CORROSION & INTEGRITY MANAGEMENT: A NOVEL APPROACH TO SAFETY MANAGEMENT

O. Gasior[1], P. Farinha[2]
Curtin University of Technology, Perth, Western Australia[1]
Extrin Consultants, Perth, Western Australia[2]

SUMMARY: The effects of corrosion are easily recognisable at home with evidence of corrosion products or rust commonly found on everyday items such as tools and furniture; however, this form of general corrosion is of little consequence. Of far more consequence is how underlying and undetected corrosion can affect our lives (Health & Safety Executive 2001). The corrosion of steel reinforcing, for example, can significantly impact on the loading capacity of reinforced concrete (RC) thus significantly increasing catastrophic failure of bridges, tunnels and other retaining structures (Davis 2000, 3). The flow on effects, which are primarily economic in nature, cost approximately $30.0 billion per year as (Jones 1996, 3; Davis 2000, 10) direct result of; plant downtime, loss of production, loss of efficiency, overdesign of structures (i.e. increased corrosion allowances) and contamination of goods (Jones 1996, 3; Davis 2000, 10).

Corrosion can take an even more significant toll of human health and safety, for instance, the accident in Bhopal which claimed the lives of 3000 people (Roberge n.d) and more recently the Varanus Island explosion which did not result in any death of any person but there were many lessons which need to be learned from this accident (West Australian Department of Mines and Petroleum 2009). Implementing a Corrosion and Integrity management plan will result in the reduction/elimination of corrosion related damage of assets and assist in compliance with regulatory requirements, improvement in safe operations and decreased repair cost (Rahim, Refsdal, and Kenett 2010, 93).

Keywords: Process Safety, Corrosion, Integrity, Corrosion Management

1. INTRODUCTION

The word 'Corrodere' is Latin in origin and can be loosely defined as "to gnaw to pieces"; consume by chemical action as in the oxidation or rusting of a metal; to eat away or be eaten away (Davis 2000, 2). It is the originator of the English word 'Corrosion' which today can be defined as the destructive chemical reaction between a metal alloy and a reactive environment (Jones 1996, 5). For instance, consider the deterioration of jetty piling. The steel piles corrode due to the reaction of the marine environment (i.e. highly oxygenated seawater) however, water velocity, temperature, chemical composition and microbial content need to be considered given that all of these parameters will affect the aggressiveness of corrosion.

From a chemical perspective, corrosion can be most simply defined by the process of oxidation and reduction (Redox) the equations are as follows:

$$Fe(s) \rightarrow Fe^{2+}(aq) + 2e^- \text{ (Oxidation – Anodic reaction)} \qquad (1)$$

$$O_2(g) + 2H_2O(l) + 4e^- \rightarrow 4OH^-(aq) \text{ (Reduction - Cathodic reaction)} \qquad (2)$$

2. DISCUSSION

2.1 Common Corrosion Mechanisms

Corrosion is the chemical degradation of metals as a result of their reaction to the surrounding environments (Jones 1996, 5). In some instances corrosion results in failure of components when the dissolution of material is so significant that the remaining structure cannot support the applied loads; alternatively corrosion creates susceptibility to failure by some other mode (e.g. fatigue) (Findlay 2002). There are various forms of corrosion that exist, each of which poses different problems to structures. The most common types of corrosion observed are discussed below.

2.1.1 Uniform Corrosion

Uniform attack is considered the most common form of corrosion. This form of corrosion is typically characterised by a chemical reaction that proceeds uniformly over the entire surface or over a large area. The metal becomes thinner and eventually fails. Uniform attack represents the greatest destruction of metal on a tonnage basis (Fontana 1978, 39).

2.1.2 Galvanic Corrosion

Galvanic corrosion occurs when dissimilar metals are in direct electrical contact in a corrosive environment (Findlay 2002). Any alloy that is less noble/positive that is coupled to an alloy with more noble potential in the Galvanic Series preferential corrosion will occur at the more negative or anodic site while the positive or cathodic material is protected from corrosion (Jones 1996, 11; Fontana 1978, 41).

2.1.3 Crevice Corrosion & Pitting Corrosion

Crevice corrosion is localised corrosion that occurs within crevices on metal surfaces exposed to corrosives. This type of attack is usually associated with small volumes of stagnant solution caused by holes, gasket surfaces, crevices under bolt and rivet heads.

