Asset Integrity and Profitability Enhancement at Three Process Facilities through Corrosion Prevention, Control and Management

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Abstract

Corrosion is no doubt an undesirable phenomenon in process facilities as it results in equipment deterioration, increased operating expenses and downtime, as well as safety and environmental issues that emanate from its effects. It therefore behoves every operator to institute and sustain a robust corrosion prevention and management program in order to prolong the lifespan of its assets as metallic parts constitute the greater proportion of structural and moving parts. This study mirrors such programs as exist in the product storage terminal, gas processing plant and refinery of three independent operators in the downstream sector of the Nigerian petroleum industry, with suggested modifications currently under implementation and early results recorded. Online corrosion monitoring was observed to be more proactive and cost-saving than offline monitoring in the three facilities under review, as illustrated by the ruptured cargo transfer pipeline that took two weeks of fault diagnosis and repairs, avoidable maintenance costs and downtime to rehabilitate. Anodic protection was also found to work in some situations where cathodic protection had failed. A graphical workflow illustrating the corrosion prevention and modified programs designed and implemented for each of the three facilities are presented, as well as cost savings over five year operating periods. The modified corrosion inspection, monitoring and response recommended by this paper would readily find application in similar facilities of other companies operating in the downstream, midstream and upstream sectors of the petroleum industry across the globe.

Keywords

Asset integrity; profitability; storage terminal; refinery; gas plant

Introduction

Corrosion involves the reaction of a metallic material with its environment and is a natural process in the sense that the metal is attempting to revert to the chemically combined state in which it is almost invariably found in the earth's crust. Whilst it is, therefore, a process that may be expected to occur, it should not be regarded as inevitable and its control or prevention is possible through a variety of means. The latter have their origins in electrochemistry, since the reactions involved in causing corrosion are electrochemical in nature, but corrosion control is as much in the hands of the engineering designer as it is the province of the corrosion prevention specialist. To the engineer, corrosion may be regarded as resulting in a variety of changes in the geometry of structures or components that invariably lead, eventually, to a loss of engineering function e.g. general wastage leading to decrease in section, pitting leading to perforation, cracking leading to fracture.[1]

Metal parts in process facilities and equipment are usually made up of metallic ions in combination with ions from other elements that give the desired mechanical and chemical properties for each particular component, device or system. When this chemical distortion in a metallic compound occurs, the metallic part loses the properties that enable its proper functioning. Corrosion is an electrochemical process that requires the presence of air and moisture (or water), amongst other factors, to take place.

Corrosion occurs at the anode, where metal dissolves. Often, this is separated by a physical distance from the cathode, where a reduction reaction takes place. An electrical potential difference exists between these sites, and current flows through the solution from the anode to the cathode. This is accompanied by the flow of electrons from the anode to the cathode through the metal.

For steel, the typical anodic oxidation reaction is:

$Fe = Fe_2^{+} + 2e^{-}$ ------------------ (1)

This reaction is accompanied by the following:

$Fe_2^{+} + 2OH^{-} = Fe(OH)_2$ ------------- (2)

The ferrous hydroxide then combines with oxygen and water to produce ferric hydroxide, $Fe(OH)_3$, which becomes common iron rust when dehydrated to Fe_2O_3.

The primary cathodic reaction in cooling systems is:

$O_2 + H_2O + 2e^{-} = 2OH^{-}$ -------------- (3)

The production of hydroxide ions creates a localized high pH at the cathode, approximately 1 – 2 pH units above bulk water pH. Dissolved oxygen reaches the surface by diffusion, as indicated by the wavy lines in Figure 24-1. The oxygen reduction reaction controls the rate of corrosion in cooling systems; the rate of oxygen diffusion is usually the limiting factor.

Another important cathodic reaction is:

$2H^{+} + 2e^{-} = H_2$ ------------------ (4)

At neutral or higher pH, the concentration of H^{+} ions is too low for this reaction to contribute significantly to the overall corrosion rate. However, as pH decreases, this reaction becomes more important until, at a pH of about 4, it becomes the predominant cathodic reaction.

Corrosion prevention moves from design optimization and proper material selection, but it includes much more following phases like a correct finish specification and plans for effective inspection, maintenance and repair (IMR). Corrosion prevention is devoted to:

- Material design
- Surface treatments, finishes and coatings
- Corrosion inhibitors compounds and sealants

- Preservation techniques.

Corrosion control, in this meaning including prediction and diagnostics, is complementary to prevention and it is actually the field where more efforts are provided, because early corrosion detection is the easiest way to avoid costly equipment and facility damage or structural failures. Corrosion control includes:

- Corrosion detection
- Corrosion removal
- Renewing the protective systems.

The entire process including all these phases has been recently called corrosion surveillance, indicating the increasing interest from operators in this matter, largely due to the growing number of aging process facilities. In effect, considering that corrosion can account for 60% of all maintenance and repair costs, economic factors must be considered as the most important constraint affecting both prevention and control.

Corrosion management is the term given to actively observing and assessing metal loss, while assuring that the functionality of the structure or process is maintained. An obvious example of the direct application of corrosion management with or without coating is the "corrosion allowance." The corrosion allowance is the additional steel the designer will add to a platform component to account for the 8-12 mills per year of corrosion. Such practice is common and fundamentally sound practice.[2]

Some corrosion measurement techniques can be used online, constantly exposed to the process stream, while others provide offline measurement, such as that determined in a laboratory analysis. Some techniques give a direct measure of metal loss or corrosion rate, while others are used to infer that a corrosive environment may exist. Corrosion monitoring is the practice of measuring the corrosivity of process stream conditions by the use of "probes" which are inserted into the process stream and which are continuously exposed to the process stream condition. Corrosion monitoring "probes" can be mechanical, electrical, or electrochemical devices. Corrosion monitoring techniques alone provide direct and online measurement of metal loss/corrosion rate in industrial process systems. Typically, a corrosion measurement, inspection and maintenance program used in any industrial facility will incorporate the measurement elements provided by the four combinations of online/offline, direct/indirect measurements.

- ❖ Corrosion Monitoring — Direct, Online
- ❖ Non Destructive Testing — Direct, Offline
- ❖ Analytical Chemistry — Indirect, Offline
- ❖ Operational Data — Indirect, Online

In a well controlled and coordinated program, data from each source will be used to draw meaningful conclusions about the operational corrosion rates with the process system and how these are most effectively minimized.

