for reasons of liability or simply because the evidence disappeared in the catastrophic event; others have made the headlines. Some devastating corrosion accidents that have claimed lives and incurred substantial economic losses are included in Table 2.

Table 2: List of some renowned corrosion accidents.

Name of Accidents	Year	Place	Reason and Damage
Silver Bridge Collapse	1967	Ohio, USA	The U.S. highway 35 bridge in between Point Pleasant, West Virginia and Kanauga, Ohio, fall down into the Ohio river. Stress corrosion cracking and corrosion fatigue was responsible for this collapse. This accident claimed 46 lives.
Bhopal Accident	1984	Bhopal, India	Methylisocyanate (MIC) storage tank leaked due to corroded pipelines, valves, and other safety equipment at Union Carbide India Ltd caused the release of MIC and other chemicals into the surrounding area. This incidence claims 3000 people killed, and 500,000 people were injured.
Swimming Pool Roof Collapse	1985	Uster, Switzerland	After 13 years of use, the concrete roof supported by stainless steel collapsed due to stress corrosion cracking. This claim 12 people killed.
The Aloha Incident	1988	Island of Maui, Hawaii	A 19-year-old Boeing 737 lost a significant portion of the upper fuselage in operating flight due to multiple corrosion fatigue damage. 1-flight attendant lost her life.
Guadalajara Sewer Explosion	1992	Guadalajara, Mexico	This sewer explosion caused by galvanic corrosion of a galvanized steel pipeline blocking with a steel gasoline pipeline. This explosion killed 215 people, injured 1500 people, and damaged 1600 buildings.
EL AL Boeing 747 Crash	1992	Amsterdam, The Netherlands	The crash occurred due to the two right engines separated from the wing because of the fuse pins that hold the strut to the wings were debilitated by corrosion pits and fatigues. This crash killed all 4-people on board and more than 50 people on the ground.
Sinking of the Erika	1999	Brittany, France	The tanker broke in two while carrying »30000 tons of heavy fuel oil due to corrosion in the main deck coaming, the portside and starboard inert gas system risers. »19800 tons spilled and cause severe economic consequences on the region.
Carlsbad Pipeline Explosion	2000	New Mexico, USA	El Paso Natural Gas exploded due to severe internal corrosion in a 30-inch natural gas pipeline. This incidence killed 12 people and a 3-vehicle destroyed.
Prudhoe Bay Oil Spill	2006	Prudhoe Bay, Alaska	This massive oil spillage due to the failure of BP's field pipeline corrosion monitoring and leak detection systems. »267,000 gallons of crude oil leaked from a corroded transit pipeline.
Rupture of a High-Pressure Vessel	2009	Illinois, USA	Stress Corrosion Cracking of the walls of a pressure vessel causes Nihon Dempa Kogyo (NDK) Company explosion. This explosion killed 1-person and wounded several others.
Rupture of a Natural Gas Transmission Pipeline	2016	Pennsylvania, USA	A 30-inch diameter natural gas transmission pipeline ruptured due to corrosion along with two of the circumferential welds. This incidence results 1-home destroyed, 3-homes partially damages, and several homes evacuated.
Ohio State Fair accident	2017	Ohio, USA	A pendulum-type thrill ride failed during operation due to the rust (thickness of the ride beam's wall reduced). The malfunction left 1-person dead and several others injured.

Cost of Corrosion

Corrosion is considered as one of the significant problems for most of the industrialized countries. Before designing any industry, the effect of corrosion on the equipment and its surrounding always deserve to be a considerable issue. The oil companies all over the world to mitigate this corrosion problem have expensed a lot of money. Nevertheless, disasters such as casualties, economic losses, and environmental side effects triggered by corrosion, still happen quite often [7]. Corrosion can cause severe failures in boiler tanks, pressure basins, blades of motors/turbines, harmful/aggressive chemical containers, airplane parts, automotive routing devices, and bridges.

Furthermore, the losses caused by corrosion are not only limited

to metals but also extend to water, energy, and the manufacturing phase of the metal frames [8]. Jayaherdashti reported the typical maintenance cost of corrosion-related issues for a particular country varies from 1-5% of its gross national product (GNP) [9]. NACE international conducted a global study on corrosion costs and preventative strategies in 2013, which was utilized in the World Bank economic sector and global Gross Domestic Product (GDP) data to relate the cost of corrosion. This study showed that the estimated global cost of corrosion was approximately 3.4% of the GDP (Figure 1a) [10]. To address the economic sectors across the world, World Bank divided the global economy into economic regions with similar economy categories and presented in Table 3 (Figures 1a & 1b).

Table 3: Global cost (Billion US\$)^a of corrosion by sectors and regions.