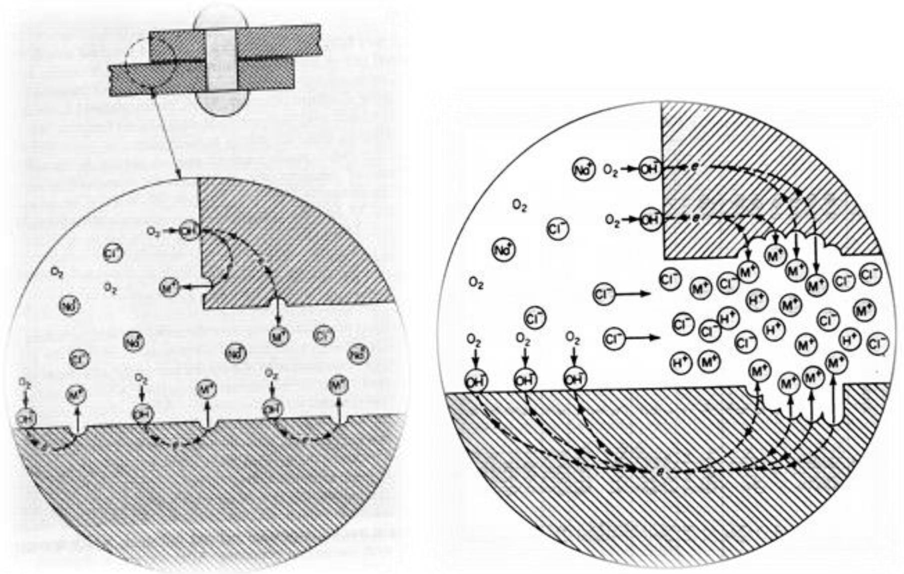

Figure 1 Diagrammatic depiction of the chemical reaction that occurs within a crevice (Fontana 1978, 54, 55).

Crevice corrosion can be explained by the following oxidation and reduction reactions

Oxidation: $M \rightarrow M^+ + e$ (3)

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

Initially these reactions occur uniformly over the entirety of the surface, including the interior of the crevice. Every electron produced during the formation of the metal ion is immediately consumed by the oxygen reduction reaction (Figure 1). Also one (1) hydroxyl (OH-) ion is also produced for each metal ion in solution. As the available oxygen is used up the oxidation reaction will no longer occur, although the dissolution of the metal will continue as shown in the figure above (Fontana 1978, 53).

Secondary reaction: $M^+ Cl^- + H_2O = MOH + H^+Cl^-$ (5)

The equation above shows that a typical metal chloride will dissociate into an insoluble hydroxide and a free acid. Both hydrogen ions and chloride ions accelerate the metal dissolution rate of most metals and alloys (Fontana 1978, 53).

2.1.4 Corrosion Fatigue

A frequent cause of the premature fracture of structural components is corrosion fatigue cracking (CFC). CFC occurs under cyclic stress conditions while under the influence of a corrosive environment and is characterised by brittle fractures within the alloy while the overall visible corrosion remains low. Both alloys and pure metals are susceptible to CFC and do not require specific electrolytes to occur in (Jones 1996, 17; Fontana 1978, 139).

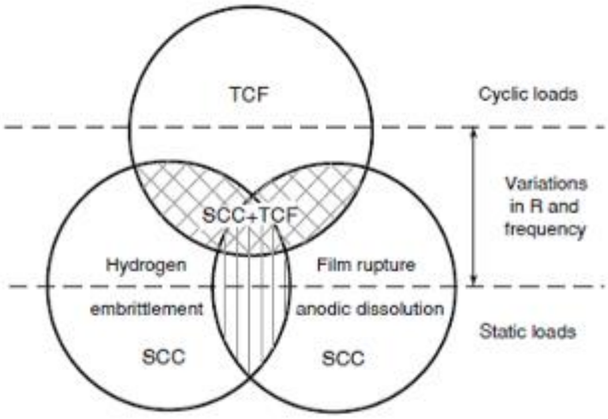

Figure 2 Venn diagram illustrating the interrelationship among stress corrosion, corrosion fatigue, and hydrogen embrittlement (Milella 2013, 795).

2.2 Case Studies

2.2.1 Bhopal

In 1984 Union Carbide India Limited (UCIL), an industrial chemical production plant, had a significant failure of their safety systems which lead to the release of toxic material known as methylisocyanate (MIC) into the nearby town which caused the death of 3,000 people and injured thousands more (Roberge n.d). The disaster occurred when water inadvertently entered the 40 ton MIC storage tank. The inclusion of chloroform and corrosion product resulted in an uncontrollable production of gases. Furthermore, several shortcomings in the reliability of safety and monitoring systems in place such as pressure gauges and the gas scrubber flare stack, which contributed to the disaster (Roberge n.d).

2.2.2 Aloha Airlines

In 1988 the catastrophic failure of Aloha Airline 19 year old Boing 737 during a routine flight raised major speculation on ageing aircraft within the public & aviation community. The disaster occurred when the upper portion on the fuselage was lost at 7,300 meters above sea level; one flight attendant was swept from the plane. Investigators determined that the cause of the sudden failure was fatigue cracking localised along all of the lap-joints. A build-up of corrosion product between the joints prised the rivets apart significantly weakening the structure (Roberge n.d).

