Effects of Environmental and Metallurgical Factors on Corrosion of Steel- A Review

T.N. Guma [1], S.Y. Aku [2], D.S. Yawas [3], and M. Dauda [4]
[1] Department of Mechanical Engineering,
Nigerian Defence Academy, Kaduna, Kaduna State, Nigeria
[2, 3, 4] Department of Mechanical Engineering,
Ahmadu Bello University, Zaria, Kaduna State, Nigeria

Abstract-Steel by far the most important engineering alloy but the problem with it is that, it rust-corrodes into serious consequences and lots of money far more than any other material is spent in protecting it from corrosion. Corrosion of steel accounts to 90% of all corrosion problems worldwide. The extent of its corrosion depends upon a number of factors; the most important of which are its composition, surface condition and the corrosivity level of the environment it is exposed to. A fundamental approach to any methodical corrosion control or study requires consideration of these factors for optimal results. Steel-corrosive environments vary widely and include the atmosphere, aqueous solutions, soils, acids, bases, inorganic solvents, liquid metals, and last but not the least the human body. A survey of factors that influence corrosion of steel in the atmosphere, water and soil as principal environments where the alloy finds applications has been undertaken and information obtained from various sources is presented this paper. Elucidated facts from the paper show that the amounts or levels of environmental impurities, aeration, moisture contents, microbiological activities, electrical conductivity and acidity; and metallurgical composition, surface condition, surface exposure and fabrication processes are the salient influential factors in corrosion of steel. The aim of the paper is to posit the information as a compendium for better insight and consideration by the researcher, protection practitioner, student and professional; for more positive efforts in combating corrosion for technological and economic advancement.

Keywords-Moisture, air, atmosphere, water, soil, corrosivity level, steel type, chemical composition, surface nature, exposure, pollutants, variations.

I.   INTRODUCTION.

The most important material to meet strength requirements such as structural works is steel due to its optimal strength to weight ratio, good cost to weight ratio, availability, ability to be readily supplied at relatively cheap price in a range of different product forms with a useful range of material properties, formability and fabrication properties, possibility of enhancing desired mechanical properties by heat treatment, worldwide existence of abundant quantities of iron ore within the earth crust from which steel originates and possibility to produce the alloy from the ore using relatively economical extraction, refining, alloying and fabrication techniques compared to any other material. Steel can be supplied with strength level from about $250N/mm^2$ up to $2000N/mm^2$ for common structural applications. The material is normally ductile with good fracture toughness for most practical applications. Its product forms range from thin sheet material, through optimized structural sections and plates, to heavy forgings and castings of intricate shapes. In 2013, the total world's crude steel production was 1.6072 billion tonnes (Metals and Minerals Review, 1998; Burdekin, 2001; Callister, 2004 and INTERNET, 2014).

Steel is basically iron alloyed with small amounts of carbon from 0.02 to 2% by weight and other elements to provide particular mechanical and physical properties and enhance corrosion resistance. Corrosion resistance of steel increases with the levels of its carbon and, or alloy contents. Steel is divided principally into stainless, high carbon, medium carbon and low carbon types. Of all the types, stainless steel which contains at least 10% chromium often with combinations of nickel is the most resistant type to corrosion because of its high alloy contents but is the most costly and least available and also has least fabrication and formability properties; so, it is used in fewer and mostly special applications. High carbon steel contains from 0.7 up to 2% carbon, medium carbon type contain between 0.3 and 0.7% and low carbon type contain up to 0.3% carbon. The low carbon steel has fair strength with high ductility and excellent fabrication properties such as machinability, rollability, weldability, forgeability, drawability and bendability but is the least resistant to corrosion. It is the structural steel used in very large quantity in amounts of up to 90% of all steels for bridges, buildings including industrial structures, ships, road vehicles, boilers and pipelines. Because of the critical role played by steel in infrastructural and overall economic development, the steel industry is often considered to be an indication of economic prowess of any country. Small wonder, then that steel is by far the most important engineering alloy, and low carbon steel is the most versatile and used on the tonnage basis of all types. Although corrosion of steel can occur in different forms, the most important fault of steel including all other ferrous materials is that it rust-corrodes and often considerable amounts of money is spent

---

in protecting it from atmospheric and other environmental corrosion (Higgins, 1993; Rajan et al 1997; Callister, 2004 and Dr. Eng. MI Masoud, 2014). According to Cotterel (1985), the most important corrosion problem worldwide is the rusting of structural steelworks. Rusting is a uniform or nearly uniform form of corrosion and occurs only in the presence of both oxygen and water. The most important environments where steel is kept disposed off, kept and applied are atmospheric, water and soil environments. The aim of this paper is to revisit and present the salient factors in metallurgical structure, fabrication properties and basic environments that affect steel corrosion for better insight, reawakening of positive research interest and application considerations for overall economic and technological developments.

II.   METHODOLOGY

Information presented in this paper was obtained from various literature sources, discussions with professional colleagues and other competent workers in the field and refined with several years of teamwork experiences as engineering professionals, academics, researchers and fieldworkers.

III.   RESULTS AND DISCUSSIONS

A   Atmospheric Environment

Atmospheric environment in this context is a region of natural free air accessibility around the earth. Steel and other metals are more frequently exposed to the atmosphere than to any other corrosive environment. On a tonnage basis, atmospheric corrosion accounts for the greatest losses. This type of corrosion is also the oldest corrosion problem known to mankind. The principal reason for this lies in the complexity of the variables, which determine the kinetics of the corrosion reactions. Thus corrosion rates vary from place to place, from hour to hour and from season to season. The approximate nominal composition of the atmosphere at a temperature of $38°C$ and pressure of $100KN/m^2$ as given by Meetham (1956) is shown in Table 1.

