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# Corrosion in Mining and Mineral Industry

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**Abstract:** *Mining, Mineral processing and extractive metallurgy industries are concerned with a wide range of corrosive media. Mining equipment, installations and plants are subjected to high rates of corrosion due to harsh operating and environmental conditions and corrosive chemicals. Corrosion can lead to structural failure or loss of containment, costly repairs, lost or contaminated products, environmental damage, risk to personnel, and loss of public confidence. Corrosion monitoring continuously focus on critical equipment, avoiding catastrophic failure and maintaining safe and reliable operation.*

*The mining industry presents one of the harshest environments, pushing process equipment to the extreme.* Pipes are considered the arteries of a mining operation, which means they need to be built to withstand a variety of extreme operating environments, including metal extraction where process chemicals reach temperatures of up to 90°C. Carbon steel or even most stainless steel alloys are not recommended for use in these aggressive environments.

*Corrosion of physical infrastructure vehicles, and machinery at mining operations and manufacturing facilities must be managed effectively to maintain safe and profitable operations. This article deals with detection, monitoring, determining corrosion rates, identification of potential hazardous conditions, promoting the transition from a reactive to a proactive safety culture, reducing maintenance costs and selection of various materials in mining and mineral processing equipment.*

*This paper also focus on review of effects of corrosion on mining, mining equipment, infrastructure, logistics, Implementing cost-effective inspection and maintenance programs on items with a high probability of failure and ensure the integrity and safety of assets, and contribute to a successful health, safety and environmental (HSE) management program.*

**Keywords:** *Mining, Mineral processing, corrosion, safety and failure of equipment.*

## 1. INTRODUCTION

Mining is one of the few industries that can use low quality water for processing. Mines are located in extreme climates like arid climates, frigid zones etc. In the last decade, this has resulted in mines moving towards the use of seawater to supply their operations. Sometimes water has to be transported 100s of km inland from the coast. The corrosiveness of seawater introduces an increased corrosion risk for these projects and is not always managed in a proactive way from the design stage. This can have severe implications for the ongoing operational performance of the mine.

Corrosion in mining will cause number of technical, project schedule and budget impacts during the commissioning stage of the project. The mining industry presents some unique and challenging corrosion risks, however, similar to other industries, these technical challenges cannot be considered in isolation. Without considering human factors, any proactive approach to corrosion-control will struggle to take a foothold. There is a wide variety of corrosion challenges associated with mine sites. Degradation can occur due to external atmospheric attack (on structural steel and concrete), erosion-corrosion (in the crushing-grinding circuit and slurry lines), high temperatures and aggressive solutions (within process streams) and, in large part, due to the water source quality and soil condition.

This paper will review the effect of corrosion in mining and mineral industry, various techniques to fight corrosion, challenges and lessons learned with corrosion in NMDC mines and others mines in India due to extreme conditions of weather, quality of water, grinding, slurry transportation etc.

### 1.1 Causes of Corrosion

Corrosion is the deterioration of metal caused by a chemical reaction to its surrounding environment. In most cases this means electrochemical oxidation of metals in reaction with an oxidant such as oxygen. Corrosion can be accelerated by the presence of dust, moisture, high relative humidity, high temperatures, salt, acids, solvents and chemicals. How quickly corrosion occurs depends not only on the environment, but also on the specific type of metal. Cast iron, for example, rapidly oxidizes and forms red rust if left in its raw state, simply from exposure to the air, so it requires some form of protective finish. Other metals, such as stainless steel, have an inherently higher resistance to corrosion without the need for special coating. Fig. 1 shows the effect of dissolved oxygen, temperature on corrosion rate and Fig.2. shows the effect of pH and temperature on corrosion rate [1]. Corrosion is a complex electrochemical process still to be understand.

