Corrosion Cost and Impact

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1 Background

The Australian Corrosion Association (ACA) is a not-for-profit association that disseminates information on corrosion and its prevention or control by providing training, seminars, conferences, publications and other activities. The ACA commissioned Resona to investigate the impact corrosion has on a range of Australia's and New Zealand's national infrastructure assets. The ACA's mission is to reduce and mitigate the effects of corrosion in Australasia. By undertaking this report, the ACA is aiming to elevate the discussion around the timely, cost effective prevention of corrosion while highlighting the annual financial impact corrosion has on our national assets. The overall objective is to provide a resource that will help ensure corrosion is managed sustainably and cost effectively to ensure the health and safety of the community and protection of the environment.

Research from NACE International[1] indicates that the effects of corrosion can contribute between 3.5 per cent to 5.2 per cent (average of 4.35%) of global gross domestic product. If these results are extrapolated for Australia's GDP[2], this equates to a high estimate of $78 billion per annum being spent on remediating assets affected by corrosion. While New Zealand has a smaller economy[3], using the same estimated impact, the cost of corrosion is approximately $NZ16 billion. The NACE study postulates that using "available corrosion control practices, it is estimated that savings of between 15- 35% of the cost of corrosion could be realised (i.e. between US$375 and $875 billion annually on a global basis).

Corrosion occurs in many sectors. While the NACE research identifies the estimated total cost to a country, the actual costs are borne by various sectors within each country. This study has prioritised the following sectors as being prone to corrosion-related issues, and therefore to costs:

- Oil and Gas
- Water and Wastewater
- Construction and Infrastructure
- Defence

Other sectors may be subject to corrosion and the associated costs to maintenance/ repair, such as the automotive and agricultural sectors. As there is relatively limited data published regarding the costs in these sectors, they may be the subject of future investigation.

2 Executive Summary

There are various methods that can be used to calculate the cost of corrosion to the economy as a whole or to any sector within the economy. Each method incorporates varying complexity, and each risks inclusion or exclusion of cost components such as indirect or remedial costs.

In the Oil and Gas industry, corrosion impacts on pipelines, refineries, and petrochemical plants. It is generally caused by water, carbon dioxide and hydrogen sulphide, and can be aggravated by microbiological activity. The costs associated with corrosion can be grouped as follows:

- The loss of the oil or gas product
- Direct costs (e.g. design, cost of inhibitors)
- Indirect costs (e.g. plant shutdowns, maintenance labour)
- Remediation costs

Calculation of the costs of any of these components is complex. There is minimal data in the literature that measures the costs to the economies of Australia or New Zealand. In Australia, the cost of corrosion mitigation and repair in the Oil and Gas industry was estimated in 2013 to be $A20 billion[12].

Water and Wastewater infrastructure is extensive across both Australia and New Zealand. The causes of corrosion in the water and wastewater industries vary based on both the material used in the infrastructure and whether that infrastructure is used for water or wastewater.

In Australia, the value of sewer infrastructure in 2001 was estimated to be worth $A28 billion[20]. The New Zealand stormwater infrastructure has an estimated replacement value of $NZ8.6 billion, while the wastewater infrastructure has an estimated replacement value of $NZ15.8 billion.

In Construction and Infrastructure, corrosion rates vary considerably based on geographic factors. Latitude and distance from the coast are the primary causes of variation, while vegetation, humidity and landforms all have an effect. In New Zealand, building codes vary based on the perceived corrosion risk.

There are no comprehensive details associated with the costs associated with corrosion. The cost of corrosion-related maintenance of infrastructure (e.g. bridges) in Australia is currently estimated to be $A8 billion[4]. This does not include the cost of corrosion to housing.

Steel and reinforced concrete are the primary materials that are at risk of corrosion in major infrastructure. Bridges are commonly identified in the literature as being at risk of corrosion. In New Zealand, in 2004, a bridge that was constructed from precast pre-tensioned concrete was found to have corrosion in the steel. Following investigation of the structure, a further 137 bridges were identified as being at risk, with corrosion subsequently found in 29 bridges. Other infrastructure at risk of corrosion includes electricity transmission lines, dams, water storage tanks and diversion walls. The costs associated with identification and remediation in any one situation are likely to be in the millions, or tens of millions.

In housing, there are a range of corrosion risks including fasteners, roofing and joinery.

Corrosion poses a severe threat to the operational readiness of defence forces. A cost analysis of corrosion prevention was conducted on four RAN frigates. Depending on the costing method, the cost of corrosion across the RAN in 2015 was between $A137 and $A242 million[64]. The RAAF has planes with a range of ages. Older airframes can suffer from corrosion that leads to nonconformance. The cost of corrosion over a two-year period was $A2.49 million. For new airframes, improved components incorporating carbon composites are causing significant issues due to galvanic corrosion around metallic fasteners.

3 Methods of Cost Calculation

There are various methods that can be used to calculate the cost of corrosion to the economy as a whole or to any sector within the economy. Each method incorporates varying complexity, and each risks inclusion or exclusion of cost components such as indirect or remedial costs. When considering the total cost of corrosion to the sectors of the Australian and New Zealand economies, it is important to note that different sources are likely to have implemented different costing methods, and as a result, a meta-analysis of these data may lead to data with a notable but indeterminant margin of error.

