The Australasian Corrosion Association Inc.
Corrosion Challenges Project

A report on the impact of failure of infrastructure assets through corrosion as a result of current practices and skilling in the Australian mainland urban water and Naval defence sectors.

Terms of Reference and Sector Reports

November 2010

CORROSION CHALLENGES -
TERMS OF REFERENCE

BACKGROUND

Numerous studies have been undertaken in advanced Western economies to determine the economic impact of corrosion and it's degradation of infrastructure and assets.

Typically, these studies have provided credible estimates ranging from 3 to 5% of GDP as the cost of corrosion to their economy. In Australasian terms, this represents an annual cost to the Australian economy of between $36B and $60B per year. For the New Zealand economy, the estimate lies between $5.5B and $9.2B annually.

What is not clear from these studies is the size and impact of what part management and inappropriate technology applications contribute to corrosion costs, and what opportunities are available to reduce such costs.

OBJECTIVE

The objective of this Project is to examine, identify and estimate corrosion failure costs attributable to industry practices, industry skilling and regulatory frameworks, and estimate potential corrosion failure cost reductions by implementing avoidable/preventable strategies. The Naval defence and mainland Australia domestic water industries were chosen as test cases, based on the availability of industry professionals and access to data.

The project methodology and final report will enable the ACA as representative of Industry to:

- develop strategies to address deficiencies in knowledge
- develop set of criteria for more effective corrosion management
- seek assistance to extend the study to other industry sectors

It is expected that a key outcome of the first Objective will be to expand and improve the ACA's training program and general education activities. By achieving these objectives, the ACA is fulfilling its mandate and serving the interests of its Membership though this leadership initiative on corrosion in Australasia.

1. The Project Team will examine, identify, estimate and make recommendations relating to the costs directly attributable to the administration of corrosion management programmes in the Defence and Water Industries. The corrosion costs are to be categorised as follows:

- Failures (or avoidable costs)
    - unplanned repairs/failures
        - stoppages
        - breakdowns
        - incidents
        - injuries
        - compensation
        - rework
        - lost production
        - environmental impact
- Prevention
    - asset management policies/planning
    - design materials
    - training
    - procurement & sustainment practices

- Controls
  - monitoring
  - maintaining
  - inspection
  - treatment

2. Using the best available information and knowledge from the Water and Defence industries, current practices/policies which are outdated and contributing to corrosion costs will be identified. Estimates of the cost/availability impact of these will be made, followed by recommendations of practices/policies to be adopted so to reduce those costs significantly.

3. Regulatory frame-work such as Standards, statutory regulations, policies or regulatory structures that impact on corrosion costs in the Defence and Water Industries will be examined. Recommendations will identify where improvements should be made, and will incorporate a cost-benefit analysis of such improvements.

4. Advancements in technology, tools and materials that show promise in reducing cost of ownership and improving asset availability (applicable to the Water and Defence Industries) will be identified and recommendation of associated policy changes will be made.

5. The current training and educational framework for the management, prevention and mitigation of corrosion in each Industry will be examined and recommendations for improvements be made.

6. The Project Team will identify and make recommendations as to how best the ACA, in partnership with Government and Industry, can further provide leadership and training in corrosion prevention, mitigation and management.

7. Significant matters identified as relating to the Objectives of this Project will be recognised and any associated recommendations made.

PROJECT TEAM

The project team shall comprise the following personnel:*

- ACA President
- ACA Project Manager
- Water industry expert in Corrosion
- Defence industry expert in Corrosion

** Note: Additional personnel with specific expertise may be used from time to time.*

DELIVERABLES

A budget has been allocated by the ACA for this Project.

A draft of the Report addressing all items in the Scope of this study is to be submitted to the ACA President by 1st October 2010.

The final report shall be submitted on 1st November 2010 to the ACA Executive via the ACA CEO.

It is anticipated that this Report will be published in the December or February issue of the ACA journal Corrosion & Materials**.