 

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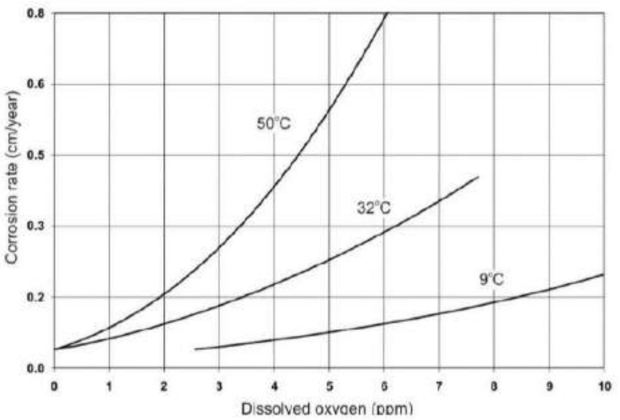


**Fig. 1.** *Effect of oxygen on the concentration on the corrosion of low carbon steel in tap water at different temperatires.*

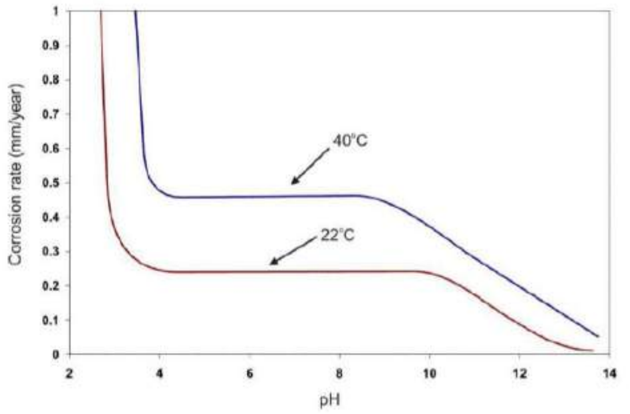


**Fig. 2.** *Corrosion of steel in water containing 5 ppm of dissolved oxygen at two different temperatures as a function of water pH.*

Table 1. *Corrosiveness of soils*

| Corrosiveness | Resistivity (ohm/cm) | pH |
|---|---|---|
| Normal | 2000 – 5000 | 5 – 10 |
| Aggressive | 700 – 2000 | 5 – 10 |
| Very aggressive | <700 | <5 |

**Table 2.** *Saturation Index and recommendations*

| Saturation Index (SI) | Description | Recommendation |
|---|---|---|
| -3.0 to -5.0 | Very severe corrosion | Treatment required |
| -1.0 to -3.0 | Moderate corrosion | Considered for Treatment |
| -1.0 to +1.0 | Balanced | No treatment required |
| +1.0 to +3.0 | Moderate scales | Consider treatment |
| +3.0 to +5.0 | Very severe scale | Treatment recommended |

## 2. THE COST OF CORROSION

NACE International, released the "International Measures of Prevention, Application and Economics of Corrosion Technology (IMPACT)" study, in which it estimates the global cost of corrosion to be US$2.5 trillion, equivalent to roughly 3.4 percent of the global Gross Domestic Product (GDP). The two-year global study released at the CORROSION 2016 conference in Vancouver, B.C., examined the economics of corrosion and the role of corrosion management in establishing industry best practices. The study found that implementing corrosion prevention best practices could result in global savings of between 15-35 percent of the cost of damage, or between $375-875 billion (USD). Several scholars had studied the cost of corrosion in the economy of various countries and estimates as high as 7% of GDP of the country [2 – 5 ]. Cost of corrosion in United States has been increased from USD 278 billion to USD1100 billion, presented in Table 3 [3]. Table 4. Presents detailed break up of cost of corrosion (Coc) of India for the year 2011-12.