For calculation of corrosion costs, there are a range of factors that need to be considered. Across all sectors that are included in this study, there is a pre-determined economic life for There are a range of methods that can plausibly be used to measure the total cost, as outlined in Cassidy (2015)[5]. This paper identifies a range of cost methods used in identifying the total cost of corrosion. While the article is written from a military perspective, the cost options can generally be applied to other sectors.

None of the methods are particularly accurate in measuring the indirect costs of corrosion. These may be significant in situations where the corrosion has resulted in a failure of infrastructure, where the failure has led to environmental damage, the need for use of alternate infrastructure, or in extreme events, the loss of life.

3.1 Input/ Output

This approach is a general equilibrium model; and is used by the US National Bureau of Standards. In this model, each aspect of production is rated as the proportion of total costs for $1.00 of output – effectively identifying the percentage of output that is attributable it each input. The value for each input is called the coefficient.

Each input coefficient is adjusted to identify the proportion of cost that is specifically related to corrosion. For example, the cost of the protective coating on a steel pipe is only present to mitigate the risk of corrosion. Therefore, the cost associated with the coating is removed from the coefficient for piping. Once all modified costs associated with corrosion have been removed, the coefficients are adjusted to add to $1.00. This cost represents the cost for the product in the absence of corrosion.

The primary drawback of this approach is the ability to identify the cost of the mitigation associated with corrosion prevention as part of each coefficient. Indirect costs are not measured. The variability in cost associated with sourcing the various cost coefficients may vary based on unrelated variable factors (such as transportation). As a result, there will always be variability in the data for each coefficient, making this approach less than ideal.

3.2 Net Present Value

This approach was used by NACE when assessing corrosion costs in the USA across 26 industry sectors. Costs generated using the Net Present Value approach are based on three stages:

(1) Determination of the cash flow for corrosion related activities

(2) Calculation of the present value of the cash flow

(3) Calculation of the annualised equivalent rate

The drawbacks of the approach include the lack of inclusion of training, facilities, and test equipment. Indirect costs are also not included.

3.3 Top-Down

This approach has a starting point of identification of all annual cost associated with an output. As this is the total cost, the cost of corrosion management and maintenance must be lower than this. The costs associated with the output that have nothing to do with corrosion are removed. This provides an efficient assessment of the cost of corrosion, without the need to identify all the costs that are directly or indirectly associated with corrosion. While the approach is reasonably simple to implement, it cannot identify the drivers associated with the cost of corrosion.

3.4 Bottom-Up

This approach aggregates all costs associated with individual corrosion events, including corrosion-related labour, and material costs components of the events. The starting point is to measure all maintenance activity, then separating corrosion-related maintenance from other maintenance activities. Other direct costs are also allocated.

While this approach is comprehensive, it is time-consuming to manage, and presumes all relevant labour and material costs can explicitly be allocated to corrosion maintenance in any one project.

4 Oil and Gas

4.1 Causes and Management of Corrosion

Corrosion is an issue which is encountered in many stages of the oil and gas industries, including oil and gas pipelines, refineries, and petrochemical plants. Corrosion in oil and gas industry is usually caused by water, carbon dioxide (CO_2) and hydrogen sulphide (H_2S). It can be aggravated by microbiological activity[6].

4.1.1 Pipelines

Pipelines used in oil and gas processing operate in an environment that differs significantly from pipes in water and wastewater environments. The flow regimes of multiphase fluids greatly influence the corrosion rate. When the flow rate is high, flow-induced corrosion and erosion-corrosion may occur, while when the rate is low, pitting corrosion is more common, and corrosion is generally related to the amount and nature of sediments. High-velocity flow is likely to flush sediments from the pipeline, while low velocity allows sediments to settle at the bottom, providing sites for pitting corrosion[6].

One issue that adds complexity to management and maintenance of oil and gas infrastructure is the need to ensure corrosion is managed in various environments[7]. As oil and gas extraction industries move into more extreme environments, the complexities of infrastructure development, and corrosion-mitigation of that infrastructure increase[8]. Various environments include seawater, fresh water, air, and soil. Seawater extraction may be in shallow water, deep water, or ultra-deep water, which affects the pressure and temperature requirements of the infrastructure. Extraction may occur in tropical, temperate, or arctic conditions. Each of these environments introduces different chemicals to the pipe infrastructure, and requires various corrosion management initiatives. Where pipes cross environmental boundaries such as shorelines, the complexity of corrosion management increases.

Management of corrosion in oil and gas pipes is commonly conducted using corrosion inhibitors[9]. There are three general categories, being anodic, cathodic and mixed corrosion inhibitors; and can also be categorised as organic or inorganic. Many of the inhibitors are unique mixtures that may contain surfactants, film enhancers, demulsifies, and/ or oxygen scavengers.

Techniques such as managing casing of pipelines across environmental boundaries are being developed[10]. Willis *et al.* note that it can be complex to predict the exact current flow of the cathodic protection system onto the pipeline. Environmental transitions may result in variable resistivity due to factors such as tidal wetting and drying, groundwater movements or captured run-off. Additional complexity is caused by the coating insulation resistance being likely to become variable across the electrolyte over time. This can lead to coating defects being unevenly scattered, and exposed steel having an uneven covering of calcareous film.