*** Note: For Editorial reasons, the final Report may be published in an abridged format.*

CORROSION CHALLENGES - URBAN WATER INDUSTRY

Greg Moore
Moore Materials Technology Pty Ltd

1. INTRODUCTION

Numerous studies have been undertaken in advanced western economies to determine the economic impact of corrosion and its degradation of infrastructure and assets. Typically, these studies have provided credible estimates ranging from 3 to 5% of GDP as the cost of corrosion to their economy. What is not clear from these studies is the size and impact that the role of management and inappropriate technology applications contribute to corrosion costs, and what opportunities are available to reduce such costs.

The objective of this Project is to examine, identify and estimate corrosion failure costs attributable to industry practices, industry skilling and regulatory frameworks, and estimate potential corrosion failure cost reductions by implementing avoidable/preventable strategies using the Australian Naval Defence and urban Water Industries as test cases.

The project data collection in this instance has been confined to Australian water Utilities.

2. SCOPE

The effects of corrosion of water distribution and sewerage collection pipework and infrastructure impacts upon every man, woman and child and covers a wide ranging list of assets. This includes assets from urban and rural water Utilities, industry, agriculture and domestic environments. Establishing the cost associated with corrosion in all of these sectors is in itself challenging and, as a result, the scope of investigation was limited to urban water Utilities. This limitation is not intended to marginalise the effects of corrosion on the other sectors, but is based on the practicality and the available time to collect data which has some credibility. Indeed, corrosion of industrial, agriculture and domestic water and sewerage pipe can be significant, but the major costs are incurred by the major water Utilities. This is also true for industry practices, industry skilling and regulatory frameworks.

Urban water Utilities consist of approximately 52 water Utilities, most of which are members of the Water Services Association of Australia; the Peak Industry Association for the urban water Utilities. In Australia, with few exceptions, all water Utilities are government corporations, government agencies or local councils. There has been no major privatisation of Australian water Utilities.

3. METHODOLOGY

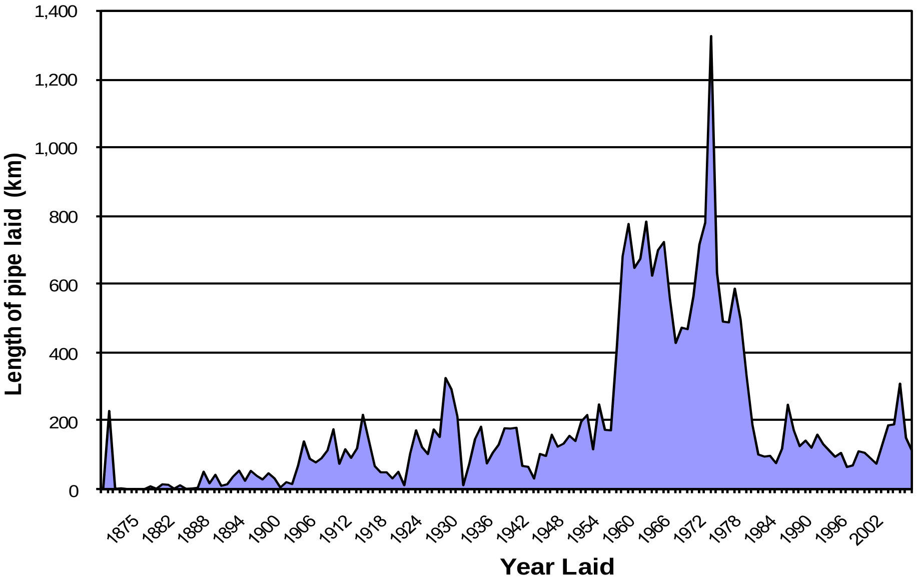
The Water Services Association of Australia (WSAA) is the peak body representing the Australian urban Water Industry which provides innovative, sustainable and cost effective delivery of water services. Some activities undertaken are the facilitation of strategic standardisation, industry performance monitoring and benchmarking, the outcome of which is reported in the annual National Performance Report[1]. This report records and measures up to 117 indicators from 73 water Utilities across Australia serving approximately 75% of Australia's population. A number of these indicators were able to be used and interrogated along with other information to determine costs associated with corrosion. This was supplemented with specific information obtained from 4 major water Utilities.