**Table 3.** *Corrosion cost in United States*

| Year | Estimated cost (USD) |
|---|---|
| 1998 | 278 billion |
| 2013 | 1000 billion |
| 2016 | 1100 billion |

**Table. 4.** *Cost of corrosion (Coc) by sector for India 2011-12 study*

| Sector | Coc (USD million) | GDP (USD million) | % Coc of GDP) |
|---|---|---|---|
| Agriculture, Forestry & Fishing | 12,496 | 203,934 | 6.0% |
| Industry | 22,805 | 4,48,110 | 4.7% |
| Mining & Quarrying | 1619 | 26,388 | 6.1% |
| Petroleum & Natural Gas | 172 | 11,677 | 1.5% |
| Mining (other than P &N above) | 417 | 14,711 | 2.8 % |
| Manufacturing | 10,277 | 1,78, 757 | 5.7 % |
| Construction | 8015 | 2,51,266 | 3.2 % |
| Electricity, Gas, Steam & AC supply | 2102 | 18,445 | 11.4 % |
| Water supply, sewage, waste management & Remediation | 792 | 13,254 | 6.0 % |
| Services | 13471 | 3,96,093 | 3.4% |

## 3. IMPACT OF CORROSION ON MINING INDUSTRY

### 3.1 Support Systems in Underground Mines

Roof support is a fundamental requirement for all underground mining operations. Hard rock mining operations can vary widely depending on the nature of the deposit and require varying degrees of ground support to provide a safe working environment. Blasting and seismic loading can create additional hazards for the rock mechanics engineer who must design an effective support system for these conditions. Nonetheless, the fundamental aspects of rock support remain the same, keep the rock from moving when possible and maintain support as the rock deforms when it is not possible to achieve complete equilibrium. Several advancements in roof support technology have been made in the past 10 years, providing a host of new products that improves all three measures of support design; namely strength, stiffness, and stability. The cross pollination of support applications has also grown, with supports developed for gold mine applications transformed to coal mine roof support systems and vice versa. However, there is no and never will be a universal support that will be effective in all conditions. The goal remains to match the support performance characteristics with the ground response - that will always require a site-specific design to achieve support optimization.

Falls of ground (FOG) still account for around 35 percent of all fatalities in underground mines, and to reduce FOG, appropriate support technology needs to be implemented. A shift in mindset and culture will see the reduction of stoppages due to FOG, which are very costly. In underground mining operations, the use of temporary support components offers some protection to workers while permanent and generally more elaborate support systems are installed or constructed. The mining industry has adopted underground support technologies in order to reduce safety risks and enhance productivity, for instance coal mining has adopted leading technologies over the years, Platinum and chrome mines have also shown significant moves towards adopting leading and appropriate support technologies, seeing noteworthy changes in injury statistics for better. Support system performance under different corrosion conditions, rate of corrosion and mapping in underground mines is available elsewhere in the literature [6 – 13].

## 4 IMPACT OF CORROSION ON MINE WATER SUPPLY SYSTEM

Water scarcity is one of the most important challenges for the mining industry. Most of the mining operations are located in extreme climatic conditions like a deserts, high altitudes, where the main local water supply is from limited, typically low quality groundwater sources. Most of the mining activities would outlast the local water reserves, and therefore many projects have considered, and continue to develop, the use of seawater or desalinated water to supply their operations.

The natural corrosivity of seawater or desalinated water impacts not only on materials selection and costs but it also affects the mine process, the system availability, safety and environmental issues, among other factors. Water samples were collected, tested as per standards and presented in Table 5. Corrosivity of underground water in Indian coal mines, selection of materials is available in the literature [14 – 15].

**Table 5**. *Water quality of Kirandul (Deposit 14) Bailadila.*

| Parameter | Range |
|---|---|
| Dissolved solids (ml/L) | 59 – 71 |
| pH | 7.06 – 8.34 |
| Electrical conductivity (µS/cm) | 116 – 489 |
| Turbidity (NTU) | 0.7 – 15.1 |
| Total Hardness | 78 - 186 |
| Dissolved oxygen | 2.40 – 5.25 |
| Chloride | 126 - 294 |

## 5 IMPACT OF CORROSION IN MINERAL PROCESSING INDUSTRY

An adequate supply of water in required quality is essential for mineral processing operations. Water is used mainly for processing and transportation of ore, fire protection equipment, cooling and domestic purposes. Water in mineral processing operations is primarily used as process water. Process water is recovered and reused to reduce the water supply cost, to reduce pollution of nearby water ways and water bodies. Reclamation and reuse or recycling of process water reduces makeup water requirement and cost. Water availability is of major importance in mineral processing. Development of a dependable and adequate water supply and its storage and transport are indispensable. Corrosion of material handling system in mineral industry was studies by several scholars [16]. Fig. 3 and Fig. 4 shows the effect of corrosion on raw water GI pipe line and Process plant structural support respectively in Kirandul Complex, Bailadila Iron ore mine.