Table 1: Approximate Constitution of the Atmosphere at 10^oC and $100KN/m^2$ excluding Impurities (Meetham, 1956)

Constituent	Weight [g/m^3]	Weight [%]
Air	1172	100
Nitrogen	879	75
Argon	15	1.26
Water Vapour	8	0.70
Carbon Dioxide	0.5	0.04

The composition is global and for components is reasonably constant for all locations, but water vapour content vary according to the climatic region, season of the year, time of day, etc. Rusting of bare steel is controlled by the climatic condition at the exposure site. The main factors are the availability of moisture, and the extent to which the air is polluted, but other less important ones, such as temperature, exposure conditions, and mass of steel (Uhlig, 1971 and Shreir, 1979)

Moisture: For a given atmospheric condition, corrosion will be more severe the more humid and oxygenated it is. This is why exposed and unprotected steel structures are quite durable in arid regions but rapidly attacked in humid climates. The quantity of moisture required for rusting to occur need not be great. The corrosion reactions will proceed, albeit slowly on a steel surface in such minute quantity as to be invisible. The moisture can reach the exposed steel surface, directly in liquid form as a result of precipitation processes that is rain and dew (Johnson, 1965). The vapour that is always present in air can also, under certain conditions cause steel to rust at relative humidity well below saturation. This important fact was demonstrated by Vernon (1935) in a series of classical experiments. He showed that rusting is minimal in pure air of less than 100% relative humidity but that in the presence of minute concentrations of impurities, such as sulphur dioxide, serious rusting can occur without visible precipitation of moisture once the relative humidity of the air rises above a critical and comparatively low value. This value depends to some extent upon the nature of the atmospheric pollution, but when sulphur dioxide is present, it is in the range of about 70-80%. Below the critical humidity rusting is inappreciable even in polluted air. The presence of moisture on steel above the critical humidity but below the saturation point may be caused by an adsorption mechanism or by the presence of particles of deliquescent salts on the surface of the metal. Once rusting has begun, the composition of the rust already formed will influence the relative, humidity at which further rusting will occur, because rusts formed in polluted atmospheres contain hygroscopic salts (Shreir, 1979).

Although humidity plays a vital part, the impurities in the air are decisive in determining the rate of rusting in atmospheres of the requisite humidity; in their absence rusting is not serious even in highly humid air. Typical concentrations of atmospheric impurities

_____

of 350µg/m^3 during winter and 100µg/m^3 during summer in industrial regions; 100µg/m^3 during winter and 4µg/m^3 during summer in rural regions; suphur trioxide of about one percent of sulphur dioxide content; hydrogen sulphide of about 1.5 to 90µg/m^3 as measured in spring in industrial regions and 0.15 to 0.45µg/m^3 in rural regions; ammonia of 4.8µg/m^3 in industrial region and 2.1µg/m^3 in rural areas; chlorides of 8.2µg/m^3 in winter regions and 2 to 7µg/m^3 in summer as well as air sampled rural coastal annual average of 5.4µg/m^3 has been reported by Shreir (1979). Although the most important impurity in industrial atmosphere is sulphur dioxide, chlorides and ammonium salts also may have an effect. Generally, near the coast chlorides have the most pronounced effects. In the presence of chlorides, rusting can continue at relative humidity as low as 40%. As a rule, steel rusts at almost incredible rates on surf beaches in the tropics where it is exposed to a continuous spray of sea salts on the surf. This is apparent from the results of some tests made with ingot iron exposed for one year in Lagos, Nigeria on behalf of the British Iron and Steel Research Association (BISRA) by the former Tropical Testing Establishment, Ministry of Supply Britain, and given in Table 2.

Table 2: Effects of Sea Salt on the Rate of Rusting (BISRA, In:Shreir, 1979)

Distance from the Surf (Yards)	Salt content of Air (%)	Rate of Rusting (mm/year)
50	11.1	0.95
200	3.1	3.80
400	0.8	0.055
1300	0.2	0.040
25 miles	-	0.048

In most districts, sulphur dioxide and dust particles are the main corrosive pollutants. Chandler and Kilcullen (1968) have demonstrated that there is direct relationship between sulphur dioxide in the atmosphere and the corrosion of steel exposed to it as shown in Figure 1.
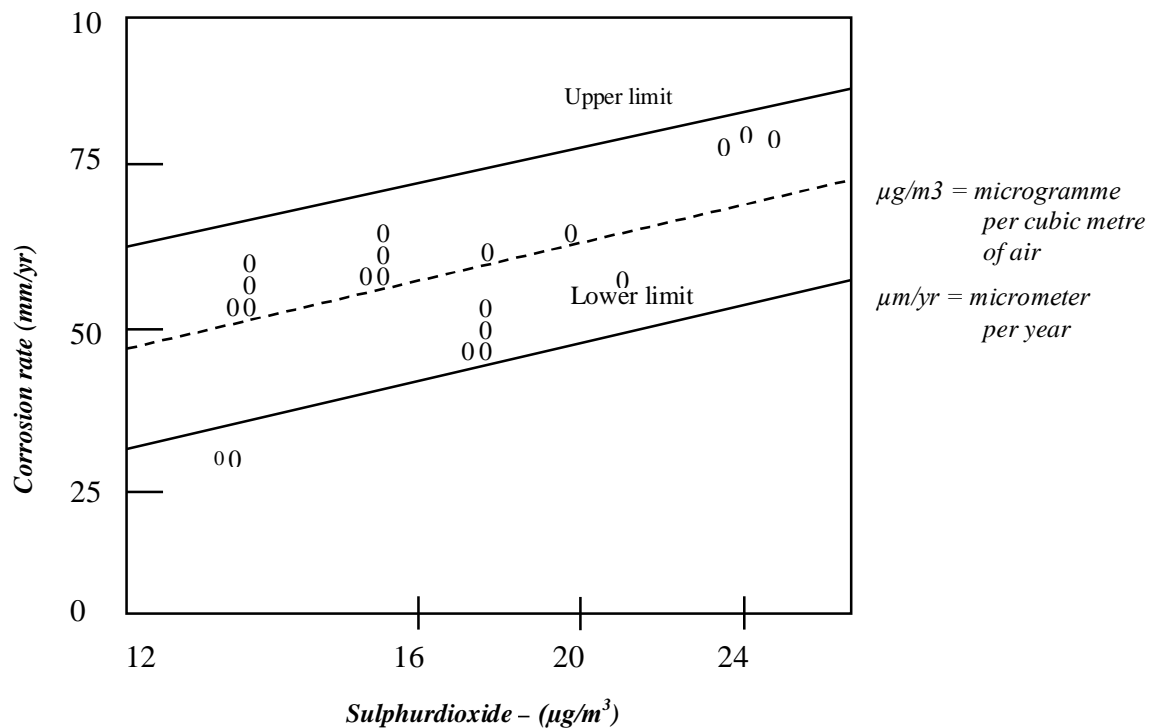

Fig. 1: *Relationship Between Sulphur Dioxide and Corrosion of Steel (Chandler and Kilcullen, 1968)*