Economic Regions	Sector					
	Agriculture	Industry	Services	Total	Total GDP	% GDP
United States	2	303.2	146	451.3	16,270	2.7
India	17.7	20.3	32.3	70.3	1,670	4.2
European Region	3.5	401	297	701.5	18,331	3.8
Arab World	13.3	34.2	92.6	140.1	2,789	5
China	56.2	192.5	146.2	394.9	9,330	4.2

Russia	5.4	37.2	41.9	84.5	2,113	4
Japan	0.6	45.9	5.1	51.6	5,002	1
Four Asian Tigers Plus Macau	1.5	29.9	27.3	58.6	2,302	2.5
Rest of the World	52.4	382.5	117.6	552.5	16,057	3.4
Global	152.7	1446.7	906	2505.4	74,314	3.4

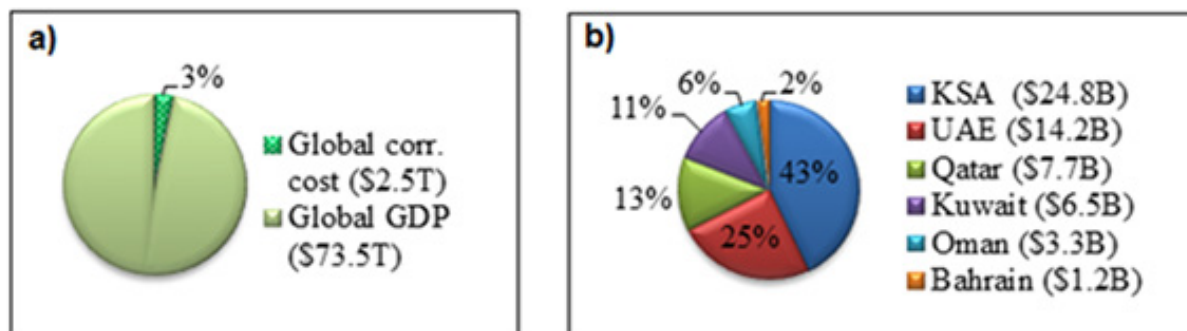


Figure 1: a) Global cost of corrosion (2013), b) Cost of corrosion in GCC countries (2011).

Lim investigated the corrosion-related cost for the Gulf Co-operational Council (GCC) and presented in Figure 1b [11]. This study suggested that the Kingdom of Saudi Arabia (KSA) spent the highest to tackle the corrosion. Besides, the UK spent £13.65 B to handle the corrosion-related issue in 1969 [12]. A 2-year study conducted by the USFHWA and NACE in 2002 disclosed that the estimated annual cost of corrosion in the country was US\$ 276 B, which was 3.1% of the US GDP. Nearly half of the amount was allotted for establishing corrosion mitigation methods, such as the selection of mechanically resistant plastics and corrosion-resistant alloys, development of protective coatings, corrosion inhibitors, and cathodic protectors [3]. Gas and oil production is one of the leading energy sectors, contributes a considerable portion of the direct costs for corrosion [13]. The total cost of oil and gas production and exploration is approximately US\$ 1.4 B, while chemical/petrochemical manufacturing contributes US\$ 1.7 B, and petroleum refining adds US\$ 3.7 B [14].

Mitigation of Corrosion

Corrosion mitigation in a corrosive environment is a considerable challenge, and one of the most significant costs faced by industry across the world. NACE international commences a global study on corrosion costs and preventative strategies. The study showed that the USA E&P sector, chemicals, and refining and downstream spent US\$1.4 B, US\$1.7 B, and US\$3.7 B per annum, respectively. Therefore, it is in time demand for exploring smart and corrosion mitigation techniques.

To increase the shelf life of the equipment and/or plant/industry is still very challenging for industry personnel. There are several methods have been proposed for controlling corrosion. They can be categories with the classes as

- Choosing proper construction material for a particular application.
- Choosing proper or modifications of corrosive media.
- Producing a barrier between the metal and medium to circumvent the direct interaction.

To control the corrosion and to choose suitable corrosion mitigation techniques, the corrosion mechanism should be clearly understood. As a whole, the corrosion attack in a plant/industry can be minimized by applying the internal and external mitigation methods. The internal corrosion mechanism can be observed in aqueous corrosion systems, which caused by soluble corrosive gas, such as CO_2 , H_2S , and O_2 . In addition to these mechanisms, microorganisms can also influence corrosion. To mitigate this type of corrosion, scavenging and biocide treatment can be used. Importantly, the use of corrosion inhibitor (10-1000 ppm continuously or 1-20% in a batch) could be the most essential and standard form to mitigate internal corrosion. The inhibitors usually affect the anodic and/or cathodic electrochemical reactions. They influence the corrosion process, therefore reduce the corrosion rate. Scavenger can be used to mitigate internal corrosion if the inhibitor could not reduce the corrosion rate. Considering the importance of a specific corrosive environment where corrosion failure can be caused by oxygen corrosion from seawater pipelines and fatigue failure from design and stress exerted onto the line or inexplicable mechanism, the external mitigation technique can be applied. In these settings, the coatings and cathodic protection are the best choices of external mitigation technique. The corrosive environment, which causes corrosion, can be segregated, providing a layer on the surface of the pipe. For cathodic protection, the metal needs to be converted to cathodic for another metal or anode.

However, when considering the design of a cathodic protection system, the detailed methodological information and suitable standards are required to be considered.

Conclusion

This review article briefly discusses the basic concept of corrosion, followed by a discussion on the impact of corrosion, consequences, and cost of the corrosion. Moreover, different corrosion mitigation methods have also discussed briefly with an understanding of the corrosion mechanism, which is very important before considering various material options for applications.

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Conflict of Interest

The author declares no conflict of interest.

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