**Fig. 3.** *Photograph of corroded GI pipe line of raw water at Kirandul, Bailadila Iron ore Mine, India.*

## 6 CORROSION OF WIRE ROPES

Wire rope is an intricate device made up of a number of precise moving parts used in underground as well as surface mining. The amount of corroded metal is a function of the surface which oxygen can attack. Steel wire ropes have an exposed surface about 16 times larger than the a steel bar of the same diameter and will therefore corrode correspondingly faster. Wire ropes are used in shovels, drag lines, over head cranes etc. Corrosion of wire rope is a typical problem. Pitting of wire rope often leads to corrosion fatigue failure of the strands, but it also has been associated with stress corrosion cracking.

Corrosion can seriously shorten wire rope life, both by metal loss and by formation of corrosion pits in the wires. These pits act as stress-concentration points in the wires in much the same manner as do nicks. Pitting, erosion, and surface effects of many different types can all result in corrosion damage.

**Fig.4** *Photograph of corroded process plant structural support at Kirandul, Bailadila Iron Ore Mine, India*

The amount of corroded metal is a function of the surface which oxygen can attack. Steel wire ropes have an exposed surface about 16 times larger than a steel bar of the same diameter and will therefore corrode correspondingly faster. Wear and corrosion are characterized by a reduction in the cross section of the rope. If external or internal wear in steel wire ropes is in general uniform, corrosion is local and often overlaps to other anomalies.

Wear is classified into external or internal depending on whether it is on the outside of the rope or inside. Internal wear is due to the contact and movement which occurs between wires. In the field the extent of wear of a wire rope is normally measured as a reduction in rope diameter. However, since the rope is not a rigid body, a reduction in rope diameter can be a summation of wear and other factors such as collapse of the core. In the case of abrasive wear, true external wear of the rope can be assessed by measuring either the loss in diameter of the outer wires, stated as a loss in their depth, or by measuring the width of the flats formed on the outer wires by wear. The former requires prising open the outer wires which can be difficult. The later is convenient to measure in practice but care must be taken to ensure that the measurement is accurate.

Abrasive wear is also accelerated under such conditions. Wire and strand movement is restricted. This increases the risk of failure by bending fatigue. The reduction of wire area due to corrosion will lead to failure under tensile loads. Corroded steel wire rope will lose its strength and flexibility. Corroded wire surfaces will form fatigue cracks much faster than protected surfaces. If high local stresses help propagate these cracks, the mechanism is called stress corrosion.

The amount of corrosion can be reduced by reducing the exposed surface. This can be done by galvanizing the rope wires. A steel core can also be protected by a plastic coating. An internal and external lubrication will also reduce or prevent corrosion. Steel expands when it corrodes. Therefore, sometimes an increase in rope diameter over time might be an indication that the rope is corroding internally. Static ropes (suspension ropes or rope sections lying over a saddle or an equalizer sheave) are more likely to corrode faster than running ropes/ winding ropes. This has been illustrated with failure analysis of two different types of wire ropes one guide rope which is static in nature and one winding rope which is a moving rope.

## 7 CORROSION IN SLURRY PIPELINES

The transport of iron ore concentrate in slurry for through pipe lines has several advantages over other modes of transport over long distances such as low rate of accidents, low power consumption, high reliability, savings in transport cost and relatively low environmental impact. The transport capacity of slurry pipe lines is directly related to the roughness of the pipe. Due to this corrosion plays an important role. Transporting the iron ore slurry from the beneficiation process to the filtering and pelletising process subjected to corrosive which alters surface roughness. Corrosion in aqueous media represents 90% of metal corrosion failure [18]. Transportation of mineral concentrate is ever increasing through pipe lines.