Sulphur dioxide in the air originates from the combustion of fuel and influences rusting in a number of ways. For example, Russian workers consider that it acts as a cathodic depolarizer, which is far more effective than dissolved oxygen in stimulating the corrosion rate. However, it is the series of anodic reactions culminating in the formation of ferrous sulphate that are generally considered to be of particular importance. Sulphur dioxide in the air is oxidized to sulphur trioxide, which reacts with moisture to form sulphuric acid, and this in turn reacts with the steel to form ferrous sulphate. Examinations of rust films formed in industrial atmospheres have shown that 5% or more of the rust is present in the form of iron sulphates and hydrated ferrous sulphate has been identified in shallow pits. Workers who have studied atmospheric corrosion processes are generally agreed that the loss of iron as a sulpahte accounts in only a small measure for the effects of suphur dioxide (Shreir, 1979). There is no complete agreement on the detailed mechanism but once ferrous sulphate has been formed it is able to promote further rusting. This has been demonstrated by Schikorr (1963) by allowing steel to rust in an atmosphere containing sulphur dioxide and then transferring it to a clean atmosphere where the corrosion continued at enhanced rate, at least for a time. There is cyclic variation in the amount of sulphate found in rust formed on steel exposed at different times of the year, and the amount depends on the month of the year rather than on the period of exposure, at least for periods up to two years as demonstrated by Chandler and Stanners (1963) at Battersea atmospheric environment. The variation is shown in figure 2. Consequently, the month of exposure can have an important influence on the corrosion rate up to a year or so as shown in Table 3.

Table 3: Effect of Month of Exposure on the Corrosion Rate of Steel (Shreir, 1979)

Month Test Begun	Rate of Rusting [mm/year]
January	0.081
March	0.064
May	0.076
July	0.070
September	0.94
November	0.89

In one test, specimen exposed for two months from September corroded at 0.035 mm/year compared to 0.0136mm/year for specimen exposed from May, and the amount of rust formed on steel follows this cyclic pattern over periods of up to two years and possibly for longer periods (Shreir, 1979).
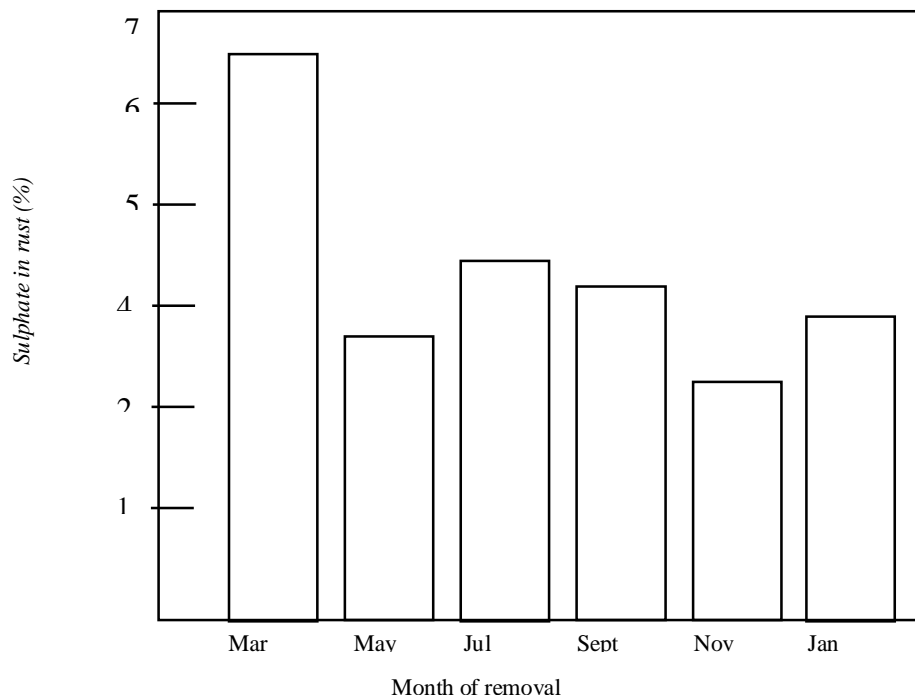

Fig. 2: Sulphate in Adherent Rust on Steel Exposed at Battersea in January (Chandler and Stanners, 1963)

The effects of ammonium contamination have been studied and some workers consider that it has a significant influence on the corrosion of steel (Shreir, 1979). Dust particles also play an important role. They act as nuclei for the initial corrosion attack and as some particles are hygroscopic, their presence tends to increase the periods of wetness of the steel surface (Shreir, 1979).

Temperature: Although ambient temperature would be expected to have an influence on the rate of rusting, its effect is not clearly defined despite the efforts of workers to establish a relationship. However, it has an effect on relative humidity and consequently an indirect effect on corrosion. However, fluctuations in temperature may be more important than average temperatures because they influence condensation and the rate of drying of moisture (Shreir, 1979). Higgins and Morrow (1977) have found that within the limits of atmospheric temperatures, every 10°C rise in temperature increase the rate of rusting.

Effect of exposure conditions: The absolute values for the rate of rusting would be affected by the mass of the specimen itself and by other factors such as the orientation of steel, climatic conditions prevailing at the time of exposure, and the duration of exposure. The Orientation of the steel influences the rate of rusting through its effects on the amounts of moisture and pollutants that can reach its surface. For a given exposure, corrosion will be more severe the more humid the prevailing atmosphere. Corrosion on the skyward or the sunny side of a steel surface that is the side which is not shaded is less severe than on its ground-facing or shaded side. This is because the moisture on the sunny surface is more rapidly evaporated due to the drying action of the sun and often of wind; while the other side is shielded from the drying action, so that moisture tends to remain in contact with the steel side for longer periods (Johnson, 1965; Shreir, 1979). Moreover, harmful solid particles and soluble salts are not leached away on the latter side. In agreement with this consideration, the results of tests at Derby in Britain by Dearden (1948) have shown that steel specimens exposed at 45° to the horizontal corroded 10-20% more than corresponding vertical steel specimens, and 54% of the total loss was on the underside. In American tests on specimen exposed at 30°C to the horizontal, 62% of the loss was on the underside.

The rate of rusting of steel in the atmosphere is affected to some extent by the mass of the part concerned, because this determines the speed at which the surface temperatures adjusts itself to fluctuation in ambient temperature, the amount of condensation during humid periods, and the time during which dew or rain remains in contact with steel (Shreir, 1979). In a test over twelve months at the National Chemical Laboratory in Britain under sheltered conditions, thick steel plates rusted more than thin ones as shown in Table 4 (Shreir, 1979).

Table 4: Effect of plate thickness on corrosion of steel (Shreir, 1979)

Plate thickness (mm)	55	28	12.5	5
Average general penetration (mm)	0.038	0.033	0.031	0,030

Effect of surface conditions: Millscale on steel may decrease the corrosion rate over short periods. However, over longer periods the surface condition is not usually a determining factor as can be seen from Table 5 which shows the results of five-year tests at Sheffield England by BISRA (Shreir, 1979).