Types of Corrosion [2]

- Uniform Corrosion
- Localized Corrosion

- Pitting
- Selective Leaching

Table 1: Galvanic series of metals and alloys (Courtesy of International Nickel Company, Inc)

CORRODED END (anodic, or least noble)
Magnesium Magnesium alloys
Zinc
Aluminium 2S
Cadmium
Aluminium 17ST
Steel or Iron Cast Iron
Chromium-iron (active)
Ni-Resist 18-8-Cr-Ni-Fe (active)
18-8-3-Cr-Ni-Mo-Fe (active)
Hastelloy C
Lead-tin Solders Lead Tin
Nickel (active)
Inconel (active)
Hastelloy A Hastelloy B
Brasses Copper Bronzes Copper-nickel alloys Titanium Monel
Silver Solder
Nickel (passive) Inconel (passive) Chromium-iron (passive) 18-8-Cr-Ni-Fe (passive) 18-8-3-Cr-Ni-Mo-Fe (passive)
Silver
Graphite
PROTECTED END (cathodic, or most noble)

  - Galvanic Corrosion
  - Crevice Corrosion
  - Intergranular Corrosion
  - Stress corrosion cracking (SCC)
  - Microbiologically Influenced Corrosion (MIC)
- Erosion Corrosion
- Concentration cell corrosion
- Graphitic corrosion.

<u>Causes of Corrosion</u>

- The steel becomes brittle from exposure to heat and impurities from hydrogen.
- Sulphide attack causing stress corrosion
- Fresh, distilled, salt, and mine waters that cause pitting corrosion
- Rural, urban, and industrial atmospheres
- Steam and other gases such as chlorine, ammonia, oxygen, carbon disulphide, sulphur dioxide, and fuel gases
- Mineral acids such as nitric, sulphuric, and hydrochloric; organic acids such as acetic, formic, and citric; and alkalis such as caustic and ammonium hydroxide
- Soils; solvents such as alcohols and dry cleaning materials; vegetable and petroleum oils and a variety of food products.

<u>Effects of Corrosion</u>

Corrosion is one cankerous factor eating up process facilities and equipment, especially in the oil and gas industry. Its consequences are many and varied and the effects of these on the safe, reliable and efficient operation of equipment or structures are often more serious than the simple loss of a mass of metal. Failures of various kinds and the need for expensive replacements may occur even though the amount of metal destroyed is quite small. Its effects are summarised below.

- Reduction of metal thickness, leading to loss of mechanical strength and structural failure or breakdown. When the metal is lost in localised zones so as to give a crack-like structure, very considerable weakening may result from quite a small amount of metal loss. This failure of parts translates to facility deterioration as metals constitute a major part of most structural members, e.g. buckling in pipelines and tanks.
- Hazards or injuries to people arising from structural failure or breakdown (e.g. bridges, cars, aircraft) as well as leakage of fluids due to perforation of vessels and pipes resulting to flooding, accidents and environmental pollution.
- Loss of technically important surface properties of a metallic component. These could include frictional and bearing properties, ease of fluid flow over a pipe surface, electrical conductivity of contacts, surface reflectivity or heat transfer across a surface.
- Avoidable corrective maintenance costs and product losses.

- Contamination of process fluids and products in vessels and pipes (e.g. kerosene goes dirty when small quantities of heavy metals are released by corrosion)., leading to loss of corporate image and health hazards.

- Shut down of facility, with the attendant downtime and loss of precious manhours.

- Legal liabilities and regulatory sanctions.

- Reduced value of goods and buildings due to deterioration of appearance.

- Mechanical damage to valves, pumps, etc, or blockage of pipes by solid corrosion products.

- Added complexity and expense of equipment which needs to be designed to withstand a certain amount of corrosion, and to allow corroded components to be conveniently replaced.

Cost of Corrosion

The estimated annual cost of corrosion to worldwide GDP is $1.4 trillion. This number represents approximately 3% of worldwide GDP at $47 trillion. As an example: corrosion cost to the US economy is approximately $300 billion annually. This figure is equivalent to 3% US GDP of $10 trillion (*Engineering Talk, 19 June 2003*). This large sum could be put to use in so many other ways, if only we could avoid the effects of corrosion.[3] The total annual cost of corrosion in the global oil and gas production industry is estimated to be US $1.372 billion, broken down into US $589 million in surface pipeline and facility costs, US $463 million annually in down hole tubing expenses, and another US $320 million in capital expenditures related to corrosion.

Corrosion Prevention Measures

Protective Coatings

These include oil paints, epoxy powders, polyester powders, hybrid powders, zinc-rich powder coating primer and organic liquid zinc-rich primer. Epoxy wrappers are applied to pipeline sections to be buried in the earth or run through bundwalls during the construction and installation phase for corrosion prevention, as both soil and concrete have acidic, alkaline and saline components that induce corrosion.

Electrochemical Control

Since corrosion is an electrochemical process its progress may be studied by measuring the changes which occur in metal potential with time or with applied electrical currents. Conversely, the rate of corrosion reactions may be controlled by passing anodic or cathodic currents into the metal. If, for example, electrons are passed into the metal and reach the metal/electrolyte interface (a cathodic current) the anodic reaction will be stifled while the cathodic reaction rate increases. This process is called cathodic protection and can only be applied if there is a suitable conducting medium such as earth or water through which a current can flow to the metal to be protected In most soils or natural waters corrosion of steel is prevented if the potential of the metal surface is lowered by 300 or 400 mV. Cathodic protection may be achieved by using a DC power supply (impressed current) or by obtaining electrons from the anodic dissolution of a metal low in the galvanic series such as aluminium, zinc or magnesium (sacrificial anodes). Similar protection is obtained when steel is coated with a layer of zinc. Even at scratches or cut edges where some bare metal is exposed the zinc is able to pass protective current through the thin layer of surface moisture.

In certain chemical environments it is sometimes possible to achieve anodic protection, passing a current which takes electrons out of the metal and raises its potential. Initially this stimulates anodic corrosion, but in favourable circumstances this will be followed by the formation of a protective oxidised passive surface film. Cathodic protection is used in petroleum terminals to protect tanks and/or pipelines. Magnesium rods can be used to protect underground steel pipes by this same process.

Chemical Inhibition

This involves the injection of demulsifiers, corrosion, hydrate and wax inhibitors.