Finally, the crude product may be 'sweet' or 'sour'. A sweet field will be free from H_2S, while a sour field will have measurable amounts of H_2S. Both sweet and sour fields may have a significant proportion of other chemicals such as CO_2, chlorides and water. The result of this complex mix is a wide range of pH of the crude, which in turn has an impact on corrosion[11].

4.1.2 Offshore Platforms

Offshore drilling platforms are built over the water and supported by beam piles driven into the ocean floor. Each beam is surrounded by a pipe casing for protection. The structure of the towers is subject to a range of corrosive factors both above and below the waterline. A range of corrosion prevention methods are used in these structures, including:

(1) Adding inhibitors to the stagnant seawater between beams and casings

(2) Cathodic protection, with sacrificial anodes or impressed currents, of underwater structures

(3) Paints and other organic coatings to protect exposed structures above the splash zone

(4) Monel sheathing at the casing splash zone. This portion of offshore structures is the most susceptible to rapid corrosion[11].

4.1.3 Transport, Storage and Refining

There are also corrosion issues in oil and gas transportation and storage. The primary factor is the water that is present in tanks. Corrosion in the refining operations is caused by several chemical reactions, based on the presence of water, Co2, H2S, salt, nitrogen and a range of other compounds[10].

4.2 Costs of Corrosion

In the Oil and Gas industry, it has been estimated that, globally, more than seven per cent of GDP each year is spent on corrosion mitigation and repair. For Australia, in 2013, this equated to more than $A20 billion[12].

While various costs can be identified, there is minimal data in the literature that measures the costs to the economies of Australia or New Zealand. The UK's Energy Institute ranks corrosion as the second most frequent cause in initiating loss of hydrocarbon containment in offshore platforms[13].

The costs associated with corrosion in the oil and gas industry can be loosely grouped into several areas:

(1) The loss of the oil or gas product

(2) Direct costs; including designing structures to minimise the impact of corrosion, costs of inputs such as corrosion inhibitors

(3) Indirect costs; including the cost of shutting down the relevant infrastructure (i.e. pipeline, refinery, etc.) for maintenance and corrosion prevention and associated labour costs

(4) Remediation costs in situations of infrastructure failure, including the labour costs involved in remediation, the material costs of restoring the infrastructure, and the environmental costs of any leak as a result of a rupture that escapes the containment

Calculation of the costs of any of these components is complex. For example, the cost of corrosion inhibitors is inherently complex. The cost of installation and maintenance of injection equipment, inhibitor chemical(s), monitoring inhibitor concentration(s), system changes to accommodate the inhibitor, system cleaning, waste disposal and personnel safety equipment, must be factored into any economic evaluation of the use of corrosion inhibitors[6].

The cost of designing structures to minimise corrosion includes appropriate selection of pipeline materials. Iannuzzi *et al* (2017) note that high strength materials, including low-alloy steel (LAS) and corrosion resistant alloy (PH-CRA), are essential to overcome the materials hurdles associated with the production of hydrocarbons from unconventional reservoirs. Two forms of corrosion are identified, being local degradation and environmentally assisted cracking. As infrastructure is being utilised in extreme environments, management of both factors is crucial.

Fortunately, there have been relatively few instances of corrosion leading to environmental damage in Australia and New Zealand. In 2015, corrosion of an oil pipe in Tauranga Harbour, New Zealand led to an oil spill[14]. In this incident, heavy fuel oil spilled from a ship bunkering at the Port of Tauranga. The outcome was described as a boiling black mess" on the harbour's inner waterways. At least three birds were found oiled and treated at a bird sanctuary following the spill.

From a global perspective there have been many other instances of oil infrastructure failure. One well-studied incident was the Deep Horizon[15] oil spill in 2010. The cost of the clean-up has been identified as over $US14 billion. Potential catastrophic failures caused by corrosion in the Australasian Oil and Gas industry could result in costs of this magnitude.

4.3 Management Initiatives

New techniques are being developed to monitor the infrastructure for early detection of localised corrosion[16]. An example is a multiple ring pair electrical resistance sensor (RPERS) array. This concept was presented at Corrosion Prevention 2019[17]. In addition, a whole-of-life, holistic approach can be implemented that takes account of construction and projected maintenance costs of a project[8]. Using such an approach, it may be possible to incorporate materials and processes into a design that leads to reapplying surface coatings every 15 years instead of 10, with significant savings.

An example of a holistic approach is the Gorgon Project in Western Australia[18]. This incorporates the 130Km Jansz-Io subsea pipeline. It is expected that the plant will produce 15.6 million tonnes of LNG annually; as well as feeding a domestic gas plant with the capacity to supply 300 terajoules of gas each day. The holistic approach includes maintenance plans for the estimated 50-year life of the project.

5 Water and Wastewater

Water and wastewater infrastructure are present throughout Australia and New Zealand. The scope of water industries includes water treatment, distribution, plumbing, wastewater treatment, rainfall collection, industrial recycling and desalination[19].