Table 5: Effect of the Surface Condition at the Time of Exposure on the Atmospheric Corrosion of Mild   Steel Conducted by BISREA (Shreir, 1979)

Surface Condition	Average Penetration [mm]
As-rolled	0.545
Picked	0.545
Sandblasted	0.532
Machined	0.534
Polished	0.532

It is important to know whether the rate of rusting of steel outdoors increases, remains constant or decreases with increasing 'duration of exposure. The position over a long period is adequately illustrated by the curves drawn in Figure 2.3 showing the results of tests carried out for 15 years in a rural environment at Llandwrtyd Wells, and in an industrial atmosphere at Sheffield, all in the United Kingdom (Shreir, 1979). At both sites the rate of rusting fell considerably after the first year or two, but then remained fairly constant for the rest of the test period. In actual figures the average rate of rusting over the first two years was 0.058mm/year for Llandwrtyd Wells and 0.118 mm/year for Sheffield; the corresponding rates in the same units over the last 10 years were 0.015 and 0.025 respectively (Shreir, 1979).
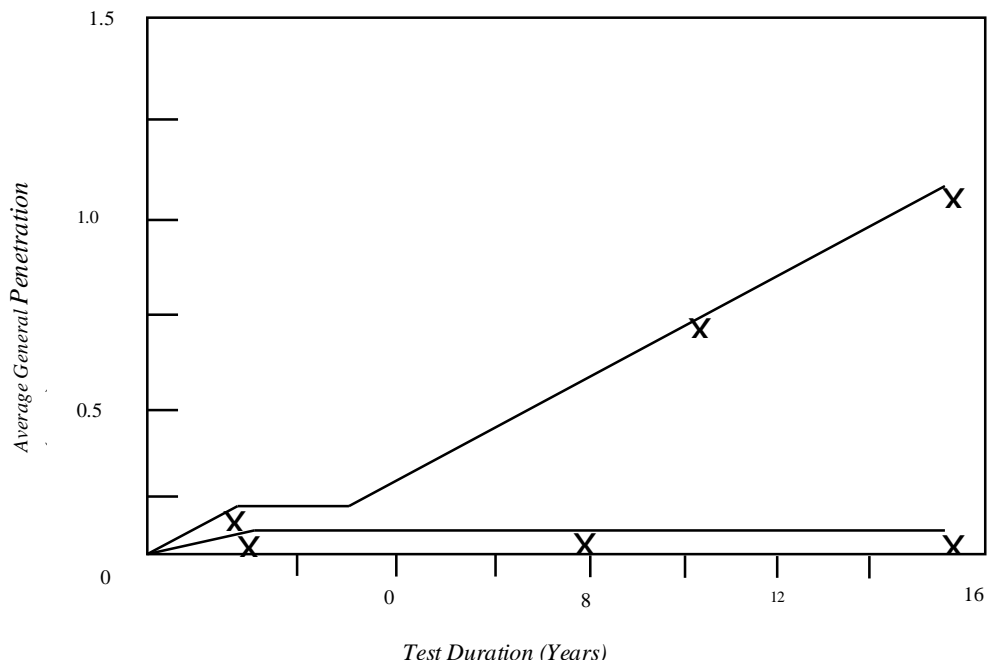
_____

Fig. .3: *Rusting of Mild Steel (0.02% Cu) in the Open Air at Sheffield and Llanwrtyd Wells*
Sixth Report of the Corrosion Committee

Types of atmospheric environment and their corrosiveness to steel: From the foregoing discussions, it can be appreciated that different places, sites, or points around the globe have different atmospheric characteristics at different times or periods, which affect corrosion of steel, due mainly to variations in climatic conditions and levels of pollution of those places or sites. An exact detailed classification of the atmospheric environment for corrosion behaviour of steel, for all times and for every location around the globe would be complex or impossible due to the complexity and variability of all the controlling factors with time and location. Exact atmospheric conditions at a location may involve reliable instantaneous or automatic technological monitoring and analysis of the level of chemical pollution and climatic conditions of the location. However, laboratory, field and service studies over the years have enabled engineers to identify four important influential atmospheres in corrosion behaviour of steel; these are; inland rural atmospheric, inland industrial atmospheric, nominal marine atmospheric and marine industrial atmospheric environments.

The inland rural atmospheric environment is any region of the atmosphere of more than two kilometers away from the coast that is not affected by industrial activities. These are essentially inland unpolluted environments. In other words, this environment is more or less nominal, and hence moisture containing dissolved oxygen is the primary corrosive agent. The only possible pollution of the environment could be from distant sources according to prevailing wind direction or topography. This is generally considered negligible. Steel corrosion here tends to be low, usually less than 0.05mm/year in exposure outdoors. The results obtained for mild steel by BISRA in [mm/year] for some sites in the environment are Godaiming (0.048); and Llanwrtyd Wells (0.069) in Britain, Teddington Khartoun in Africa (0.003), Abisko in North Sweden (0.005), State College Pa in the United States of America (0.043), and Berlin-Dahlem in Europe (0.053). Exposure indoors here, such as offices, stores, workshops, industrial production and assembly warehousing, hospitals, schools, hotels, and residential apartments have very much lower steel corrosion rates and risks compared to the outdoors (Shreir, 1979, Johnson, 2001).

An inland industrial atmospheric environment is any area around industrial and, or high urban activities in rural areas. Such activities include petrochemical, automobile, textile, and cement manufacturing. These are areas of high air-borne suphur dioxide or other pollutants from industrial or domestic sources. The sulphur dioxide sources are twofold. Firstly, from the aerial oxidation of hydrogen sulphide (H_2S) produced naturally and secondly from the combustion of suphur-containing fuels. The average steel corrosion rates here are significant, and are usually between 0.05 and 0.lmm/year, depending upon the level of sulphur dioxide, type of steel and whether exposure is outdoor or indoor. Some industrial areas here such as breweries, diaries, laundries, food processing plants or kitchens do not produce much sulphur dioxide but the corrosion is equally significant, because of frequent condensation there (Johnson, 2001; Shreir, 1979). The corrosion rate [mm/year] for mild steel obtained by BISRA and reported by Shreir (1979)

_____

for some sites in this type of environment in Britain are Motherwell (0.095), Woolwich (0.102) Sheffield (0.135), Frodingham (0.160), Derby (0.170); and for Pittsburgh, Pa in the United State of America (0.108).