Anodic Inhibitors: As the name implies they interfere with the anodic process.

$$Fe \rightarrow Fe^{++} + 2e^{-} \text{ --------------- } (5)$$

If an anodic inhibitor is not present at a concentration level sufficient to block off all the anodic sites, localised attack such as pitting corrosion can become a serious problem due to the oxidising nature of the inhibitor which raises the metal potential and encourages the anodic reaction (equation 1). Anodic inhibitors are thus classified as “dangerous inhibitors”. Other examples of anodic inhibitors include orthophosphate, nitrite, ferricyanide and silicates.

Cathodic Inhibitors: The major cathodic reaction in cooling systems is the reduction of oxygen.

$$½O_2 + H_2O + 2e \rightarrow 2OH- \qquad (6)$$

There are other cathodic reactions and additives that suppress these reactions called cathodic inhibitors. They function by reducing the available area for the cathodic reaction. This is often achieved by precipitating an insoluble species onto the cathodic sites. Zinc ions are used as cathodic inhibitors because of the precipitation of $Zn(OH)_2$ at cathodic sites as a consequence of the localised high pH (See reaction 2). Cathodic inhibitors are classed as safe because they do not cause localised corrosion.

Adsorption Type Corrosion Inhibitors: Many organic inhibitors work by an adsorption mechanism. The resultant film of chemisorbed inhibitor is then responsible for protection either by physically blocking the surface from the corrosion environment or by retarding the electrochemical processes. The main functional groups capable of forming chemisorbed bonds with metal surfaces are amino ($-NH_2$), carboxyl (-COOH), and phosphonate ($-PO_3H_2$) although other functional groups or atoms can form co-ordinate bonds with metal surfaces.

Mixed Inhibitors: Because of the danger of pitting when using anodic inhibitors alone, it became common practice to incorporate a cathodic inhibitor into formulated performance was obtained by a combination of inhibitors than from the sum of the individual performances. This observation is generally referred to a ‘synergism’ and demonstrates the synergistic action which exists between zinc and chromate ions.

Quality Control of Process Fluids and Products

Removal of water and hydrogen sulphide from liquid and gaseous petroleum products as these substances induce corrosion in process equipment. To overcome MIC in fire sprinkler piping at both the jetty and terminal, chemical treatment of water is done using disinfectants (biocides) such as chlorine, iodine, hydrogen peroxide, ozone and ammonium compounds, organo-sulphur compounds, bromines, carbamates and isothiothiaza-lone. These chemicals destroy bacteria and their habitats, i.e., biofilms. Cleansing obstructive growth inside piping via flushing and rinsing with chemically treated water has been separately suggested by two previous studies, both asserting that the most critical step in MIC mitigation is selection of a qualified corrosion control consultant.[4,5]

Figure 1: Corrosion – Protected pressurized, water-based, metal fire sprinkler pipes[6]

Proper Materials Selection and Design
Corrosion prevention begins right from this stage of any project. For instance, replacement of steel with PVC pipes for water and sewage lines; carbon steel, alloys of steel, chromium and molybdenum, and stainless steel for excessively corrosive environments; nickel, titanium and copper alloys for the most corrosive areas of process plants

Corrosion Management Methods
Corrosion management in the process plants under review is done through the following methods:

- Online monitoring
- Offline monitoring
- Sandblasting.

Online Corrosion Monitoring
An online corrosion monitoring system will allow early detection of corrosion events and the ability to manage the corrosion rates by fine – tuning the process. Some of the methods of online corrosion monitoring are:

- Linear polarization resistance
- Electrochemical noise
- Electrical resistance.

Previously, the processing of corrosion online seemed to be very slow and the details given were not enough to fill in the criteria required; besides the data collected was not always accurate. However, with improvements in science there are newer technologies that give data twice as much as they used to be in the past and specific in their accuracy. This kind of assessment is known as real-time monitoring. This enables engineers to prevent and control corrosion and also enable better output by the plant. Plants that have online corrosion information with accurate real-time measurements help to detect and reduce high corrosion rates. These kinds of technology advancements enable engineers to prevent and protect the plant by management systems called predictive management.

When crude oil is processed, the oil pipes and tanks are subject to stresses. Impurities can lead to corrosion, blockages, dirty equipment, and catalyst poisoning. For this reason, these impurities are removed by demineralization (dehydration) in the first phase of the oil refining process. During this process, conditions such as temperature, flow rate, and pressure are monitored and controlled. To prevent the pipes and tanks from corroding, it is also necessary to determine:

1. Oil and water quality changes
2. Changes in chemical composition of the oil or gas
3. If corrosion inhibitors are working correctly

These factors are detected and monitored with the aid of a proprietory detector for corrosion monitoring and control, shown in Figure 2 below. This detector allows the system operator to plan and replace components that are affected by corrosion and prevent costly equipment damage.
It helps the operator to detect general and localized corrosion (pitting). Localized corrosion in particular can lead to serious damage, as corrosion perforation can occur within a very short space of time if it is not detected at an early stage. However, if corrective action is taken promptly, the problem can be dealt with effectively.

a.

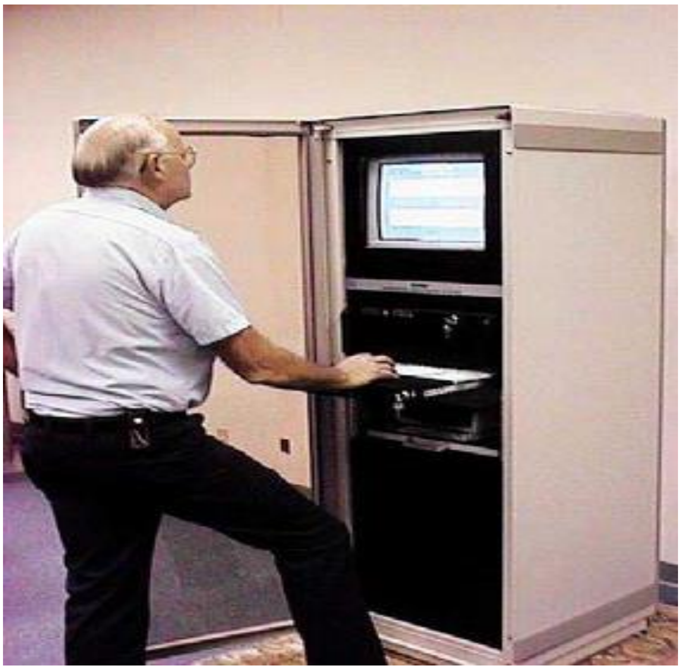
b. 