Mineral concentrates and tails are being transported to designated places using pipe lines hydraulically. Transportation of mineral concentrates and tails is a latest trend and very cheap when compared to railways and roadways. The design of slurry transport systems today is based largely on rules of thumb, practical operating experience and common sense. A slurry transportation system consists of storage, distribution, feeding and transportation systems which consists slurry storage tank, centrifugal slurry pumps, intermediate storage tanks, pipe lines, control systems etc. Various slurry pipe lines in operation, feasibility stage and engineering stage worldwide are presented in Table 6. Various scholars studied the the effect of corrosion on slurry transportation pipe lines [19 - 23]

**Table 6.** *Slurry pipe lines in Operation, engineering stage and feasibility stage*

| Country | From | To | Length (km) | Capacity (MPTA) |
|---|---|---|---|---|
| Brazil | Germano | Point Ubu Pellet Plant | 396 | 15 |
| China | Da Hong Shan Mine | Yunnan Steel mill | 171 | 3.5 |
| Brazil | Minas Rio Iron ore Mine | | 522 | 23 |
| Australia (Tasmania) | Savage river Slurry pipe line | | 85 | 4 |
| Brazil | Minasgerios | Iiheus Port | 420 | 25 |
| Congo* | Mines | Pointe Noire Port | 370 | 12 |
| Australia | Mount Gibson Range | Geraldton | 278 | 10 |
| Australia | Balla Balla Mine | Port Headland | 110 | 10 |
| India | Kudremukh | Mangalore | 68 | 8 |
| India | Kirandul | Visakhapatnam | 267 | 8 |
| India | Barbil | Kalinganagar | 230 | 4 |
| India | Joda | Paradip | 253 | 8 |
| India* | Kirandul | Visakhapatnam | 455 | 15 |
| India* | Kumundi | Meeramandal | 105 | 8 |
| India* | Barbil | Angul | 199 | 12 |

- Under feasibility and Engineering stage

## 8 COMBATING CORROSION

Corrosion is a natural process and a part of life. Even the hardiest equipment can succumb to corrosion, so it is important to make use of sacrificial anodes to increase the life of cathodic protection. An anode made of metal with a lower electrode potential--such as magnesium, zinc or aluminum--will take the brunt of corrosion during the pump's application, protecting the metal that composes the pump. These protection plates must be monitored and replaced before they corrode completely. Whether it is a Mining Industry or Marine Industry or Aeronautical Industry or Automobile Industry methods of combating corrosion are same depending up on the prevailing conditions. Corrosion may not be prevented but can be reduced by adopting following:

### 8.1 Selection of Materials:

The right material of construction should have the following properties like high mechanical strength, high corrosion resistance and low cost. Screening media (wire mesh) of vibration screen used for wet screening can be replaced with a PU panel.

### 8.2 Surface Coatings

The structure is coated with a layer of other metal or non metal which may be more noble than the structure or less noble than it e.g. steel structures can be coated with copper which is more noble than steel or zinc which is less noble. In case of coating the structure with a more noble metal care should be taken that the coat is free from pores or cracks to avoid the formation of dissimilar metal corrosion cells which would lead to corrosion of the structure.

### 8.3 Use of Corrosion inhibitors

Corrosion inhibitors are substances that are added in small amount (e.g 0.1%) to the corrosive medium stop or slow down electrochemical corrosion reactions on a metal surface. They may be cathodic inhibitors, anodic inhibitors or organic (adsorption) inhibitors.

### 8.4 Proper equipment design

The following are examples of how proper equipment design can reduce corrosion

Avoid dissimilar metal contact in the presence of an electrolyte especially when the athode/anode ratio is high.If the use of dissimilar metals is unavoidable in building the structure they should be separated by an insulator such as plastic or rubber. Dissimilar metals are sometimes used intelligently to design structures which are corrosion resistant and less expensive. It is better from the corrosion point of view to join different sections by welding rather than riveting to avoid crevice corrosion. After welding the heat affected zone (H.A.Z) should be post weld heat treated (P.W.H.T) to eliminate residual stresses which may lead to corrosion.