A nominal marine atmospheric environment is any aero-space region within a two kilometer strip around the coast that is unpolluted by industrial and, or domestic activities. The environment has high air-borne salt level, particularly sodium chloride (NaCl). In some places, this salt-contained zone may extend to a maximum of three kilometers from the coast. These are areas of frequent heavy condensation and hence the average steel corrosion rates are significant, usually between 0.05 and 0.1 mm/year, largely dependent upon proximity to the sea, type of steel, and whether outdoor or indoor (Johnson, 2001). For mild steel, the rates [mm/year] of rusting in exposure outdoor in this type of environment, obtained by BISRA around the globe are: Brixham (0.053), in Taiwan, Calshot (0.079), in Britain; Singapore (0.015), in Taiwan; Apapa (0.028), in Nigeria; and Sand Hook (0.084), in New Jersey, United States of America. A marine surf beach rate of 0.615 for the steel was obtained in Lagos, Nigeria (Shreir, 1979 and Ambler and Bain, 2012).

A marine industrial atmospheric environment, as rename implies, is any area of industrial and high human activities in a marine atmospheric environment These are polluted coastal environments coupled with frequent heavy rainfall. These environments produce the highest average steel corrosion rates, ranging from 0.05 to 0.15mm/year (Johnson, 2001). This is mainly because the steel surface is all-time awashed by rain and heavily polluted by sulphur dioxide, sodium chloride, and dilutes suphuric acid (acid rain). The mild steel corrosion rate for exposure outdoor in this environment in Congella, South Africa as obtained by BISRA is 0.114 mm/year (Shreir, 1979).

B   Water Environment

A water environment is any area, place, region or point that is entirely occupied by water to saturation all the time. Basically, there are two types of water environment, the sea and fresh water environments. Water environments can also exist as a result of industrial or commercial activities. Steel finds applications in these environments in the form of pipes, bridge structures, tanks and other containers, bodies of ships and other water-going structures, etc. The water environment is complex in diversity, quality or composition and operating conditions. This makes the corrosion of steel by both natural and industrial waters a complicated and many sided phenomenon, which cannot be completely dealt with in this paper. The difficulty arises from the fact that of the main considerations involved the composition and surface condition of the steel, the quality of the water, and the operating conditions; the last is generally the most important. Moreover, in industry the operating conditions vary widely, and many of them need individual study (Am. Soc. Met., 1975; Harrison and De Mora, 1975; Callister, 2004 and Johnson, 2001).

Effect of metal composition: All ordinary ferrous structural materials, mild steels, low-alloy steels and wrought iron corrode at virtually the same rate when totally immersed in natural waters. As shown in Table 6, the process of manufacture and the composition of mild steel do not affect its corrosion rate appreciably under water (Uhlig, 1971; Ross, 1977 and Shreir, 1979). The copper content of the tested steels varied from 0.03 to 0.11. The killed steel contained about 0.4% aluminium and 0.04% silicon. In general therefore, the least expensive steel or any other ferrous material of a given cross-sectional thickness having the required mechanical properties is the one that should be specified for water environment.

Table 6: *Rates of Rusting of Mild Steels in Sea Water Obtained by BISRA for a 2003–day Total Immersion at Plymouth, Britain (Shreir, 1979)*

S/N	Types of Steel	Analysis %				Average General Penetration (mm/y)
		C	Mn	P	S	
1.	Basic Bassemer, Rimming Ordinary	0.05	0.64	0.60	0.02	0.143
	High Phosphorus	0.03	0.31	0.14	0.143	0.143
	High Phosphorus and sulphur	0.03	0.30	0.10	0.07	0.148
2.	Openhearth, rimming	0.13	0.33	0.03	0.03	0.143
	Ordinary from haematite pig	0.03	0.32	0.01	0.03	0.140
3.	Open – hearth, killed Ordinary	0.10	0.35	0.03	0.02	0.0140
	From haematite pig	0.11	0.34	0.01	0.03	0.136
4.	Open – hearth, killed Ordinary	0.22	0.71	0.03	0.03	0.143
	From haematite pig	0.21	058	0.02	0.03	0.158

C = carbon, P = Phosphorus, MM = Maganese, and S = Sulphur, contents of the Steel.

_____

Although small copper additions generally have no influence on the corrosion rate of steel immersed in water, under certain boiler conditions small amounts of copper of up to 0.3% may have a marked effect on reducing the depth of pitting. This is attributed to the catalytic action of metallic copper on the formation of a protective layer of magnetic nature which diverts the attack sideways producing general rather than pitting corrosion. Generally, over 3% of alloying additions such as chromium are necessary to obtain any marked improvement in the corrosion resistance of steel in waters (Ross 1977; Shreir, 1979).

Effect of surface condition: The surface condition of the steel at the time of exposure is of great importance.This is because many natural waters are good electrolytes, so that there is ample opportunity for electrolytic corrosion when steel is permanently in contact with them. The presence of millscale on the surface is more dangerous, for example when steel is immersed in sea-water than when it is exposed to air, for the galvanic cell formed by millscale and bare steel can operate much more freely under the former conditions. This may lead to rapid pitting. Pits of up to 1.25mm depth were found on as-rolled steel specimen after six months immersion in sea-water at Gosport in United Kingdom. It follows that for many practical purposes, where steel is exposed to water without a protective coating such as boiler tubes, it is desirable to remove millscale before putting the parts into use (Shreir, 1979).

Effect of welds: Serious pitting may occur in the area of welds particularly in sea-water. Corrosion rates of up to l0mm/year have been reported in weld joints of ice breakers. The severe corrosion has been attributed to galvanic effects between the weld metal and the steel plate. The use of more noble electrodes for welding are reported to overcome this problem (Uhlig, 1971 and Shreir, 1979).

Effect of water composition: Saline and acid waters are particularly aggressive to mild steel, so that composition of water is clearly important in determining the rate or rusting of steel exposed to it. Some of the main factors here are the nature and amount of the dissolved solids, which influence the electrical conductivity, the degree of acidity or alkalinity, as determined by pH value and hardness of the water, the carbon dioxide and oxygen contents, and the presence of organic matter. The effect of dissolved solids is complex. The presence of inorganic salts, notably of chlorides and sulphates, should promote corrosion because they increase the conductivity of the water, thereby facilitating the electrochemical rusting process; moreover chlorides at least may be detrimental to the development of the protective films. Alkaline waters tend to be less aggressive than acid or neutral waters, and rusting can be repressed entirely by making the water strongly alkaline. It should be noted that a pH value of 7 gives a neutral liquid that is, the one that is neither alkaline nor acidic. As pH increases from 7 to higher values up to 14, alkalinity of the liquid increases correspondingly, and as pH decreases from 7 to lower values but of more than 0, the acidity of the liquid increases correspondingly. Unfortunately, at pH values just insufficient to give complete passivation to steel, there is a grave danger of severe pitting, even though the total corrosion is reduced and this for many purposes is a greater evil (Ross, 1977; Shreir, 1979; Legrand and Leroy, 1990). The most important property of the dissolved solids in fresh waters is whether or not they are such as to lead to the deposition of a protective film on the steel that will impede rusting. This is determined mainly by the amount of carbon dioxide dissolved in the waters, so that the equilibrium between calcium carbonate, calcium bicarbonate and carbon dioxide, which has been studied by Tillmans and Heublein (1912) and others, is of fundamental significance. Since hard waters are more likely to deposit a protective calcareous scale than soft waters, they tend as a class to be less aggressive than these; indeed soft waters can often be rendered less corrosive by the simple expediency of treating them with lime (Uhlig, 1971; Shreir, 1979 and Legrand and Leroy, 1990).