2.2.3 Varanus Island Explosion

In June 2008 several high and low pressure gas pipelines ruptured due to the initial rupture of the 12 inch export sales gas pipeline (SGL). The 12 inch line located within the tidal region of Varanus islands shore line was discovered to have thinned significantly due to poor coating adhesion and poor cathodic protection performance. Due to these factors, the pipe was no longer able to withstand the operating pressures and subsequently ruptured and exploded. Although no fatalities were recorded the disaster still cost over $60 million in property damage, and cost the Western Australian economy $3 billion in lost revenue (West Australian Department of Mines and Petroleum 2009).

2.3 Why Do We Need Corrosion Prevention

Workplaces within Australia are guided by the Australian Work Health and Safety Act of 2011, The Mines Safety and Inspection Act 1994 and the Offshore Petroleum Act of 2006. Each of these document places a requirement on the duty holder to provide and maintain a safe and health workplace and to ensure the integrity of equipment and plant so that to facilitate safe operation (Health & Safety Executive 2001). In hazardous environments i.e. petrochemical and some mine processing plants, this is of greater consequence given that aggressive corrosion can result in severe failures impacting on safety, the environment and asset value (Health & Safety Executive 2001).

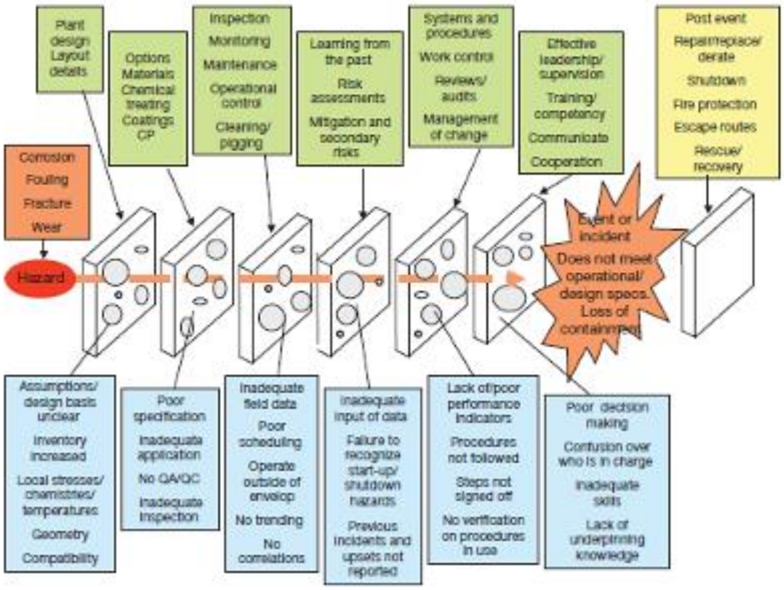

Figure 3 'Swiss Cheese Model' from a corrosion perspective. Shows how incorrectly implemented Soft & Hard controls can lead to catastrophic failures (Dawson 2010, 3035).

Over the past decade industry has focused significant resources on occupational safety which has resulted in the significant decline in incidents. However, occupational safety primarily covers topics as protective clothing, tripping hazards and safety interactions; these issues mainly resulting in near misses or minor injury (Sutton 2010, 18). Of far more consequence are issues such as fires, explosions, and the release of toxic gases (Health & Safety Executive 2001). In many instances corrosion and or integrity issues are commonly the primary causative mode of failure when plant and equipment catastrophically fail (Davis 2000, 4). Recent studies have shown that there has been a steady improvement in occupational safety in the process industries, however, despite the progress made there has been a lower rate of reduction in the number of major accidents observed in the Unites States or Europe. Simply put, improvements in occupational safety within the last decade have not impacted as positively on process safety as was anticipated (Sutton 2010, 19).

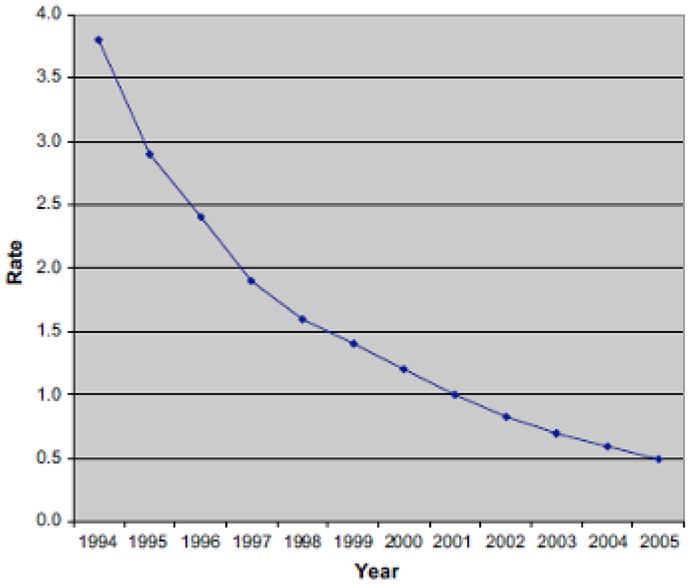

Figure 4 Trending of occupation health and safety data over an 11 year period (1994-2005), the data shows a steep initial decline however plateauing toward the later years (Sutton 2010, 23).