In New Zealand, the wastewater and stormwater infrastructure include 24,000 km of public wastewater network, more than 3,000 treatment plants and over 17,000 km of stormwater network[20]. In Australia, the total length of sewer pipes is over 110,000 km[21]. While not all local authorities provided data, in 2012 those who did provide information reported a total of 145,481Km of water mains in Australia[22].There is no easily identified measure of the water infrastructure in New Zealand.

There are a range of products that have historically been used for water and wastewater infrastructure. Common pipe options include concrete, copper, stainless steel and PVC; while fibro has also been used in some situations. Each of these materials has corrosion risks, and the risks will vary based on the environment and the use. Water will incur a different range of corrosion issues to those caused by wastewater.

5.1 Causes of Corrosion

The causes of corrosion in the water and wastewater industries vary based on both the material used in the infrastructure and whether that infrastructure is used for water or wastewater.

Stainless steel has been suggested to have a maintenance period of 60 years. Stainless steel corrosion mechanisms in water are identified as crevice corrosion, pitting corrosion, stress corrosion cracking, microbiology-influenced corrosion, and galvanic corrosion[18]. The general corrosion rate in stainless steel infrastructure is less than 2µm per annum. The causal factors in stainless steel corrosion are the chloride levels in the water, the chemicals used in treatment, the presence of any oxidant and the flow rate of the water. In addition, fluoride can be a causal factor when present[23].

Corrosion in concrete structures includes chlorine-induced corrosion, particularly in coastal structures such as wharves and piers, carbonation induced corrosion, and microbial attack in sewers[21]. Concrete is also subject to external corrosion from contact with the soil[24]. Concrete corrosion from sulphuric acid is problematic in sewer systems, where the H_2S present in the wastewater reacts to form this acid[25]. There are variations of corrosion from sulphuric acid that appear to be based on the source of the acid. Mineral acid attacks appear to have a different mode of action to that of biogenic acid attacks. As a result, field data relating to corrosion may not necessarily align with laboratory results.

Copper is commonly used in Australia and New Zealand for in-home plumbing. It was the material of choice until the early 1990s, when plastic plumbing became more widely accepted. More than 90% of Australian home have copper piping[26]. Copper corrosion is extraordinarily complex. There is an isolated and seemingly random and sporadic nature of corrosion incidents. Further research is required to fully understand the causes. There are four main mechanisms.

(1) Blue water is a discoloration of water, often resulting from initial use after a period of stagnation. The types of corrosion products include copper hydroxides, with some silicates and sulphates. Copper levels in Blue water exceed the Australian Recommended Drinking Guidelines.

(2) Pitting Corrosion, resulting in pipe wall failure and leakage.

(3) Erosion Corrosion, most commonly found in hot water systems. Grooves and gullies form in the pipe, usually in the direction of flow. Erosion can be exacerbated by dissolved gas and particulate matter. The outcome of Erosion corrosion is pipe failure.

(4) Cuprosolvency, a slow rate of uniform corrosion. This is unlikely to lead to pipe failure; but can result in blue staining of surfaces in contact with the water from these pipes.

Corrosion in sewers involves a range of chemical actions that differ from that of water infrastructure. There are also variations within the sewer infrastructure based on being in contact with the wastewater or the associated gas. A significant proportion of the corrosion from wastewater is due to abrasion or scoring, while low pH (as low as 3) can lead to cement paste degrading to gypsum, with corresponding loss of strength and increasing vulnerability to abrasion and erosion. In the airspace, the gas will attack the pipe with H_2S. Manhole covers can be a relative weak point in sewer infrastructure and are at significant risk of corrosion[27].

Fluoride is present in many water supply areas in Australia and New Zealand. Fluorides are corrosive, and the effects can include release of asbestos from fibro mains, absorption of fluoride into the matrix in concrete mains with a subsequent weakening, erosion and deposition downstream, and corrosion of domestic copper pipes, hot water systems, water meters, washing machines, valves, and solder fittings[23].

5.2 Costs of Corrosion

In Australia, the value of sewer infrastructure in 2001 was estimated to be worth $A28 billion[21]. The New Zealand stormwater infrastructure has an estimated replacement value of $NZ8.6 billion, while the wastewater infrastructure has an estimated replacement value of $NZ15.8 billion[20].

5.2.1 Water

Leaking and burst water mains are problematic in the water industry. The second most common cause of water main failure has been identified as corrosion[28]. Water main failure may result in slow leakage from the network, reducing the capacity of the network to supply water requirements for the community. One example is the small town or Renwick in Marlborough, New Zealand[29]. The town has a small population of 2,100[30]. The main industry in the surrounding districts is viticulture. The water supply is losing 300,000L per day due to leakage from corrosion in the network. The direct cost is the loss of water. The indirect cost is the implementation of watering restrictions throughout the district. Repairs are being implemented by the local council, and will continue for the next 30-40 years, at which stage repairing will become uneconomic.