Oxygen and carbon dioxide are the most important dissolved gases in water. Oxygen is an effective cathodic depolarizer and the cathodic reaction in water is generally oxygen reduction. At ordinary temperatures in neutral or near neutral water, dissolved oxygen concentration results in an acceleration of the corrosion of steel up to a certain concentration but beyond this the rate of corrosion is reduced. In slow-moving distilled water, it has been found that the critical concentration is 12ml. This value increases with temperature and in the presence of certain dissolved salts, it decreases with high velocities. Carbon dioxide affects the acidity of water and as already noted, influence the formation of protective carbonate scales. Another important factor is that most natural waters are far from being sterile. They contain greater or lesser amounts of organic matter, both living and dead. Some of the dead organic matter, for example peat residues, may render the water corrosive by making it acid, but in most cases the living organism; probably and in fresh waters algae may grow. Moreover, there are a number of strains of bacteria that can influence the rusting proper under immersed' conditions (Harrison and De Mora, 1975 and Shreir, 1979).

Effect of the operating conditions: The operating conditions have an important influence. Generally the facts involved are complex; they include temperature, rate of flow, design features and stray currents. The temperature of water affects the rate of rusting in several ways. First, the corrosion process shares the general tendency of chemical reactions to increase in speed with rising temperature. More important, however, are the effects of temperature on the nature and solubility of the corrosion products. For example a rise in temperature will often throw down a carbonate scale; moreover, it increases the rate of diffusion of oxygen through water but decreases the solubility of this gas. Some of these effects are conflicting, with the result that under certain

_____

laboratory conditions at least the rate of rusting/temperature curve for steel immersed in water passes through a maximum before the boiling point is reached - at about 80°C in experiments made by Friend (Friend, 1940; Laque, 1975 and Shreir, 1979).

The rate of water flow is also very important. This determines the supply of oxygen to the rusting surface, and may remove corrosion products that would otherwise stifle further rusting. A plentiful oxygen supply to the cathodic area will stimulate corrosion, but so may smaller supplies at a slow rate of flow, if this leads to the formation of differential aeration cells. At sufficiently high rates of flow in natural waters enough oxygen may reach the surface to cause partial passivity, in which case the corrosion rate may decrease. In sea-water, owing to the high concentration of chloride ions, the corrosion rate increases with velocity (m/s). In one series of tests, corrosion under static conditions was 0.125 mm/year, 0.50mm/year at 1.52m/s and 0.83 mm/year at 4.572m/s (Shreir, 1979).

Design must also be considered. Sharp changes in the direction of flow as in a badly designed water box, may lead to severe local damage by impingement attack. Severe galvanic corrosion can result from the injudicious juxtaposition of steel with non-ferrous metals, such as copper or bronzes. Even when the ferrous and non-ferrous metals are not in direct contact, local corrosion cells can be set up round small particles of non-ferrous metal that have been dissolved by the water and redeposited on the steel. Corrosion cells can also be formed when steel is in contact with solutions of different saline contents; for example 'long line' currents have been observed in a lock gate that was in contact with a layer of fresh river water flowing out over a layer of sea-water (Ross, 1977 and Shreir, 1979).

Sea Water environment: The sea water environment represents a chemical system on a massive scale covering 71% of the earth's surface and accounting for 97% of the surface water in the global hydrological cycle. The average depth of the sea is 3.7 kilometers but this could be greater than 10 kilometers in deep sea. Sea water is a solution of gases and solids containing both organic and inorganic material in suspension. This is a well-oxygenated solution buffered at about pH8 containing all the elements, albeit in some instances in very dilute solution. The surface temperature of the sea ranges between -2°C and 35°C, while the temperature of shallow surface layers may run even higher.

In a thermodynamic sense, the sea forms an open system as both energy and mass can be exchanged across the boundaries. Sea water is both physically and chemically dynamic in nature leading to heterogeneity within the system. Equilibrium may be attained for some reaction requiring geologic time scales. Short-term perturbations may upset these equilibria. Of greater importance may be the effect of organisms. The concentration and distribution of several elements is controlled not chemically but biologically (Harrison and DeMora 1975).

The sea environment is one of the most corrosive to steel. This is because almost all agents of steel corrosion are found here in appreciable quantities-water, oxygen, salts such as sodium chloride, etc; coupled with mechanical actions of impingement. The metal has a remarkably steady rate of corrosion when fully immersed in the water. The average corrosion rates range from 0.05 to 0.15 mm/year depending on the prevailing conditions at the point of immersion (Johnson, 2001). Test results for mild steel, obtained by the Institution of Civil Engineers; at Halifax Nova Scotia, and Plymouth in Britain, after a 15 year immersion of the metal in the water; gave average general penetration for the two sites respectively as 0.108 mm/year and 0.065 mm/year. The effect of exposure period on the corrosion rate of mild steel is also illuminated by results given in Table 7.

Table 7: *Effect of Exposure Period on Corrosion Rate of Mild Steel in Sea Water (Central Dockyard Laboratory Portsmouth-Unpublished, In: Shreir, 1979)*

Exposure Time (months)	Average Corrosion Rate (mm/year)
1	0.33
2	0.25
3	0.19
6	0.15
12	0.13
24	0.11
48	0.11

In extended exposure periods of up to 16 years in tropical seas, Southwell and Alexander (1970) obtained an average corrosion rate for mild steel as 0.18 mm/year in the first year, falling off to a constant rate after 4 years at 0.025 mm/year. They also quoted pitting rates as 1mm/year in the first falling dramatically over the second to fourth years and ultimately continuing at a rate comparable with the average rate of penetration, giving an average rate for exposure to 16 years of 0.08 mm/year. However, the pitting rate is

generally quoted as several orders of magnitude greater than the average rate of penetration with values of 0.25 to 0.4 mm/year in Shreir (1979).