Figure 2: (a) Corrosion Monitoring Detector (b) Corrosion Management Server

How the Corrosion Detector works: The central elements of the corrosion detector are patented state-of-the-art algorithms and data analysis techniques, which provide precise measurements of corrosion rates and localized corrosion (corrosion perforation). To measure the general corrosion rate, it determines the linear polarization resistance (LPR) using the generally accepted industrial standard. This process is optimized by an additional analysis of the harmonic distortion (HDA). During the measurement cycle, the corrosion detector also measures the electrochemical noise (ECN), which reliably determines the corrosion perforation. At the end of each measuring cycle, the relevant corrosion rate and the corrosion perforation values are calculated and transmitted in the form of a 4…20 mA HART signal.

It combines both processes, so that reliable and quick measurement results are achieved. This includes the automatic determination of the B-value. To increase accuracy even more, conductivity measurements are included in the calculation. The resulting values provide valuable additional information on the condition of the electrodes. The ECN method is used to measure the intensity of localized corrosion. ECN involves the measurement of spontaneous potential fluctuations that occur inadvertently on the corrosive area of contact between metal and the solution. By means of a statistical analysis of the current measured, it is possible to determine a corrosion perforation factor which indicates the speed and the intensity of the localized corrosion.

Standard corrosion detection probes consist of three electrodes. One electrode induces a low-output signal, while the others measure the potential and current generated. To achieve accurate measurement results, the electrodes must be made of the same material as the pipe or tank that is being monitored. The sacrificial electrodes are positioned directly in the flowing, corrosive medium and are stimulated by means of a weak signal. This signal is monitored and analyzed by the transmitter. The system operator then gains an accurate picture of the existing corrosion. This provides maintenance engineers with the information they need to plan repair and maintenance work in accordance with actual requirements. The device not only helps to save time and money; it also forms the basis of preventative maintenance and makes corrosion monitoring an integral part of the daily routine in the oil and gas industry.

Offline Corrosion Monitoring

Offline monitoring refers to the monitoring of the effects of corrosion after it has happened and is usually identified while doing maintenance. Of course this is not the most effective way of saving the plant but was used in older times. It used to be considered as a step taken that is better late than never. Today online system has evolved to make it more effective in solving problem before it gets worse. The case of a recently ruptured gasoline transmission line that had to be shut down for repairs in two weeks is a typical example, as illustrated in the picture below.

Figure 3: Ruptured Pipeline in the Storage Terminal hitherto monitored offline

Sandblasting

This involves the injection of a pressurised sand-air mixture with a compressor-driven jet to remove the corroded section of tanks in order to obtain a continuously plain surface, in preparation for anti-rust coating. This is followed by coating with zinc oxide primer before the application of oil paints.

a. 

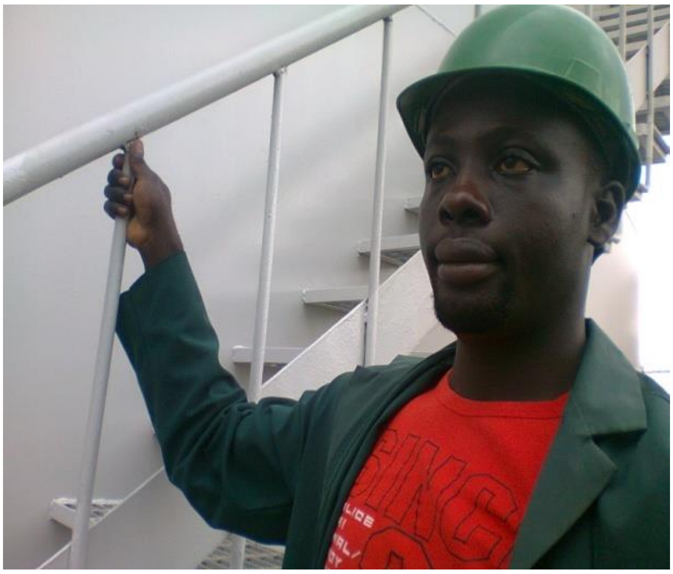
b. 

Figure 4: (a) Sandblasted Stock Tank in the Storage Terminal (b) Author about to climb same Tank to inspect Painting

Control of Corrosion

Corrosion control requires a change in either the metal or the environment. The first approach, changing the metal, is expensive. Also, highly alloyed materials, which are very resistant to general corrosion, are more prone to failure by localized corrosion mechanisms such as stress corrosion cracking.

The second approach, changing the environment, is a widely used, practical method of preventing corrosion. In aqueous systems, there are three ways to effect a change in environment to inhibit corrosion:

- Form a protective film of calcium carbonate on the metal surface using the natural calcium and alkalinity in the water.

- Remove the corrosive oxygen from the water, either by mechanical or chemical deaeration.
- Add corrosion inhibitors.

Reducing Corrosion

There are many ways to reduce corrosive effects, if not prevent them totally. Corrosion-resistant materials, such as copper, stainless steel, PVC, plastics, and concrete, are used in the construction or retrofit phase. However, these materials can be expensive.

Another method is to rustproof the system by coating metal surfaces with corrosion-resistant metals or compounds. However, some heating and cooling systems are so large that, while you may be able to coat a section here and there, coating the entire system is impractical.

The use of sacrificial anodes actually relies on corrosion itself to protect the system. These anodes are pieces of metal, such as magnesium or zinc, which have a higher potential to corrode than the base metal itself. In this system, metal bars are strategically installed on tube sheets or baffles. The sacrificial anodes corrode instead of the equipment, and are periodically replaced.

However, sacrificial anodes can only protect selected parts of a heat exchanger. Thus, the tubes will not be protected. Also, corrosion still goes on, releasing corrosive products into the water and causing deposits the system.

Using Mechanical Equipment to Control Corrosion

The use of mechanical equipment to reduce the effects of corrosion is most common in the steam heating systems of large commercial and institutional facilities. There are two primary systems, which have many variations.

Ion exchange/softening is used to condition water prior to its entry into the system. Generally, a polystyrene resin is used to remove and/or exchange various dissolved solids in the water that contribute to the scaling and corrosion process. Another process is deaeration, which involves removing the oxygen and carbon dioxide gases before they enter the boiler system. Any gases that remain after deaeration are chemically removed.