Within literature there are numerous reports of catastrophic events which have been linked to corrosion or integrity failures such as Bhopal (3000 fatalities) (Roberge n.d), Flixbourough (28 fatalities) (Roberge n.d), Guadalajara (215 fatalities) (Roberge n.d) and more recently the Varanus Island explosion (West Australian Department of Mines and Petroleum 2009). The Pipeline & Hazardous Materials Safety Administration (PHMSA) has reported that from 1993 to 2012, corrosion and integrity related failures have resulted in over 293 injures, 43 fatalities and has caused over 2.5 billion dollars (USD) in property damage (Pipeline & Hazardous Materials Safety Administration 2012).

To ensure the safety of personnel predictive maintenance should be conducted to prevent significant deterioration which has the potential to threaten health and safety (Rahim, Refsdal, and Kenett 2010, 89). Qingfeng et al. (2011, 329) recommend that approximately 30% of resources should be allocated to each form of maintenance i.e. breakdown, preventative and predictive maintenance.

When maintenance is not carried out soon enough or is incorrectly carried out, the plant may fail dangerously during normal operations phase (Hale et al. 1998, 22). Current research suggests that the traditional allocation of maintenance resources is heavily biased toward breakdown maintenance (67%) (Qingfeng et al. 2011, 329). Within industry, maintenance activity is connected with a significant proportion of the serious accidents. Hale et al. (1998, 21) also state that within the chemical industry alone, 30% of serious incidents were linked to maintenance activities, taking place either during maintenance or as a result of faulty maintenance. Furthermore, the Health Safety Executive (HSE) went on to state that out of 900 accidents they had found that 39% have occurred while conducting maintenance on faulty/corroded pipework (Hale et al. 1998, 21).

Therefore to maximise the efficiency of maintenance proper asset maintenance requires proactively planned maintenance programmes such as a Corrosion Safety and Integrity program (CS&I) (Health & Safety Executive 2001). These programs are often faced with resistance by management given they are invasive, costly and detract from production. Appropriate strategies allow for maintenance to be conducted at planned intervals which reduce the overall operating costs and significantly improve safe operation of the plant (Rahim, Refsdal, and Kenett 2010, 89).

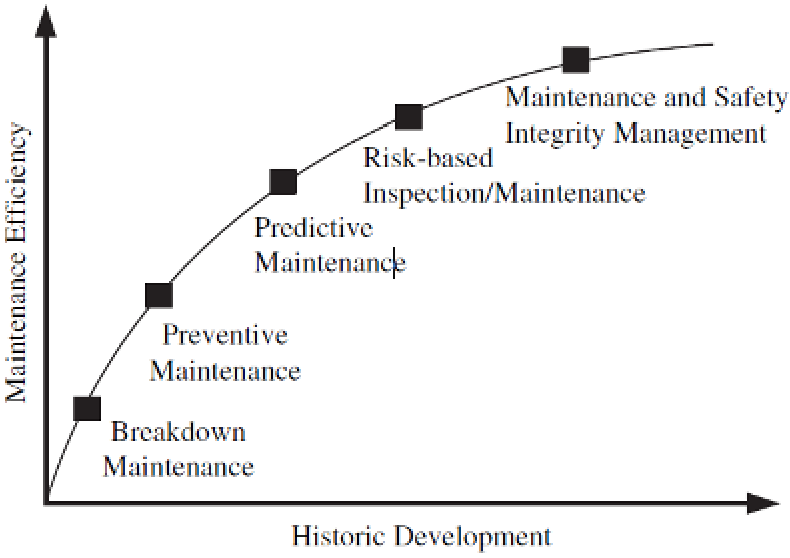

Figure 5 Efficiency of Maintenance increased dramatically with increasing impetus on safety and integrity management (Qingfeng et al. 2011, 322).

2.4 Corrosion, Integrity and Safety Management

In the operation of any processing facility, the management of corrosion lies with the duty holder's organisation, and in some instances can extend to contracting organisations (Health & Safety Executive 2001). Therefore there is a great importance when carrying out maintenance activities that they are done so in a structured and measured manner, and foremost, the roles and responsibilities of individuals are easily understood by all parties involved (Health & Safety Executive 2001).

The following framework is basic model developed by the HSE in order to establish a management plan that will ensure that best industry practice is achieved.