Similarly, research and discussions with a number of water Utilities was undertaken to assess and determine needs for training and any legislative requirements which either hinder or could be bolstered to improve the ability to manage infrastructure and influence how corrosion prevention is managed.

For the purposes of this report corrosion is defined as the physical deterioration of a pipe or structure and is limited to metallic and cementitious materials.

4. THE AUSTRALIAN URBAN WATER INDUSTRY

The Australian urban Water Industry commenced in the mid 1800's and became a major builder of infrastructure in the 1920's, peaking post World War II. The industry has a large portfolio of assets with a nominal written down replacement cost for fixed water supply and sewerage assets of approximately $49B and $57B[1] respectively. While all water Utilities have their own timelines for the development of infrastructure, including water and sewerage pipes, water and sewage treatment plants reservoirs and tanks, there is some similarity between the major Utilities. Shown in Graph 1 are typical lengths of pipe laid each year and while this is specifically for water pipes, the same trends are generally applicable to sewerage pipes, treatment facilities and other associated infrastructure.



Graph 1 Typical lengths of water pipeline and years when laid

As can be seen, the greatest infrastructure development of pipelines occurred from the mid 1950's to the mid 1970's where large numbers of pipes were laid to accommodate the major expansion of population in the major cities fuelled by immigration and post World War II development. At the same time, other infrastructure was also being built in conjunction with water pipelines. This has resulted in the Australian Water Industry having infrastructure assets consisting of approximately 139,000 kilometres of water pipes, 117,000 kilometres of sewer mains, 260 water treatment plants, 442 sewage treatment plants[1] and large numbers of water storage tanks and reservoirs, water and sewage pumping stations and other associated structures.

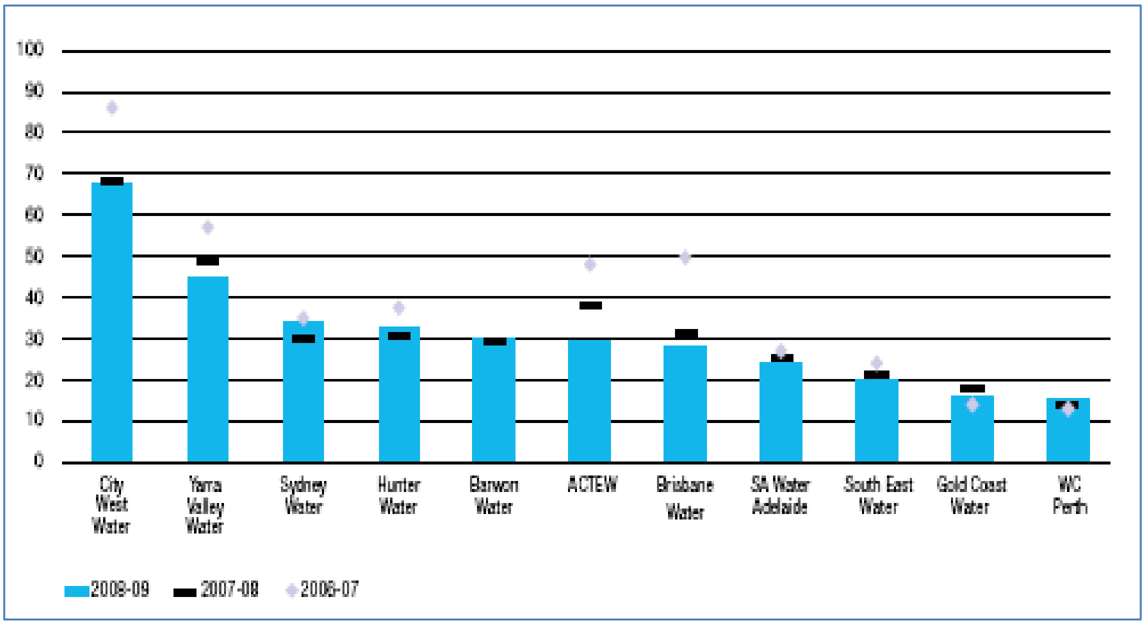
5. URBAN WATER INDUSTRY ASSETS

5.1 Pipes

Pipelines are by far the largest group of assets in the water industry. They consist of pressure pipes used for the conveyance of water and sewage, and non-pressure pipes for the conveyance of sewage. Within this group of assets there are numerous pipe types, some of which are susceptible to both internal and external corrosion. The corrosion mechanisms for the major pipe materials are detailed in Annexure A.