Alternatively, they may result in catastrophic rupturing of the water main, resulting in property damage from flooding, costs for users of affected infrastructure (such as roads) being delayed and diverted in transit, and in costs associated with remediation and repair. A burst water main in Adelaide's north-eastern suburb caused flooding in 40 residents[31]. While it may have been significant, the failure that caused the flooding was one of many. SA Water has identified a failure rate of 20-27 failures/100Km/year between 2006 and 2015. This contrasts with other water providers across Australia, where Unity Water in Queensland has the lowest rate (<5), while Yarra Valley Water in Victoria has a reported rate of nearly 40 failures per 100Km per year. While corrosion is only the second most common cause of water main failures, the rate of failures provides some indication of the cost to the community of the corrosion-related failures. The estimated less of water due to these failures has been measured at between 15-415L/connection/day[22].

During a pipeline failure event, there are intangible costs that can have a significant effect upon the wider community, including disruptions due to flooding, road closures and loss of trade. The cost of corrosion of water and in Australia has been estimated at $A91 million per annum[32]. On a pro-rata basis, this would suggest an annual cost in New Zealand to be in the range of $NZ17 million.

Ratliff[22] notes that based on the age of water pipes, replacement of those installed from the late 1800s to the 1950s is now imminent, and the replacement of pipes installed since the 1950s will require ongoing activity for the rest of the 21st century. In the USA, more than 1,000,000 miles of pipe are nearing the end of their economic life and will require the investment of over $US1 trillion in the next two decades. On a pro-rata basis, the Australian mains infrastructure is around one tenth of the US infrastructure, while the New Zealand water mains are likely to be one fifth of the Australian mains systems. Using the same replacement costs, this means the investment in Australia is likely to be $A125 billion in the next two decades, while the cost for New Zealand is likely to be $25 billion.

5.2.2 Wastewater

Microbial induced corrosion of reinforced concrete sewer pipe is currently considered one of the most serious and costly problems. The Water Industry Network (USA) conducted a survey in 2000, which estimated annual rehabilitation costs to be $13.75 billion per year. A study in Germany in 2007 reported the cost for the repair of corrosion damaged sewer pipe in Germany is estimated to be over $50 billion. In Australia in 2001, the annual cost due to the failure of water/wastewater pipeline alone in Australia was estimated to cost $250 million[21].

Optimisation programs are being established by local governments to address the cost implications of maintenance and renewal[33]. The Hastings District Council has implemented a two-stage approach for managing their sewer infrastructure. The first stage involves the determination of condition-based residual life and programming for rehabilitation or further monitoring. This is followed by stage two, targeted at optimizing the prioritization of short term (<5 years) repairs using risk matrix scoring. The funding requirements have been evened out across the infrastructure, including managing the risk of an age- based replacement where the renewal of large portions of the trunk sewers would coincide within a small 10-20-year window period.

5.3 Corrosion Management

5.3.1 Overall Strategies

Corrie (2015)[34] noted that risk-based inspection plans are increasingly accepted in organisations that understand the importance of extending the life of high-value assets for as long as possible. These plans provide an indication of the downstream dollar cost of deferred maintenance. They also compare the cost effectiveness of a range of protective options and offering optimal maintenance plans for each.

An associated factor in management of corrosion is managing of the core infrastructure in areas where load is increasing, often to the point of maximising capacity. In such instances, corrosion may not be the limiting factor in a cost/ deferred cost decision. Rather, the need for increased capacity may result in remediation plans being deferred while augmented infrastructure is put in place.

An ideal maintenance management plan for large and complex infrastructure should be designed to avoid a huge outlay every few years, with a potential complete plant shutdown. A management plan could be to divide the infrastructure into "blocks" or sections and a rotating maintenance plan is developed. By doing this, there is ongoing maintenance and frequency of inspection is managed by the risk factors found in each area, as well as by the ease of access to each section. As a result, areas that are more prone to corrosion can be inspected and maintained more regularly than those presenting a lower risk.

5.3.2 Prevention Strategies

Within sewers, management includes corrosion prevention, where forced air movement and venting are used to minimise hydrogen sulphide, and bacterial control is provided using chlorine or other sterilant. While this is possible to manage on a location basis, it is difficult to do on a large scale or in inaccessible areas. Another form of prevention is the use of materials that are not affected by acid attack such as PVC or HDPE pipes, or use of impervious liners for precast concrete pipes [35]. Introduction of chemicals that react with H_2S can reduce the rate of production of sulphuric acid. Magnesium hydroxide was identified as a product that is capable of such a reduction, with a resultant decrease in the rate of corrosion[36].

5.3.3 Environmental Factors

As with Oil and Gas infrastructure, water and wastewater infrastructure need to be managed based on a range of environments[35]. Factors that need to be managed include abrasion from strong, turbulent flows (particularly if the flow contains abrasive particles), concrete shrinkage and associated steel reinforcement corrosion, and the presence of chemicals that may lead to biogenic sulphur attack.

5.3.4 Implementing New Technologies

New technologies are providing tools to assist in identification of corrosion risks, and corresponding management of the infrastructure. The SeweX model is an example, where a simulation tool for predicting hydrogen sulphide and methane production in sewers, as well as other water quality parameters[37].

The CSIRO has been collaborating with water utilities to model sewer corrosion by focusing on data-driven approaches[38]. The work intends to help water utilities to reduce the uncertainty of corrosion factors such as the H2S concentration and pipe condition over time. The overall outcome will ideally be a significant cost saving.