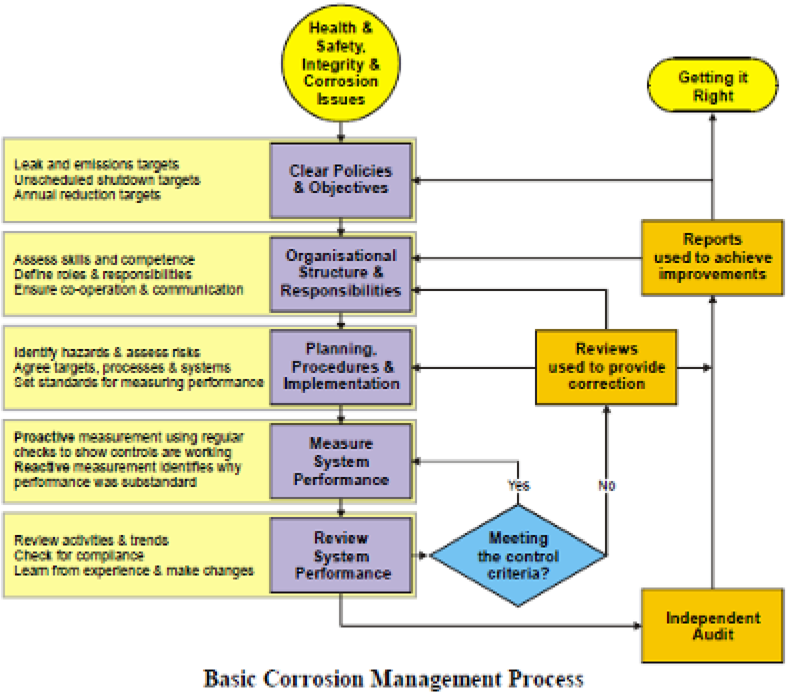

Figure 6 Basic HSE framework of corrosion, safety and Integrity plans showing how feedback loops are implemented which Facilitates continuous improvement (Health & Safety Executive 2001, iv).

2.4.1 Policy and Strategies

The Corrosion Policy is a statement that specifies how major process or operational issues should be dealt with over the long-term. The policy will form the foundation for the subsequent details in regard to the structure of the organisation, the strategies implemented, the performance standards, procedures and other managerial processes (Health & Safety Executive 2001). All companies should have policies and strategies that ensure that all hazards and risks associated with safety, health and environment are mitigated, however the majority of companies do not have written corrosion policies and strategies with corrosion management practice implied into their planning process (Health & Safety Executive 2001). The lack of a written policy may mean that actions to mitigate corrosion are ineffective and more often than not will lead to a poor "corrosion culture" at both managerial and operational levels (Dawson 2010, 3003).

2.4.2 Organisational Structures

Maintaining the safety of personnel, plant and equipment should be paramount in any organisation and the duty to ensure safety extends to everyone; employer, employee and contractor alike (Health & Safety Executive 2001). The effectiveness of any policy will be strongly linked to the leadership and involvement of managers and senior staff. To attain a positive corrosion culture, there are five pillars which form the major indicators for evaluating the state of corrosion management. The five pillars are Competence, Compliance, Coordination, Communication and Control (Rahim, Refsdal, and Kenett 2010, 89).

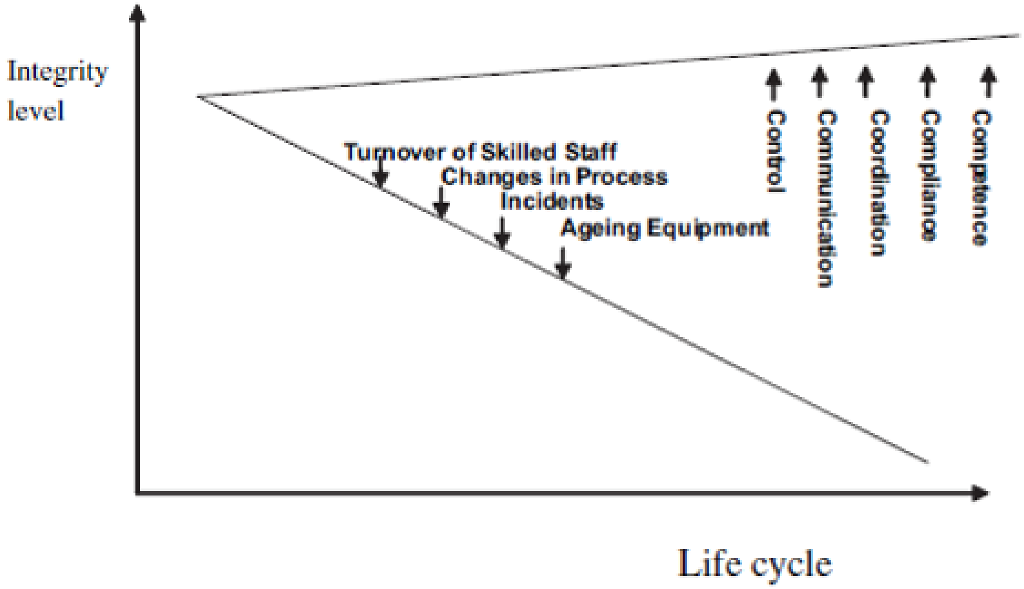

Figure 7 Application of the 5c's will ensure for high integrity of plant and equipment across the total life cycle (Rahim, Refsdal, and Kenett 2010, 93).