5.1.1 Pressure Water and Sewer Pipes

There have been a wide variety of pressure pipes used in the water industry, both metallic and non metallic, and these have provided a varying level of performance. Plastics pipes are not subjected to corrosion but the other pressure pipe materials, cast iron, ductile iron, steel, concrete and asbestos cement pipes, are all susceptible to both internal and external corrosion to varying degrees. The performance of all pressure pipes is reported in the WSAA National Performance report as water main breaks per 100km per year. There can be considerable variability between water Utilities[1] and Graph 2 highlights the extent and variability in the water main breaks per 100 km of water main for the major water Utilities. When you consider the average breaks of all major water Utilities is 19 per 100km, the extent of the issue becomes apparent when related to the 139,000km of mains. For 2008/2009 this equates to approximately 26,700 breaks per annum or one every 20 minutes. To qualify this, the breaks can be anything from a major pipe failure to a minor leak; regardless, it puts into perspective the enormity of the problem for the water Utilities.

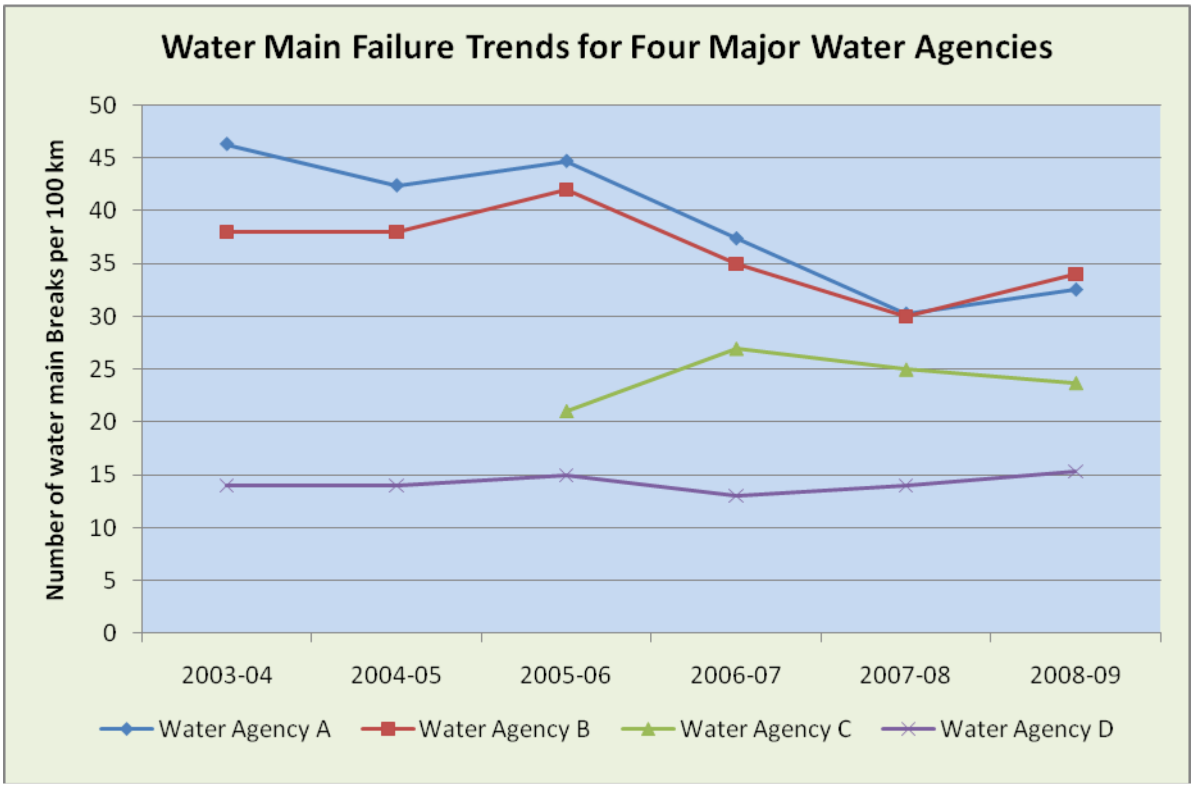


Graph 2 – Variations in water main breaks (per 100km/year) between water Utilities