High turbulence in slurry pipe lines may damage the protective oxide film on the metal and increase the rate of bare metal corrosion by increasing the rate $O_2$ transfer from the solution bulk to the metal surface.

Avoid vibration of equipment as far as possible. Vibration increases the rate of $O_2$ transfer from the solution bulk to the corroding surface with a consequent increase in the rate of steel corrosion. Vibration leads also to corrosion fatigue. Metallic objects subjects to cyclic stresses (e.g. vibrations) undergoes failure at a stress below the ultimate tensile stress of the metal especially in the presence of corrosive solutions, the stress at which failure takes place decreases with increasing the number of cycles per second. Vibrations in Crushers, vibrating feeders and vibrating cannot be avoided. Hence, vibrating screens and vibrating feeders to be checked regularly to increase the life span.

Dry equipment like packed columns pipelines, etc after testing or cleaning by passing dry $N_2$. Leaving this equipment wet for a long time before operation leads to serious corrosion. All the process equipments like slurry storage tanks, water storage tanks shall be designed for easy drainage.

Resting the tank on the floor leads to crevice corrosion of the bottom (through a differential aeration cell). Residual solution in the tank resulting from poor drainage leads to serious corrosion of the lower part of the tank because of the high rate of $O_2$ diffusion through the thin residual liquid layer left at the tank bottom.

Residual stresses left in the structure during fabrication leads to stress corrosion cracking of the metal if used in contact with certain electrolyte. Stress corrosion cracking can be avoided by either removing of residual strains from the metal by annealing or avoiding contact between the metal and electrolytes to which it is sensitive. Stresses may be also induced in heat exchanger tube if the thermal gradient across the tube wall is high (dT/dx) where dT is the difference in temperature across the tube wall and dx is the thickness of the wall.

### 8.5 Electrical protection.

Technique to reduce corrosion of a metal surface by making that surface the cathode of an electrochemical cell. Cathodic protection is a method to reduce corrosion by minimizing the difference in potential between anode and cathode. This is achieved by applying a current to the structure to be protected (such as a pipeline) from some outside source. When enough current is applied, the whole structure will be at one potential; thus, anode and cathode sites will not exist. Cathodic protection is commonly used on many types of structures, such as pipelines, underground storage tanks and ship hulls.

For existing structures, the current requirement survey *(*above) will verify the need for a cathodic protection system. For new systems, standard practice is to assume a current density of at least 2 milliamperes per square foot of bare area will be needed to protect the structure. (However, local corrosion history may demand a different current density.) In addition, cathodic protection is *mandatory* for underground gas distribution lines and for water storage tanks with a 250,000-gallon capacity or greater. Cathodic protection also is required for underground piping systems located within 10 feet of steel reinforced concrete because galvanic corrosion will occur between the steel rebar and the pipeline.

Anodic protection is carried out by connecting the structure to be protected to the positive pole of an external d.c power supply, an auxiliary cathode made of corrosion resistant material is used to complete the circuit. The anode potential of the structure is adjusted to be in the passive region i.e the region represented by the area BCDE on the passivity curve. Under this condition the structure will be coated with a layer of oxide which protects it against corrosion.

## 9. CONCLUSION

As compared to other industries, mining is behind the times in terms of corrosion prevention, with corrosion control measures generally limited to maintenance painting or coating. Corrosion is one of the most underestimated and often misunderstood forces humans deal with on a daily basis. Dealing effectively with corrosion will lead to extension of equipment life, improves the production and reduces the maintenance cost and down time. All mines are dealing with extreme corrosion. Minerals, water, chemicals and salt all combine to corrode plant and equipment at an exponential rate. Corrosion of physical infrastructure, vehicles and machinery at mining operations and manufacturing facilities must be managed effectively to maintain safe and profitable operations. Any equipment failure can be expensive in terms of lost production and cost of repairs. Corrosion of physical infrastructure vehicles, and machinery at mining operations and manufacturing facilities must be managed effectively to maintain safe and profitable operations.

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