Table 1 - The 5c's adapted from the 5C model: A new approach to asset integrity management (Rahim, Refsdal, and Kenett 2010, 90-92).

Pillar	Descriptor
Competence	Individual's abilities (knowledge, skill & physical capabilities) need to align with the task. Ongoing training of individuals promotes continuous improvement
Compliance	Safety and Integrity are reliant on organisation meeting local regulatory standards and industry best practice
Coordination	Planning interaction between the organisation and contraction personnel needs to be communicated efficiently. Having trusted quality contractors will maximise opportunities for safe operation.
Communication	Regular communication is essential for corrosion safety management as it mitigates corrosion breakdowns and improves the safety/corrosion culture.
Control	Corrosion can be curbed by implementing strategic control measures i.e. coatings, inhibitors or cathodic protection. Verification of these controls is crucial to ensure safety, integrity of plant and personnel.

2.4.3 Planning and Implementation

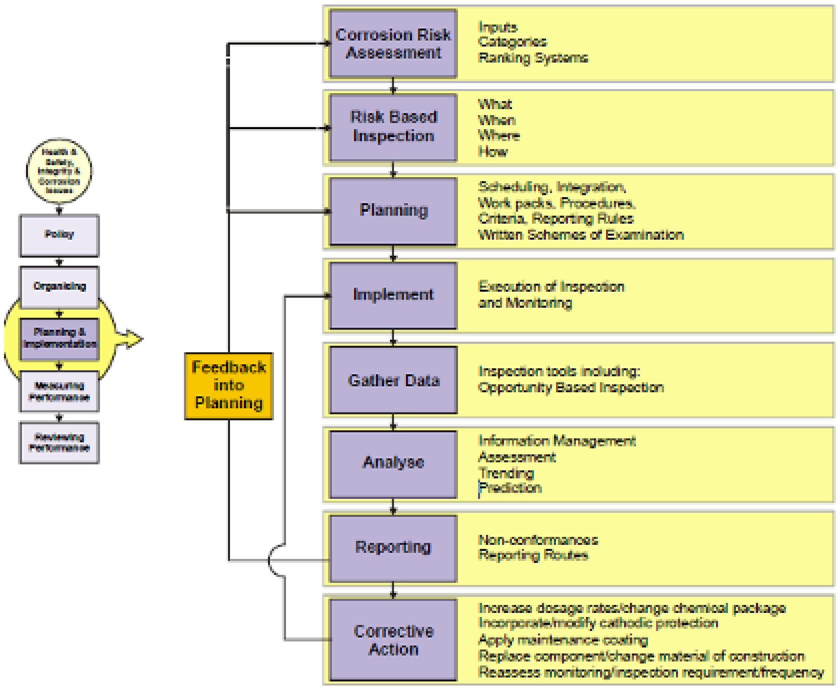

Figure 8 Planning and implementation of the corrosion policy and procedures (Health & Safety Executive 2001, 18).

Long-term objective based strategies are the basis for any effective corrosion management plan. Therefore corrosion risks need to be compared against these objectives when implementing and planning corrosion control activities (Health & Safety Executive 2001). Planning should first commence with the identification of critical plant items which are at significant risk of degradation, priority items will be more inspected and maintained on a more rigorous schedule as compared with low risk items (Sutton 2010, 82). A primary source of evaluation of risk is a Risk Assessment, in this instance, a Corrosion Risk Assessment. All risk assessments have a number of well-defined steps which provide extensive insight into the risks and how these risk impact on the day to day operation and safety (Dawson 2010, 3007).

2.4.4 Identification

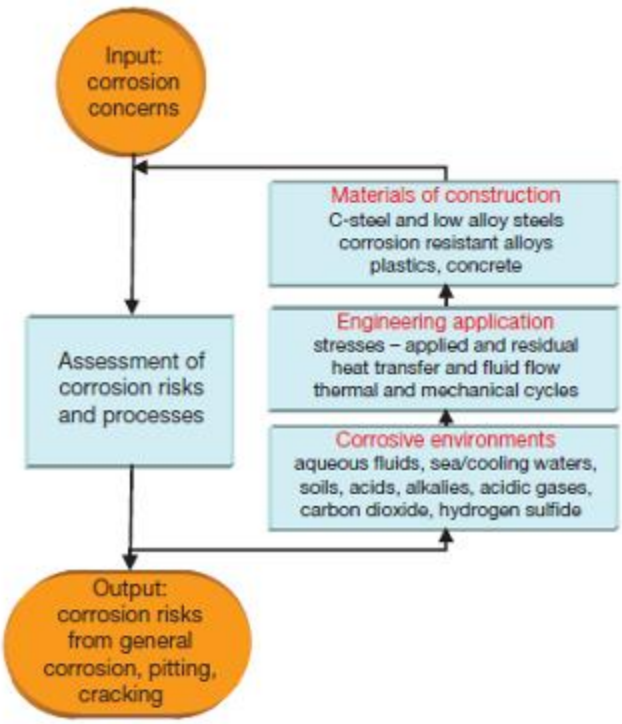

Figure 9 Identification and assessment of corrosion risks (Health & Safety Executive 2001).