The Bondi Ocean Outfall Sewer, (BOOS) was commissioned in Sydney, Australia in 2011[35]. Corrosion prevention measures included:

- Increased reinforcement cover, providing improved crack control
- Special concrete designs, including admixtures delivering higher durability, lower shrinkage, better compaction and reduced porosity
- Enclosed settlement tanks where the build-up of bacteria (aerobic and anaerobic) can be managed by the tanks being taken off-line
- Protective coating materials

6 Construction and Infrastructure

Buildings and structures that incorporate concrete and exposed metal are subject to corrosion. The nature of corrosion varies based on the type and location of the structure. Globally, corrosion-related catastrophic failure of infrastructure has been most visible in the collapse of bridges. There is a history of bridges that have failed due to corrosion, frequently with a loss of life. Examples include the Mianus River Bridge (Connecticut, USA, 1983), the I35 Mississippi River Bridge (Minneapolis, Minnesota, USA, 2007), and the Ponte Morandi (Geneva, Italy, 2018). Fortunately, in Australia and New Zealand there have been no examples of catastrophic corrosion-caused infrastructure failure.

The impact of corrosion is not limited to major infrastructure. It also impacts on residential buildings throughout both countries. While many investigators have researched the causes, impacts, remediation and prevention strategies for corrosion in the construction industry, there are no comprehensive details associated with the costs associated with corrosion. The cost of corrosion-related maintenance of infrastructure (e.g. bridges) in Australia is currently estimated to be $A8 billion[39].

6.1 Geographic Influence on Corrosion

The primary factor influencing corrosion of structures in Australia and New Zealand is salt. As a result, the distance from saltwater is a factor in the rate of corrosion. Both Australia[40] and New Zealand[41] have been mapped to measure the likely rate of corrosion. Factors that impact include distance from the ocean, prevailing wind direction and rainfall intensity.

Latitude has a significant effect, with lower rates of corrosion in tropical areas, while corrosion increases in higher latitudes. Salinity levels and corrosion rates are much higher on Australia's southern coasts than in the northern coasts. Incidence of corrosion is higher in areas close to saltwater, while high rainfall has an effect of washing the salt residue, reducing the rate of corrosion. Coastal landforms, humidity and vegetation also impact on the transport of aerosol salt. In northern Australia, the effect of high intensity rainfall effectively cleans exposed metal surfaces, reducing corrosion.

New Zealand has differentiated building codes based on the corrosion risk of the building site[42]. In New Zealand, geothermal areas with high levels of atmospheric sulphur also experience higher rates of corrosion[43]. In these areas, corrosion of mild steel was found to increase rapidly in the first six to nine months, then decrease slowly. However, the corrosion rate measured after one year was still higher than that measured after one month. Similarly, when exposed to sulphur-containing geothermal emissions, zinc corrodes quickly. Sulphide-rich clusters form on its surface, but can be removed easily by gentle rubbing, and potentially by rainwater. Claddings made of copper and copper alloys have been used in many circumstances mainly due to their high corrosion resistance in many environments. However, copper was found to corrode severely even in areas with very low concentrations of airborne hydrogen sulphide.

6.2 Causes of Corrosion

6.2.1 Concrete/ Steel Reinforced Concrete

Steel reinforced concrete is one of the most widely used construction materials around the world. It can suffer degradation over time due to the embedded steel corroding, causing the concrete to crack and "spall"[44]. The chemicals involved include chlorides, carbon dioxide and other aggressive agents. These chemicals penetrate concrete, which initiate corrosion of reinforcement that typically results in cracking, spalling and weakening of the concrete infrastructure. The reinforcing bars will rust, and in doing so, the volume of the rust increases to many times that of the original steel. This in turn increases pressure on the surrounding material which cracks the concrete. The cracks can then propagate to delamination and eventually spalling of the concrete.

6.3 Bridges

Degradation of bridges is caused by many different factors including corrosion and other stresses from both the environment and heavy vehicles passing over them. In 2018, the Australian Government committed funding for 186 additional projects to the 201 bridges already being remediated. The cost of the current remediation is $A216 million[39].

New Zealand's NZTA is responsible for maintaining approximately 2,300 bridges. The largest and most iconic, the Auckland Harbour Bridge, handles 160,000 vehicles per day. The bridge is a steel truss and box girder design. The corrosion prevention process for the bridge has been a continuous painting process using a cured urethane paint that provides 20-year protection. Many older timber rail bridges nearing the end of their useful life are being replaced by 'weathering steel' girder bridges which should provide a longer operational lifespan. Weathering steel is a high strength, low alloy steel that, when used in environments not exposed to high levels of salinity and pollutants can be left unpainted. This allows a protective rust "patina" to form and minimise further corrosion.

Many bridges in the New Zealand highway network are constructed from precast pre-tensioned concrete. These were built between 1950 and 1980. They are at risk from chlorine-induced pre-tensioned reinforcement corrosion. While the deterioration may be difficult to detect, it has structural implications, so prediction or early detection of at-risk structure is crucial to ensure the bridges achieve their required service lives[45]. Because of difficulties specific to pre-tensioned concrete, corrosion can lead to the replacement of the entire bridge superstructure.