Notes:

1. Brisbane Water is now part of Queensland Urban Utilities
2. Gold Coast Water is now part of Allconnex Water

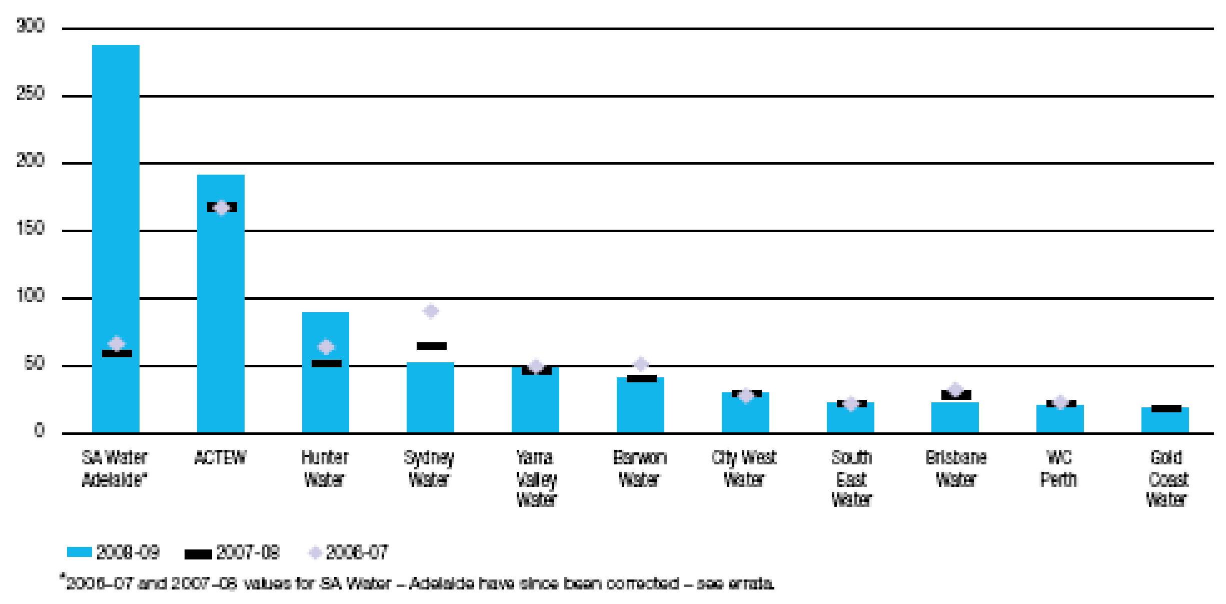
Trends in water pipeline failures are shown in Graph 3 for four major water Utilities. This shows a general flat or slightly decreasing trend in pipe failures which may be explained by general uniform deterioration rates of the pipeline combined with removal of problem pipes during the repair and gradual renewal of older mains.