The first step in any risk assessment is the identification the source of degradation (hazards) that may be sustained by structures and equipment (Health & Safety Executive 2001). The risk assessment should recognise the potential corrosion mechanisms (Section 2.1 – Common Corrosion Mechanisms) that could potentially affect integrity issues. As well as the predominant corrosion mechanisms at play, careful consideration of the corrosive environment, the type of material used and also the physical forces applied to the structure/equipment must accompany the assessment (Dawson 2010, 3012).

The second step within the corrosion risk assessment is to analyse and evaluate the risks which have been identified in order to ascertain whether or not the risk is at an acceptable level or not (As Low as Reasonable Practicable) (Dawson 2010, 39). In the simplest form qualitative assessments, such as the use of 5x5 matrices, are used to determine the probability of failure and the consequence of such failures. However higher risk industries will tend to use a more quantitative approach based on experience RBI (Risk Based Inspection) HAZOP (Hazard and Operability) or logical and analytical techniques such as Fault Tree methods or FMECA (Failure mode, effect and Criticality Assessments) (Sutton 2010, 85).

After the all of the information has been compiled and analysed, the most appropriate corrective actions need to be employed and put into place (Health & Safety Executive 2001). Depending on the type of facility and the extent of damage, the tactics used will vary however generally speaking if the risk is too high efforts in reducing the frequency or consequence are needed (Sutton 2010b, 86). There are a variety of methods available that can be used to achieve compliance and reduce the risk of corrosion and can comprise of one or a combination of controls as listed in Table 2 (Health & Safety Executive 2001; Dawson 2010, 3022; Davis 2000, 8)

Table 2 Table listing possible corrosion control options adapted from ASM and HSE (Davis 2000, 7-9; Health & Safety Executive 2001, 32)

Controls Available	Possible Considerations
Materials Selection	C-Mn steels, CRA, non-metallic
Chemical Treatments	Inhibitors, biocides O_2 scavengers
Coatings	Organic coatings, metallic, linings
Cathodic/Anodic Protection	Sacrificial Anode Cathodic Protection (SACP), Impressed Current Cathodic Protection (ICCP)
Design	QA/QC and inspection procedures
Process Control	Identify key parameters – pH, temp, pressure

2.4.5 Monitoring and Performance Evaluation & Reviews

Ongoing checks on the system should be conducted at predetermined stages of the following well established performance based standards or Key Performance Indicators (KPIs). These roles should be delegated to suitably competent persons who are not under the pressures of production (Health & Safety Executive 2001). Ongoing checks and reviews ensure that management procedures and processes are consistent with the changing requirements in production and legislation. The overall aim or performance measure of a management programme is to reduce incidents to as close to zero as possible, the system is therefore never-ending because there are always methods of improving safety, health, and operability (Sutton 2010, 18). Therefore a good CS&I plan must be a ‘live’ document that can adapt to changes over the assets life (Rahim, Refsdal, and Kenett 2010, 93).

2.4.6 Corrosion Management Audits

Audits are an essential check which provide evidence that the corrosion management system is effective and reliable given that all control measured deteriorate overtime (Health & Safety Executive 2001).The Corrosion Management Audit, which is generally conducted by an independent party, ensures that procedures are being implemented accordingly and provides information on how effective components of the Corrosion and Safety management system are being implemented (Health & Safety Executive 2008). Furthermore, audits ensure the organisation is continually improving to meet stringent OHS requirements.

Information on how the management system is performing can be obtained from three main sources (Health & Safety Executive 2008)

- Interviews
- Document review
- Visual observations

The following is an example of how a visual audit can distinguish between a well implemented corrosion management programmes against a poorly maintained plant.