Deaeration is the most important dissolved gas removal process in steam boiler systems. It is not an ultimate cure because both oxygen and carbon dioxide can enter or develop later in the system. Therefore, there is usually need for chemical treatment in addition to deaeration.

Corrosion Inhibitors

The most effective and economical way to control corrosion is corrosion inhibition, a combination of mechanical and chemical control. An effective corrosion inhibitor program will interrupt anode reactions and slow the reactions at the cathodes. Effective corrosion inhibiting incorporates three steps:

System Cleaning: A clean system is most important for any corrosion control program. Oils, scale and corrosion deposits all contribute to corrosion by developing corrosion concentration cells. The system must be clean to gain the maximum benefit from corrosion inhibition.

Pre-treatment: A newly cleaned piece of equipment is susceptible to corrosive attack. If placed back into service without chemical treatment, the corrosive attack will start immediately. Pre-treatment chemicals lay down a coating on the metal to protect it during system start-up.

Chemical Treatment: When the system has been cleaned and pre-treated, the ongoing protection process can begin. The recommended levels of inhibitors must be maintained to assure protection. Corrosion inhibitors must be used in favourable water conditions to perform properly. The acidity or alkalinity (pH) of the water and its conductivity are important in the fight against corrosion. Whenever pH drops below recommended levels, corrosion will increase.

Furthermore, when pH becomes too low, even the most powerful corrosion inhibitors are ineffective because their protective coating is stripped away from the metal. Conversely, very high pH can create scale problems and also prevent inhibitor films. Therefore, it is important to keep pH within the recommended ranges.[7]

Rationale for Corrosion Prevention in the Downstream Petroleum Industry

- To safeguard the life of assets.
- To prevent pollution from leakages and seepages into the environment.
- To avert accidents where volatile/inflammable products are handled.
- To minimise downtime arising from shutdown of facility.
- To reduce cost of repairs and lost manhours occasioned by system breakdown or process disruption. Substantial savings can be obtained in most types of chemical plants through the use of corrosion-resistant materials of construction. One example is classic in this respect. A plant effected an annual saving of more than 10,000 dollars merely by changing the bolt material on some equipment from one alloy to another more resistant to the conditions involved. The cost of this change was negligible. In another case of waste-acid recovery plant operated in the red for several months until a serious corrosion problem was solved. This plant was built to take care of an important waste disposal problem. Maintenance costs are now scrutinized because the labour picture accents the necessity of low cost operation.[8]
- Flow and quality assurance in process facilities, thus enhancing throughput, turnover and profitability of operations. In many cases the market value of petroleum products such as gasoline and aviation fuel, is directly related to their purity and quality. Freedom from contamination is also a vital factor in the storage and distribution of fuels. In some instances contamination causes adverse effects which are noticeable – for example, in the manufacture, transport and usage of dual purpose kerosene (DPK). Life of the equipment is not generally an important factor in cases where contamination or degradation of product is concerned. Ordinary steel generally lasts many years, but more expensive material is used for pipeline, tank and loading arm construction because the presence of iron rust is undesirable from the product standpoint.
- Conformance to regulatory requirements and industry best practices.

Table 2: Corrosion Mitigation Case Histories

CASE	Situation	Solution	Results
1	Uncontrolled localized corrosion in product receipt line traversing mountainous, environmentally sensitive terrain.	Replace continuous injection with site-specific chemical batch treatments. Assess changing marine tanker and refinery conditions via modelling, inspections and coupons.	Reduced corrosion rates and exposure to environmental risks. Decreased operator's costs by 75 percent (USD $395,000).
2	Corrosion at product receipt jetty sump and manifold requires environmentally friendly inhibitor that treats overboard discharge and does not form sludge or emulsions or cause foam.	Perform rigorous laboratory and ecotoxicological tests. Continuously apply an inhibitor, approved by a Nigerian regulatory agency.	Corrosion was controlled, foam and emulsions were not present and oil-in-water values for discharged water were 15-55 percent lower than the environmental standard.
3	Installation of 400-mile LPG line requires environmentally safe, effective and biodegradable hydrotest chemicals for source water.	Add oxygen scavenger five miles downstream of injection pump and environmentally friendly biocide downstream of scavenger.	Hydrotest procedure of filtered source water, gas blanket and cost-effective hydrotest chemicals resulted in non-significant levels of bacteria.

Corrosion Prevention and Control at the Terminal

The Loading Gantry

Corrosion prevention starts from proper material selection and design, which is what the terminal operator implemented in her loading gantry, as seen in the picture below. The walkways, rails, H-bars, panels, fire water hydrant lines (painted red) and all other metal parts are made of carbon steel and regularly coated with oil paints on a biannual basis. Weekly inspections are however carried out by maintenance personnel to detect any leaks or material deterioration for prompt response. During construction and installation, roof drains are provided to divert rainwater away from gantry equipment; epoxy wrappers used to coat buried sections of product and hydrant pipelines from corrosion due to contact with the soil and concrete (Figure 6), while H-bars are cathodically protected (Figure 7).

Figure 5: Corrosion Prevention in Metal Parts at the Tank Truck Loading Bay

Figure 6: Author inspecting Epoxy Coating on buried gasoline pipeline at the Truck Loading Bay

Figure 7: Cathodic Protection of a buried H-bar at the Truck Loading Bay

The Tank Farm

As in the loading bay, all pipelines in the tank farm and product pump house (which is equally covered by a roof) are coated with oil paints before installation, repainted biannually and inspected weekly. All stock tanks and slop tanks are cathodically protected (renewed every five years), spray-washed and also coated with oil paints (renewed every year). Regular tests for earth resistance are conducted for each tank every five years, with records displayed on the body. Pipe sections traversing bundwalls are equally epoxy-coated. Daily routine checks have been instituted over the years as a maintenance culture directed towards corrosion prevention and control, as well as loss prevention.

Figure 8: Coated Pipe Sections awaiting Installation on the Jetty – Tank Farm Route

Figure 9: Painted Pipelines in the Tank Farm, with colour codes for specific products

Figure 10: Epoxy Wrapper on Pipe Section across a Bundwall

Figure 11: Cathodic Protection of a Storage Tank

Corrosion Management at the Gas Plant

The external corrosion protective coating of critical buried flowlines experienced premature coating failure in specific applications at a gas plant in Nigeria, shown in figure 12. This section looks at specific issues associated with the external coating's performance under high operating temperature conditions and continuing efforts to restore the integrity of these pipelines. The gas plant was commissioned as part of a master gas system to process the associated gas from oil wells. It has several underground pipelines as an integral part of the operation and their integrity will have direct impact on the plant's operations.