Fresh water environment: A fresh water environment is any environment that is occupied by water of no or negligibly very small salinity, such as most river, lake and commercial waters. These waters contain dissolved solids and gases and sometimes colloidal or suspended matter which may affect the corrosive properties of the water in relation to the steel with which it is in contact. The concentrations of these various substances are relatively low but vary considerable. The important constituents are classified as follows (Shreir, 1979 and Legrand and Leroy, 1990; Callister, 2004):

i.   Dissolved gases which include oxygen, nitrogen, carbon dioxide, ammonia, sulphurous gases, etc.
ii.   Mineral constituents; including hardness salts, sodium salts (chlorides sulphates, nitrates; bicarbonates etc), heavy meals, and silica.
iii.   Organic matter, including that of both animal and vegetable origin, oil, trade (including agricultural) waste constituents, and synthetic detergents.
iv.   Microbiological forms including various types of algae and slime-forming bacteria.

Some of the organic matter such as oil form films on water surface which isolates the water from air, so that in polluted water anaerobic conditions may develop with the encouragement of objectionable bacterial corrosion activities. The various kinds of organic growths, including algae and slime-forming bacteria have a direct or indirect effect on the corrosion of steel. The effects may be of two main types: masking effect of living or dead organisms which is a little different from that of other materials; and effect of alterations in composition of the water brought about by the organism, algae, for example, may remove carbon dioxide and produce oxygen while other organisms often consume oxygen.

The pH of fresh waters is in fact, rarely outside the fairly narrow range of 4.5 to 8.5. On the overall, steel corrosion in this water is much lower than that of sea water, mainly because the concentration of corrosive salts here is much lower than that of sea waters. Moreover, the sea is generally more physically and chemically dynamic than fresh water environments. The average steel corrosion rates in fresh waters range from 0.03 to 0.05 mm/year (Shreir, 1979).

C   Soil Environment

Soil is a complex system of solid, liquid and gaseous phases, physically and chemically associated with each other. The solid phase is by far the most heterogeneous component, even in small volumes of soil, being composed of different sized organic particles of silica, silicate, clay, metal oxides, and other minor components all associated to some extent with organic material. The organic matter consists of a number of materials ranging from un-decomposed plant or animal tissue through various intermediate levels of decomposition to a comparatively stable amorphous brown and or black material. Compositional variables of a soil include moisture, oxygen, salt content, acidity, as well as the presence of various forms of bacteria. Climatic factors; temperature, rainfall, air movement, sunlight, etc, can cause marked alterations in properties of soil. Steel, particularly plain carbon ones are found most economical for underground   structures, especially in forms of long pipelines (Am. Soc. Met., 1975; Harrison and De Mora, 1975 and Basalo, 1992).

No two soils are exactly alike, and extremes of structure, composition and corrosive activity are found in different soils. The type of soil affects the corrosion rate of steel much more than any variation in the steel material or in its method of manufacture. In general, dry, sandy or calcareous soils with high electrical resistance are the least corrosive. At the other end of the scale are the heavy clays and the highly saline soils, whose electrical conductivity is high. Other steel-corrosive soils include organic deposits such as peat and organic silt and, river and harbour mud. Although it is difficult to assess the corrosiveness of a particular soil before hand, much useful information can be obtained from a well-conducted soil survey on the site. The corrosivity assessment methods include determination of the soil's resistivity, redoxpotential to assess the soil's capability of anaerobic bacterial corrosion, acidity (pH), and water and oxygen contents. Highly acidic soils, that is, those with pH less than 3.0, can be very corrosive. Bacterial activity often plays a major part in determination of corrosion of buried steel. This is particularly so in waterlogged clays and similar soils where no atmospheric oxygen is present as much. If these soils contain sulphates, for example gypsum and the necessary traces of nutrients, corrosion can occur under anaerobic conditions in the presence of sulphate-reducing bacteria which reduce sulphates in the soil to sulphides which are corrosive to steel. The depth of water table is also important; much depends on whether it is alternately wet or dry. It has however been found that the depth of burial has no consistent effects, which should not be surprising since the average depth of the water table and seasonal fluctuations vary from one site to another (Ross, 1977 and Shreir, 1979).

Finally, extensive field tests made at different sites around the globe indicate that steel's rusting rate could become less and less rapidly as time of burial goes on, or it could be roughly proportional to the duration of burial; depending on the type or properties of the soil. The maximum general soil corrosion rate reported in tests carried out by the United States National Bureau of Standards on

_____

mild steel is 0.068 mm/year. The maximum rates obtained in tests carried out in the United Kingdom by BISRA and the National Physical Laboratory is 0.035 mm/year and 0.050mm/year respectively. However, the pitting rate was much greater with reported maximum pits of 0.25mm/year from American and 0.30 mm/year from British tests (Shreir, 1979). Table 8 shows the effect of depth of burial on the rusting of mild steel in different soils as obtained by BISRA at different sites in the United Kingdom (Shreir, 1979).

Table 8: Effect of Depth of Burial on the Rusting of Mild Steel Fiats as obtained by BISRA – (Test Duration was 5 years) (BISRA) (Shreir, 1979)

Site	Type of Soil	Average General Penetration (mm/year)	
		1.37m Depth	0.61m Depth
Benfleet	London Clay	0.0185	0.0361
Gothan	Keuper mart	0.0132	0.0094
Pitsea	Alluvium	0.0353	0.0284
Rothmsted	Clay with flints	0.0201	0.0213

Effect of steel composition: Corrosion of steel in soil is generally electrochemical in character but the conditions are such that the corrosion products usually remain in contact with the metal. Moreover, the rate of oxygen supply is often low in comparison with that in air or water. This is probably the main reason why there are no major differences in the general corrosion rates of ordinary steels when buried in most soils. The rates of general attack ate comparatively low, say 0.038 mm/year over a 10-year period of burial in a clay soil, as compared with 0.1 to 0.13 mm/year for complete exposure outdoors in an industrial atmosphere. The cheapest type of steel or iron of a cross-sectional thickness having the required mechanical properties is therefore suitable for underground structures (Uhlig, 1971; Shreir, 1979 and Johnson, 2001).

IV.   SUMMARY AND CONCLUSIONS

Corrosion is the destructive attack of a material by reaction with its environment. The serious consequences of corrosion have become a problem of worldwide significance. In addition to our everyday encounters with this form of degradation, corrosion causes plants' shut downs, waste of valuable resources, loss or contamination of product, reduction in efficiency of plants or systems, costly maintenance and expensive overdesign. Furthermore, it jeopardizes safety and inhibits technological progress. Corrosion control is achieved by recognizing and understanding mechanisms by using corrosion-resistant materials and designs, and by protective systems, devices and treatments. Corrosion of steel is the most important corrosion problem in the world's socio-economic and technological development and accounts to about 90% of all corrosion problems worldwide. Factors that influence corrosion of steel are complex and vary from location to location, point to point and time to time. This paper has presented results and analysis of a survey of metallurgical and environmental factors that are influential in corrosion of this most important engineering alloy. Elucidated facts in the paper show that the amounts or levels of environmental impurities, aeration, moisture contents, microbiological activities, electrical conductivity and acidity; and metallurgical composition, surface condition, surface exposure and fabrication processes are the salient influential factors in corrosion of steel. The information is posited as a compendium for better insight and consideration by the researcher, protection practitioner, student and professional for more positive efforts in combating corrosion for technological cum economic advancement.