Corrosion was discovered in the Hamanatua Stream Bridge in Poverty Bay, New Zealand in 2004[46]. The chloride ions had penetrated the cover concrete and their concentration at the steel's surface was high enough to cause the steel to corrode. Following this discovery, an investigation was conducted into bridges using the same design throughout New Zealand. In the case of Tiwai Point Bridge in Southland, the entire superstructure of the bridge was replaced due to the difficulty and cost associated with restoring the lost capacity and arresting severe, widespread corrosion within the pre-tensioned beams[47]. A further 137 bridges have been identified as being at risk. Most are located within 1Km of the coast. Inspections were carried out on 30 bridges, and all but one exhibited signs of corrosion. The implications involve costly repair, and the risk of structural failure with minimal warning[48]. Two were identified as needing prompt assessment and remediation.

In another corrosion scenario[49], two Southland bridges were found to have an alkali silica reaction, with extensive cracking, spalling, and surface erosion below the water line. Chemical reactions in the concrete were causing it to expand and contract.

6.4 Examples of Corrosion Impacts

6.4.1 Ohau Diversion Wall, Lake Rotoiti, New Zealand[50]

A diversion wall was built across Lake Rotoiti with the aim of diverting nutrient-rich water from the lake into a diversion channel, which in turn would improve water quality, reduce algal blooms, and restore the lake fishery. The construction was completed in 2008, and consisted of a 1,275m sheet pile wall, 75 metres offshore. The wall was designed for a 50-year life, based on an assumed corrosion allowance of 0.04mm/year of the uncoated steelwork in the freshwater and 0.015mm/year for the steelwork embedded in the soil. The steel in the water was found to be corroding at the rate of 0.5mm/year in 2014. As a result, the wall was expected to collapse within seven years. Options for remediation were investigated and costed, with costs ranging from $NZ1.3 to $18.1 million.

6.4.2 TransGrid Transmission Line, Sydney[51]

TransGrid provides infrastructure to deliver electricity in NSW. Line 959/92Z was constructed in 1965. It includes 61 transmission structures and extends for 23.7Km through parts of Sydney including national parks and urban areas. A significant proportion of towers are corroded, and there is a risk of conductor drop. The risks associated with this include a significant electricity outage through parts of Sydney, and the risk of bushfire. The cost of remediation has a budget of $A7.13 million.

6.4.3 Catagunya Dam, Tasmania[52],[53]

Hydro Tasmania has several dams which were designed and constructed in the 1950-70s with fully grouted, post-tensioned anchors. While the method used was leading edge in its day, it does not achieve the cable protection of modern methods which provide two barriers against corrosion and are monitorable. Inspection of the anchors in the 1990s identified that corrosion of the grouting meant remediation and re-anchoring would be required, with significant re-construction costs.

6.4.4 Water Storage Tanks, South Australia[54]

SA Water has responsibility for 700 concrete water storage tanks. Many of these tanks are approaching 100 years of age, having been commissioned in 1920s. SA Water is now using Remotely Operated Vehicles, submersibles and drones to spot the beginnings of corrosion. The cost benefit is significant, as for each tank whose life can be extended, there is a saving up to $A1 million a year.

"New water tank design doesn't include guttering nowadays, which means water can pond at the base of the tank and depending on the surrounding soils, can accelerate concrete corrosion," Jonathan Morris a senior asset management consultant explained. Concrete sewers are also subject to corrosion from chlorides, sulphates, thermal cracking, and other challenges that pipes carrying organic waste need to withstand. Exhumed sewer pipes are often found to be very thin at the crown, where acidic condensates formed by microbial action on hydrogen sulphides have eaten into the concrete. In extreme cases, this can result in complete loss of the pipe wall. "Acidic and high sulphate conditions are very bad for concrete," Morris explained. "A slime layer forms below the surface level of the wastewater, which houses bacteria that convert sulphates into hydrogen sulphide. When the hydrogen sulphide escapes from the water, it can be converted into sulphates in the above-water slime layers, which are converted into powerful acids by other bacteria."

6.4.5 Housing

Where construction is from timber, metal is used as a fastening tool. Nails and nail plates are subject to corrosion[55]. The rate of corrosion also varies based on the nature of the roof structure. Houses with concrete tile rooves were found to have a higher rate of nail plate corrosion than those where alternate roof material was used. The inclusion of building paper in the concrete tile roofs mitigated the effect of the corrosion.

While corrosion of metal fasteners is partly as a result of salt, it is also caused by the action of the arsenic used to treat the timber[56]. Specifically, three compounds were tested. Alkaline Copper Quaternary (ACQ) and Copper Azole (CuAz) were contrasted with Copper Chrome Arsenic (CCA). Test results showed that the two alternate treatments resulted in higher levels of corrosion of the metal fasteners than the traditional CCA treated timber. Subfloor spaces were also identified as being a risk-site for corrosion in coastal areas, with the possibility that sea salt could be transported into the sub-floor cavity[57].