Figure 12: The Gas Plant in Eastern Niger Delta, Nigeria

External Coating Performance

Most of these flowlines are buried, with the fusion bonded epoxy (FBE) coating system as the primary method of external protection with impressed current CP systems installed at the wellheads providing supplemental protection. The FBE coating system applied on these flowlines had a temperature resistance of 210ºF and subsequently experienced premature failure to a varying extent, with respect to the temperature excursion and exposure.

Restoring Corrosion Protection

A comprehensive evaluation was conducted to determine external coating condition of these gas flowlines. The objective was to assess the condition of these pipelines, prioritize the pipelines for corrective actions and develop options to restore the integrity from external corrosion. As part of this evaluation, numerous bell holes were excavated to expose these pipelines for a meaningful assessment. The evaluation results confirmed that external coating experienced serious failure, leaving large sections of the surface bare. The root cause of the failure was the incompatibility of the coating system in terms of temperature resistance. Further evaluation revealed the coating to have deteriorated gradually with each temperature excursion. In fact, these flowlines have been used on an as needed basis to meet the production demand, mostly during the harmattan months to avail the maximum feed. However, the future mode of operation will require continuous use of these lines to meet the operational commitment.

Figure 13: External FBE coating failure on hot flowline (source: NACE Corrosion 2008 Paper 08044).

With the projected increase in operation of these lines, complete coating failure can be expected to occur much more rapidly, therefore, the probability of failure due to external corrosion was very high. Considering the operational criticality of these lines, higher operating pressure of 1,200 psig and the hazardous service, it was crucial to explore suitable corrosion protection options to restore the integrity of these lines as well as to extend the remaining life for continued operation. Several possible methods of providing external corrosion protection to these flowlines were reviewed and each of these methods appeared to be technically feasible. A conceptual design was prepared for each method with advantages and disadvantages including a preliminary cost estimate. Based on an in-depth study, two options were selected for further field trial, which include: rehabilitation of deteriorated external coating by new coating replacement and installation of polymeric anode in lieu of coating replacement.

Flowline A Rehabilitation

During 2008-2009, flowline A was exposed, which revealed serious coating failure. At this time, there were no coating systems available for rehabilitation to meet the temperature requirements of 250ºF. However, one manufacturer came forward to develop a new organic coating based on a phenolic system, which required plural component application. After the screening process, this new coating system was successfully applied in conjunction with the deployment of new line travel application technology.

Flowline B Polymeric Anode

During 2009-2010, installation of a polymeric anode system was also pursued as a new technology item, as an alternate option to coating rehabilitation. This option was based on the proposition that it would be more cost effective than the coating rehabilitation. This anode system was piloted on this flowline with an approximate length of 5 km. Due to the length of this flowline; the polymeric anode system was fragmented into four segments, each with its own transformer rectifier.

Corrective actions for the remaining flowlines were deferred pending a follow-up evaluation of these two options. Under these circumstances, the custody of these flowlines was transferred to the gas processing plants. As part of this reorganization, the plant received 13 out of 20 flowlines.

Evaluation Options

A thorough evaluation of these two options as well as the “Do Nothing” option was performed, the evaluation results highlighted below.

After the first coating rehabilitation of flowline A, several coating manufacturers developed coating systems, which include amine cured epoxy systems that can be applied with the conventional airless spray application.

The overall cost of the polymeric anode system, including design, material and construction turned out to be not cost effective as it was closer to the coating rehabilitation cost. In addition to specific design requirements, use of the polymeric anode system added additional workload in terms of CP monitoring. Further evaluation revealed the polymeric anode system could be an appropriate option, if the pipeline experienced limited coating damage. Furthermore, these flowlines intercept several inter-regional pipelines from other organizations and are bonded to each other. Therefore, all these pipelines are interconnected to each other in terms of CP. The CP design standards require bonding of crossing pipelines to mitigate interference corrosion. In this type of construction, the polymeric anode system can not function as a dedicated CP system for the concerned flowline. Moreover, in order to have a dedicated CP system, insulating flanges need to be installed at both ends of the flowline to ensure the polymeric anode system provides the required protection for the intended flowline. Furthermore, the structure-to-soil potentials from the existing conventional CP systems revealed adequate protection.

In consideration of the findings, coating rehabilitation was considered to be an ideal option for the remaining lines. Accordingly, a 4.5 km long flowline 593 was rehabilitated. During this rehabilitation, the soil conditions surrounding the pipeline were closely evaluated. The soil conditions were observed to be very rocky. Furthermore, large rocks were observed as part of the backfill. These can shield the CP and result in localized external corrosion at the locations, where coating had already failed. Therefore, the “Do Nothing” option may only serve as a temporary approach to defer the remedial actions and buy time to prioritize and plan for the permanent remedial action.

Based on these findings, rehabilitation of the coating has been identified as an ideal option for the external protection of these cross country flowlines. However, at the same time it is crucial to ensure the CP systems are healthy at the wellheads with sound bonding connections at the pipeline crossings.

However, the option of polymeric anode requires further evaluation on a case by case basis to determine the need for a dedicated CP system based on economic justifications and taking into consideration complications to other structures.

The external coating is a crucial aspect of corrosion protection and its performance at high operating conditions requires periodic comprehensive review to ensure safe and reliable operation. In general, most of these pipelines exist in buried conditions, which require close attention and timely revalidation.

Remedial actions planned should take into consideration recent developments in the industry in order to avail the best options that offer the least complexity. Based on our operational experience, a sound external coating system as the primary method of external protection with a healthy CP system as a secondary method of protection and an effective corrosion inhibition program to mitigate internal corrosion are crucial for long-term reliability. The above-to-below ground transition points also require special attention, especially at the asphalt/concrete areas, where a new technology involving nonmetallic sleeve application was introduced to enhance the external protection of transition points. Furthermore, by implementing periodic integrity management programs including new inspection technologies for corrosion assessment of these non-piggable lines, non-intrusive corrosion monitoring techniques, adapting to a management of change culture will add value to extend the life cycle of these critical flowlines.