REFERENCES
[1]. Am. Soc. Met. (1975). Metals Handbook Volume 10: Analysis and Prevention. Published by the ASM Handbook Committee, American Society for Metals, Metals Park Ohio, pp. 168-227.
[2]. Ambler, H.R. and Bain, A.A.J. In: Atmospheric Corrosion by G. O. Llyod. Extracted from http://www.npl.co.uk/upload/pdf/atmosphericcorrosion.pdf (20/10/2012).
[3]. Basalo, C (1992). Water and Gas Mains Corrosion, Degradation and Protection. Ellis Horwood Ltd, Chichester, England, pp. 4-393
[4]. British Iron and Steel Research Association-BISRA, In: Shreir, L. (1979). Corrosion Volume 1: Principles of Corrosion and Oxidation. Butterworth Publishers, London, pp. 3.9
[5]. Central Dockyard Laboratory Portsmouth-Unpublished, In: Shreir, L. (1979). Corrosion Volume 1: Principles of Corrosion and Oxidation. Butterworth Publishers, London, pp. 2.56
[6]. Burdekin, M. (2001). Applied Metallurgy of Steel. In: Owens, G.W. and Knowles, P.R. (Ed.), Steel Designers' Manual, 5th Edn. Blackwell Science Ltd., Oxford, pp. 199-225.

_____

[7]. Callister, W.D. (2004). Material Science and Engineering: An Introduction, 5th Edition. John Wiley and Sons Inc. New York, Pp 357-601.

[8]. Chandler, KA. and Kilcullen, MB. Variation in Environmental Content of Sulphur Dioxide on the Corrosion of Steel, British Corrosion Journal, 3 March, 1968. **In:** Shreir, L. (1979). Corrosion Volume 1: Principles of Corrosion and Oxidation. Butterworth Publishers, London, England, pp.. 3.6.

[9]. Chandler, K.A. and Stanners, J.F. (1963). Proceedings of 2nd Int. Congr., on Met. Corr., NACE, Houston, 325. In Shreir L. (1979) Corrosion Volume 1: Principles of Corrosion and Oxidation. Butterworth Publishers, London, pp.3.6.

[10]. Cotterel, A. (1985). An Introduction to Metallurgy, 2nd Edition. Edward Arnold Limited, London, pp. 451-523.

[11]. Dearden, J. (1948). Journal of Iron and Steel: **In:** Shreir, L. (1979). Corrosion Volume 1: Principles of Corrosion and Oxidation. Butterworth Publishers, London, pp..3.10.

[12]. Dr. Eng. M.I. Masoud. Metallurgical Factors Affecting Corrosion in Petroleum and Chemical Industries. Industrial Engineering Department, Faculty of Engineering, Fayoum University. Extracted from www.scibd.com/doc/69379881/metallurgical-Factor

[13]. Harrison, RM and De Mora, SJ (1975). Introductory Chemistry for the Environmental Sciences. Cambridge university Press, Cambridge, pp.290-360

[14]. Higgins, R.A. (1993). Engineering Metallurgy: Applied Physical Metallurgy, 6th Edition. Arnold, Hodder Headline Group, London, pp.507-537

[15]. Higgins, RH and Morrow, LC (1977). Maintenance Engineering Handbook. McGraw-Hill Book Company, New York, USA, pp. 16.1-16.12

[16]. INTERNET: List of Countries by Steel Production-Wikipedia the free encyclopedia.Extractedfrom enwikipedia.org/wiki/steel_production_by_country (23/10/2014)

[17]. Johnson, K. (2001). Corrosion Resistance. In: Owens, G.W. and Knowels, P.R. (Ed). Steel Designers Manual, 5th Edition, Blackwell Science Limited, Oxford England. Pp 998-1025

[18]. Johnson, SM (1965). Deterioration, Maintenance and Repair of Structures.McGraw-Hill Book Company, New York , pp. 20-57

[19]. Laque, F.L. (1975) *Marine Corrosion*. A Wiley-Intersceince Publication, New York, pp. 12-317

[20]. Legrand, L and Leroy, p (1990). Prevention of Corrosion and Scaling in Water Supply Systems. Ellis Horwood Ltd. Chichester, England, pp. 15-143.

[21]. Meetham, AR. Atmospheric Pollution, Its Origin and Prevention, Pergamon, London (1956) and Stern AC (Ed.) Air Pollution Academic Press, New York, 2nd Edn. (1968).

[22]. Metals and Minerals Annual Review. Published by Mining Journal Ltd London (1998). pp. 10-25.

[23]. Pludek, V.R. (1977). Design and Corrosion Control. The Macmillan Press Ltd London. pp. 1-35 Rajan, T.V., Sharma, C.P., and Sharma, A. (1997). Heat Treatment Principles and Techniques. Prentice-Hall of India Ltd, New Delhi, pp. 236-390

[24]. Ross, RB (1977). Engineering Design Guides 21: Metal Corrosion, Oxford University Press, Oxford, 1-35

[25]. Schikorr, G. (1963). Werkstoffe Korros 14 No. 2.69. **In:** Shreir, L. (1979). Corrosion Volume 1: Principles of Corrosion and Oxidation. Butterworth Publishers, London, pp. 3:8

[26]. Shreir, L. (1979). Corrosion Volume 1: Principles of Corrosion and Oxidation. Butterworth Publishers, London, pp. 2.1-2.30.

[27]. Sixth Report of the Corrosion Committee, Special Report No. 66, Iron and Steel Institute London, 1959

[28]. Southwell CR and Alexander and Alexander, AL (1970). Materials Protection In: Shreir, L. (1979). Corrosion Volume 1: Principles of Corrosion and Oxidation. Butterworth Publishers, London, pp. 2.56

[29]. Uhlig, HH (1971). Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering, John Wiley and Sons Inc, New York, USA, pp. 1-270.

[30]. Vernon, W.H.J. (1935). Transactions Faraday Society, London. **In:** Shreir, L. (1979). Corrosion Volume 1: Principles of Corrosion and Oxidation. Butterworth Publishers, London, pp. 3.5