The impact of corrosion on housing stock can affect other surfaces including metal roofs, metal wall cladding, aluminium joinery and metal fixings[58],[59]. When two metals are in electrical contact while in the presence of moisture or another corrosive electrolyte, there is enhanced aggressive corrosion at the joint area. For example, when galvanic zinc coating is damaged and steel is exposed, there will be aggressive corrosion of the steel. Similarly, when aluminium alloys are joined to steel or copper, the aluminium will corrode more quickly than would otherwise have been the case. Other corrosive electrolytes can include fluid waste and bird guano[60].

In aluminium joinery, corrosion can occur when crevices in the aluminium expose the aluminium under the barrier of aluminium oxide[61]. This rarely occurs due to the rapid oxidation of the exposed aluminium. However, in the presence of mortar, bricks and concrete, a chemical reaction may occur between the aluminium oxide and the matrix. The result is the formation of aluminium hydroxide and hydrochloric acid. The acid can then corrode the metal.

6.5 Corrosion Prevention and Management

When corrosion effects are considered in the design stage of an infrastructure basis, structures can be built to be protected and to last longer[60].

A change in the constituents of cement can have a positive impact on corrosion. The commonly used 'Portland Cement' can be replaced with alternative components such as 'fly ash', polymers, recycled car tyres and fibres[43]. Incorporation of these products can reduce the rate of corrosion, with a corresponding increase in the life of the structure.

Further enhancements can be made to corrosion protection in reinforced concrete by using a two-stage corrosion protection system that may combine cathodic protection, galvanic protection and electrochemical treatments[62].

Historically, testing has been conducted to measure electrical resistivity (the inverse of electrical conductivity) and a chloride and sulphate measurement to measure the degree of corrosion hazard. For concrete testing, laboratories are now offering a service[63] that measures a much broader range of potential risks including the following:

Soil Tests: pH and EC, Texture, Permeability Class, Sulphate ion, Chloride ion, Resistivity

Water: pH and EC, Sodium ion, Magnesium ion, Calcium ion, Ammonium ion, Sulphate ion, Chloride ion, Co_3^2 and HCO_3, Calculated $CaCo_3$ saturation index.

7 Defence

It is essential for defence forces to have equipment and infrastructure that is functional and operationally ready. Corrosion poses a severe threat to the operational readiness of defence forces. Analyses have been conducted into the impact of corrosion in the Australian Defence Force (ADF)[64].

7.1 Royal Australian Navy

The RAN operates in environments that are harsh and subject to corrosion. Knight *et al.*[64] report on a corrosion cost analysis of corrosion on four frigates in the RAN. Three different costing methods were used (a direct analogy of USN frigate corrosion costs, a proportional analogy of USN frigate costs and a bottom-up method).

Method 1 (comparison to U.S. studies) gave an estimated corrosion cost between $81 million to $126 million Australian dollars (AUD); Method 2 (mixed costing approach) gave much lower estimates of $41 million to $72 million AUD; and Method 3 (detailed costing using RAN maintenance records) showed an estimated cost of ~$94 million AUD. The costs were then extrapolated across the RAN fleet. Using corrosion costs relative to total maintenance costs from the USN, and MSA costs for the RAN, the cost of corrosion for the entire RAN fleet during the 2015 calendar year was estimated to be between $A137 to $A242 million.

Costs of corrosion in the RAN can be reduced through implementation of effective technologies. The Australian Defence Magazine reported in 2018[65] that the RAN was investing in Envelop protective covers for use initially on HMAS Canberra and Adelaide. These Envelop covers have been shown in the USN to save $US30,020 of corrosion maintenance cost within the first two years of use[66]. The USN has made the use of these covers mandatory on all vessels.

7.2 Royal Australian Air Force

RAAF aircraft are operated beyond their original design life. As a result, more corrosion is likely to develop in airframes as protective coatings deteriorate. The costs of dealing with corrosion are likely to increase[67]. The use of Structural health monitoring (SHM) systems that provide diagnostic and prognostic information on corrosion-related damage will enable maintainers and operators of aircraft to manage the prevention and control of corrosion in aircraft structural components on a condition basis rather than on elapsed number of (flying) hours[68].

In defence, older airframes are reporting that corrosion can be the primary cause of structural nonconformances, and that non-availability due to inspection and correction can be upwards of 10%. The cost of corrosion for the period from January 2010 through to December 2011 was assessed as $2.49 million[69]. For new airframes, improved components incorporating carbon composites are causing significant issues due to galvanic corrosion around metallic fasteners, and original equipment manufacturers are mandating extensive inspection regimes where 70 to 75% of maintenance actions are for corrosion control.

The Defence Science and Technology Organisation (DSTO) has been developing tools to monitor the atmospheric corrosion of military aircraft[70]. Initially, this work involved the development and use of sensors, both corrosion and environmental. The work has evolved to include corrosion models and prognostic capabilities to give a more complete corrosion prognostic health management (CPHM) system. The anticipated outcome is to facilitate condition-based maintenance for corrosion prevention, which will replace maintenance dictated by either flying hours or service duration.

Corrosion is also an issue with helicopters. A joint development program between DSTO and researchers at Monash and Swinburne Universities has developed a silane coating. This coating is completely biodegradable and non-toxic so people can handle it safely. It also delivers the maximum corrosion resistance ever achieved for magnesium alloys. It could be used to repair the corroded gearbox housings of SeaHawk helicopters[71].

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