Corrosion Management at the Refinery

The cause of the refinery (shown in Figure 14) corrosion is the presence of contaminants in crude oil as it is produced. Corrosive hydrogen chloride evolves in crude preheat furnaces from relatively harmless magnesium and calcium chloride entrained in crude oil. In petrochemical plants, certain corrosives may have been introduced from upstream refinery and other process operations, while other corrosives can form from corrosion products after exposure to air during shut-down: polythionic acids fall into this category. Corrosive contaminants are as follows:

- air
- water
- hydrogen sulphide
- hydrogen chloride
- nitrogen compounds
- sour water
- polythionic acids.

Severe corrosion problems can be caused by process chemicals, such as various alkylation catalysts, certain alkylation by-products, organic acid solvents used in certain petrochemical processes, hydrogen chloride stripped off reformer catalyst, and caustic and other neutralizers that, ironically, are added to control acid corrosion. Another group of process chemicals that are corrosive, or become corrosive, is solvents used in treating and gas-scrubbing operations. These chemicals are as follows:

- acetic acid
- aluminium chloride
- organic chloride
- hydrogen fluoride
- sulphuric acid
- caustic
- amine
- phenol.

Figure 14: Aerial view of the refinery

The oil and gas industry relies on chemical corrosion inhibitors to protect majority of its pipelines and facilities. These chemicals, which need constant replenishing, form a thin layer protecting the internal metal from the fluids it carries. Without them, corrosion would eat away at the insides of pipelines, meaning these inhibitors are vitally important to operations. Chemical inhibitors are injected into pipelines by means of 'chemical injection skids', which are collections of pumps, valves, filters and piping. But like all pieces of equipment, these skids are prone to break down. Breakdown in this case means the critical chemical does not get to the right place at the right time. The first sign of a problem is often when someone happens to notice that a pump is not working, or a chemical storage tank is empty.

For a process so critical in protecting its facilities, the terminal operator decided a new approach was needed. The result is the 'highly reliable chemical injection system'. The system is inherently reliable in two ways.

First, for all components that are prone to failure, standby parts are included so that when failure is detected, the spare kicks in to keep the inhibitor flowing. The addition of a twin or spare part means that the skid is available to inject chemical more than 99.5% of the time.

Second, instruments on the skid provide real-time data to a unique piece of proprietary software that helps chemists and engineers to manage corrosion more effectively. Users can see the condition of the skid and the injection rate from their desktops or laptops.

Furthermore, should inhibitor dosage fall below specified levels, users receive instant alerts by email, allowing them to rectify the underlying issue quickly. This level of data is allowing the assets to state with greater confidence that they are meeting their tough chemical injection availability targets – the amount of time that chemical is running through the pipelines.

The software shows chemists on their desktop the condition of the skid – whether the hardware is working; the dosage of the chemical at its delivery point; and the ratio between the chemical injected and the amount of production fluid in the process. The highly reliable chemical injection system has started to have a major impact, rapidly going from pilot to wide scale roll-out across the company's product storage and transmission division and on its new marginal field development project. All of her process facilities should benefit from the new approach to chemical inhibitor injection by the end of 2014. A technology that has proven successful in refineries will also go on trial at upstream operations over the next few years. The new permanently-installed waveguide wireless sensors can measure the thickness of a pipe or a vessel wall to a resolution of 0.1 millimetres. Any unexpected changes in the wall thickness alerts maintenance engineers to an unduly corrosive process.

Wall thickness has always been routinely measured at refineries as part of a corrosion monitoring regime, but never before has such consistent and regular information been available. Some points in the refinery can be hard to reach, meaning technicians would have to go out with harnesses and take readings from scaffolding. Several of the crudes used as feedstock were found to cause a higher rate of corrosion than others, thus necessitating a technique of running them without corroding through the side of the pipe. Without the permanent sensors, infrequent information readings would mean that engineers might not be able to identify with confidence the exact process or crude that had the most corrosive effect.

The waveguide wireless sensors have been permanently installed at Gelsenkirchen refinery in Germany and many refineries across the globe. Thousands more are set for deployment in the US, Europe and Australia. The success of the sensors in monitoring corrosion has led to the research and modification team trialling these and similar sensors with a view to deploying them in both downstream and upstream operations over the coming years.

Figure 15: The 'highly reliable chemical injection system' deployed at the refinery, providing real-time data to a unique piece of software that helps field personnel manage corrosion more effectively.[9]

The sensors were first developed by Peter Cawley's non-destructive evaluation group team at Imperial College, London. The department is concerned with solving real problems in industrial inspection and monitoring. At the same time, the operator was looking for permanently-installed monitors that could cope with temperatures above 800ºC (1,472ºF) and provide continuous readings. The basic idea of the sensors is like a metal handle of a saucepan; the sensor at one end and at the other end, it sits bolted to a pipe that reaches 800ºC. Over the 30 centimetre (12-inch) length of the waveguide, the temperature drops 800ºC with the cool end of the waveguide housing electronics that won't tolerate high temperatures contained in a bright orange box. The name waveguide is a clue to its shape, and is the key to its success. An ultrasonic pulse is transmitted along the length of the stainless steel waveguide and reaches the joint at the bottom. The pulse transmits into the pipe and then returns to the electronics contained in the orange box on the top, which wirelessly transmits the measurements to the corrosion engineer's desktop, thus achieving higher resolution and far better repeatability compared to manual measurements. This technology reduces human error and the wireless transmission capability gives a greater volume of data that enables him detect changes in operations with higher levels of accuracy.

The sensors do not do away with corrosion inspectors, but they are freed to devote their skills to higher-level tasks. Asset managers are now able to make better decisions on the time to replace process equipment and whether to accept crudes that have been shown to have an impact on asset integrity. This technology is a major breakthrough, giving refiners the ability to understand and actually see what is happening inside the pipe. A new company had been spun out of Imperial College which commercialised the technology, making the waveguide wireless sensors available for use by other operators interested in revolutionising corrosion management in their facilities.

A New Approach: Lessons Learnt from Hungary

According to a comprehensive NACE report it is estimated that about 40% of refinery maintenance costs are in association with corrosion caused failures. It is also indicated that 10 – 40% of the corrosion costs (according to the type of industry) can be avoided with operating appropriate corrosion management systems.[3] Moreover indirect costs of corrosion (Loss of Gross Margin – LGM) due to unscheduled unit shutdowns and environmental pollution can be even one magnitude higher then direct costs. Corrosion failures not only increase direct maintenance costs and indirect costs but are associated with high risk of accidents the frequency and severity of which has an increasing tendency worldwide.