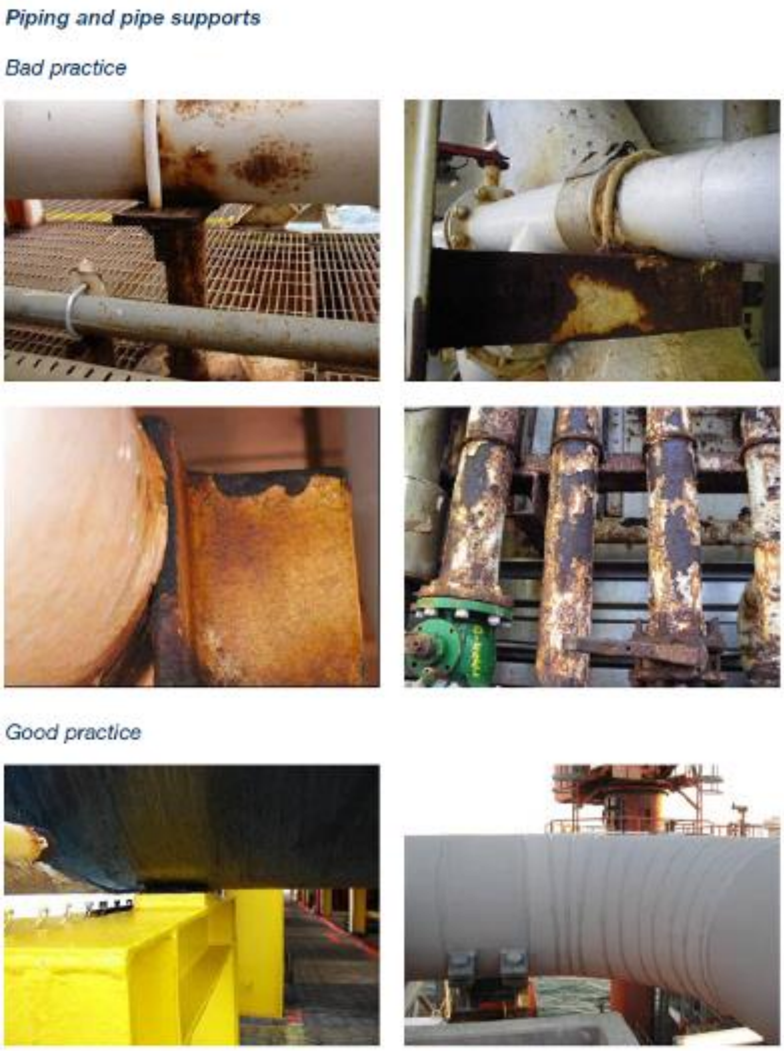

Figure 10 Example of good versus poor implementation of corrosion controls observed during a visual audit conducted by the HSE. (Health & Safety Executive 2010, 23)

3. CONCLUSIONS

Over the past few decades, there have been numerous reports on how major incidents which have claimed the lives of many which have stemmed from poor maintenance practices (Rahim, Refsdal, and Kenett 2010, 93), where maintenance procedures were often focused on breakdown maintenance (Qingfeng et al. 2011) or not conducted at all (Hale et al. 1998, 22). Throughout history there have been incidents which have garnered significant media attention such as Bhopal, the Aloha incident and the Varanus explosion. Despite the scrutiny, industry at large continues to observe poor equipment performance and shorter asset life and ongoing safety concerns as a result of corrosion. Reoccurring corrosion issues poses the question, is industry learning from its mistakes (Dawson 2010, 3035)?

The Corrosion and Safety Management plan outlined above provides a framework that highlights the importance of having effective plans to control, monitor and review corrosion control measures to secure health and safety of personnel (Health & Safety Executive 2001). The effect, therefore, of implementing appropriate Corrosion Management Systems that result in the reduction and/or elimination of corrosion related damage of assets not only assists in compliance with regulatory requirements (Health & Safety Executive 2001)but also leads to improved operation efficiency, improved safe operations and decreased repair costs (Rahim, Refsdal, and Kenett 2010, 93). Furthermore, the knowledge gained benefits organisations by implementing real solutions cost effectively, rather than focusing of an undefined problems and causes (Rahim, Refsdal, and Kenett 2010, 93).

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5. AUTHOR DETAILS

Oliver Gasior has been involved in the Corrosion Industry for the past 5 years focusing on failure analysis and applying mitigation strategies for clients to best deal with the long term integrity of assets. He has been the Project Manager on numerous projects, involving client and contractor liaison, regular status reporting, technical support to Cathodic Protection (CP) system inspection & assessment, project design and quality control, in addition to major other CP design projects.

Specifically trained in OHSE, Oliver is responsible for all internal safety issues and work procedures which the engineering team work toward. Over the past year Oliver has been working toward attaining AS: 1480 Safety Management certification by developing and improving upon the organisations' Safety Management Plan, Injury management policies, return to work policies and procedures

As a specialist qualified Corrosion Engineer, holding both a MSc and PhD in Corrosion Engineering, Dr. Peter Farinha has been involved in identification and problem solving of corrosion related issues in steel corrosion and reinforced concrete including inspection, identification, failure analysis, materials selections, coatings, specification and repair methodology for over 30 years.

He is a specialist in Microbiological Corrosion related issues, having gained his PhD in the corrosion of steel piling by sulphate reducing bacteria in ports and harbours in 1982.