It was realized that the ambitious profit goals of Hungary’s national refinery could not be accomplished without maintaining high asset availability by focusing on prevention and significantly reducing the frequency of corrosion failures. Refining management launched the 3A (Anti-corrosion Application and Actions) initiative and a Corrosion Team was established with the following targets:

1. Setting up effective corrosion management organizational structure for all the company’s refineries.

2. Supporting work of Maintenance by unified corrosion failure reporting, compiling central corrosion database and applying advanced corrosion monitoring and inspection techniques.

3. Elaborating methodology for calculation of valid costs of corrosion prevention and mitigation. Use SAP (ORACLE) for providing sound base for project type decisions about corrosion protection investments.

4. Dissemination of corrosion information and refinery best practices, raising knowledge level and commitment of employees by regular training and education.

The above strategic goals were then broken down into short and medium term action plans and development projects according to the actual corrosion management status of each refinery.[10] As was expected, after successful execution of the above projects corrosion caused failures as well as associated maintenance costs and risk of accidents were minimized with increase in profitability of refining. This should serve as a classic model for adaptation by other process plants on a case-by-case basis. The roadmap in figure 6 is thus recommended as an exemplary template.

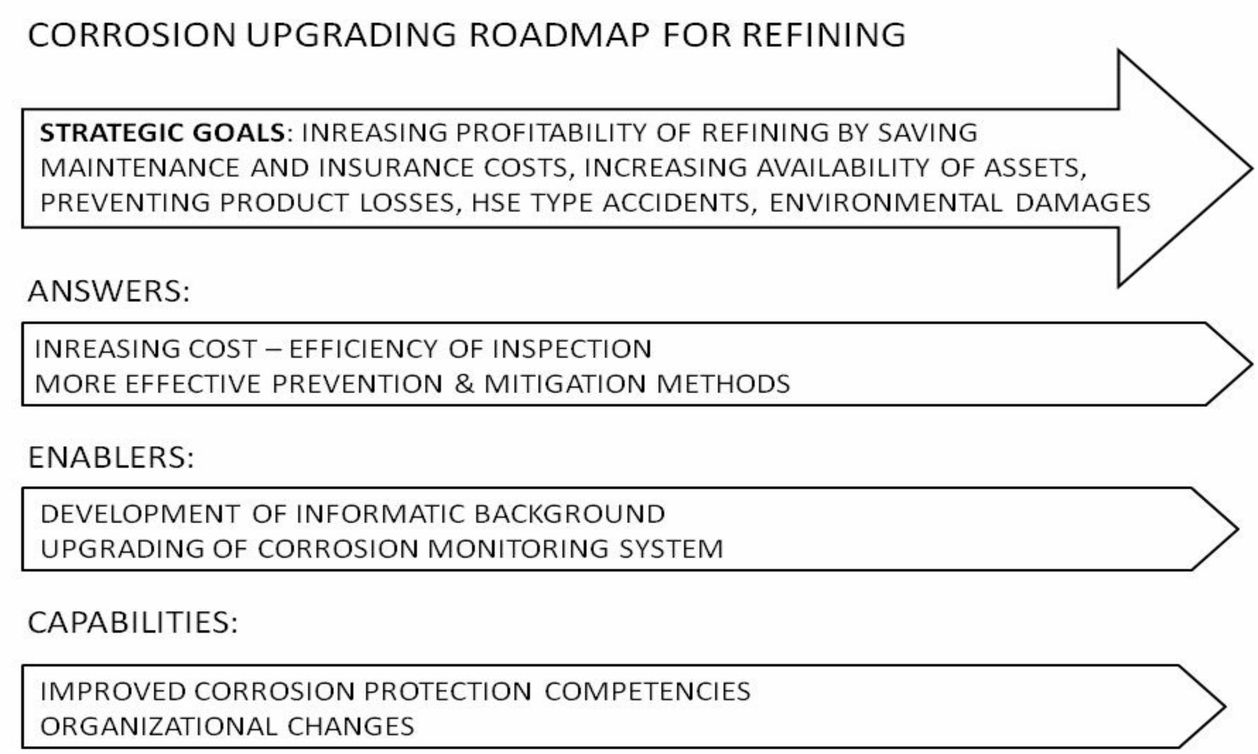


Figure 16: Part of the Refinery Corrosion Management Upgrading Roadmap[10]

Table 3: Comparison between Cathodic and Anodic Protection[11]

Galvanic Anode	Impressed Current
No external power	External power required
Fixed driving voltage	Voltage can be varied
Limited current	Current can be varied
Small current requirements	High current requirements
Used in lower resistivity environment	Used in almost any resistivity environment
Usually negligible interference	Must consider interference with other structures

Conclusion

Corrosion is truly a major industry but, unfortunately, one which is "in reverse." Its waste obliges all concerned to minimize or eliminate it in so far as possible. It is an undesirable phenomenon in all process facilities as its management is a costly venture. It should therefore be prevented as much as possible using the best available and sustainable technology (BAST) at any time. In any corrosion monitoring system, it is common to find two or more of the techniques combined to provide a wide base for data gathering. The exact techniques which can be used depend on the actual process fluid, alloy system, and operating parameters. Corrosion monitoring offers an answer to the question of whether more corrosion is occurring today as compared to yesterday. Using this information, it is possible to qualify the cause of corrosion and quantify its effect.

Although monitoring and inspection are essentially output measurements, they are critical to determining the effectiveness of a corrosion control program. Comprehensive monitoring tracks results in the short and medium term that are ultimately validated by a thorough risk – based inspection program. There is therefore need to collect, analyze and report data to keep both operations and maintenance personnel informed, enabling them work as partners to preserve system integrity throughout facility life. Available corrosion monitoring techniques range from the traditional (corrosion probes, coupon tests, copper-iron displacement, water analyses, and other non-destructive inspection methods) to more advanced, real-time techniques that may include technologies to accurately quantify metal loss or measuring parameters indicative of corrosion rate, such as hydrogen flux in sour environments. As no single approach provides a comprehensive analysis, operators and service providers must implement several and rely on the collective strengths of various techniques to compensate for individual limitations.

Robust and comprehensive corrosion prevention, control and management culture thus needs to be instituted and sustained in all existing and future process facilities in order to prolong the lifespan and usability of assets, as well as minimise operating expenses. This would greatly boost customer confidence and occupational convenience for personnel by improving the aesthetics of the facilities.

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