Graph 3 – Trends in water main breaks

5.1.2 Non-Pressure Sewer Pipes

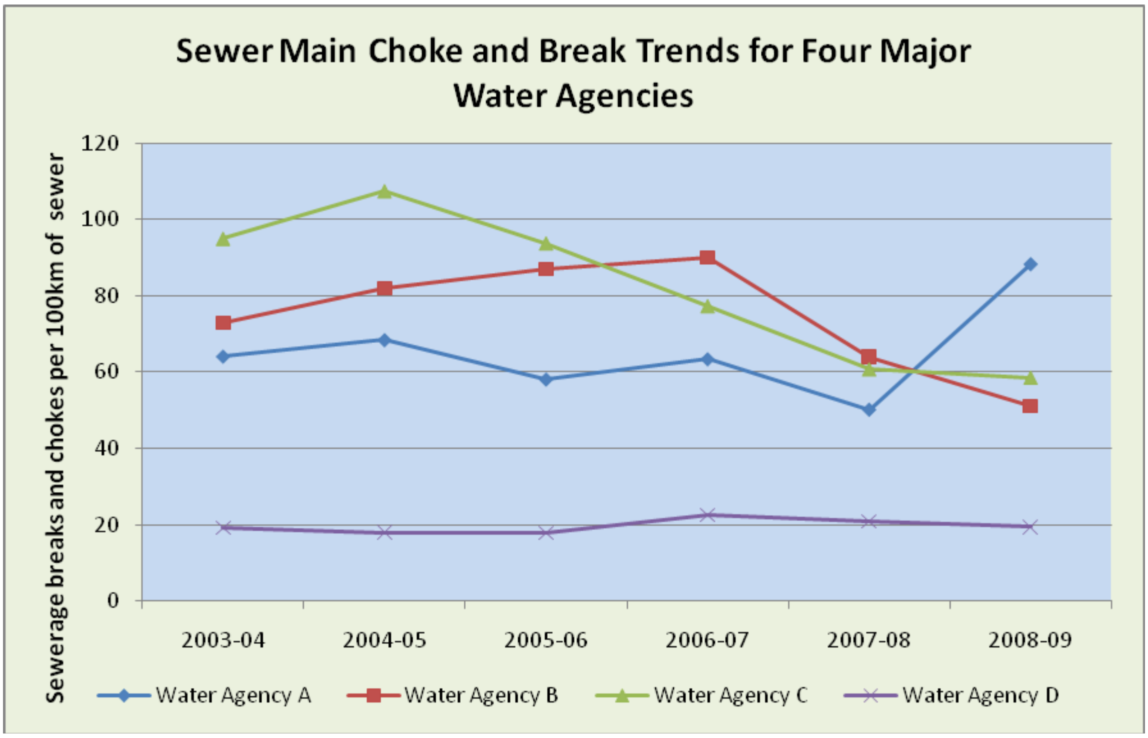
Sewer reticulation systems in Australia are generally designed as vented systems to minimise the build up of hydrogen sulphide gases, which can promote the corrosion of cementicious and ferrous materials by the formation of sulphuric acid. Non-pressure sewer pipes are predominately vitrified clay, plastics (PVC or GRP) or reinforced concrete. Concrete pipes are susceptible to internal corrosion from hydrogen sulphide even in vented systems and it is these pipes which have the greatest issues with internal corrosion. The performance of all sewer pipes is reported in the WSAA National Performance report as the number of chokes and breaks per 100km per year[1]. Like water main breaks, there is considerable variation in the number of chokes/breaks between water Utilities as shown in Graph 4. Chokes or blockages are usually associated with tree roots, and these are the greatest problem for sewer non-pressure mains while corrosion itself is generally not a major contributor except for concrete.



*2006-07 and 2007-08 values for SA Water – Adelaide have since been corrected – see errata.

Graph 4 – Number of sewer chokes and breaks per 100 km of sewer mains per year

Trends for sewer main failures are shown in Graph 5 and, as can be seen, show a decreasing number of failures.



Graph 5 – Trends in sewer main chokes and breaks

5.1.3 Water and Sewage Treatment Plants

There are 260 water treatment plants and 442 sewage treatment plants forming part of the major urban water Utilities. While some water supplies are only disinfected, the majority of supplies are also filtered and treated to remove impurities so to ensure the water quality meets the Australian Drinking Water Guidelines (ADWG). Water treatment plants have ongoing maintenance and repair issues, but in most cases the consequences of failure are generally not as serious as a pipeline failure. Nevertheless, they can be significant.

Sewage treatment plants treat raw sewage and are subjected in most cases to more aggressive environments than water treatment plants, primarily due to the presence of hydrogen sulphide which is always associated with these treatment processes. As a result, corrosion in these plants can be considerably more aggressive than water treatment plants.

5.1.4 Other Infrastructure

There are large numbers of water storage tanks, reservoirs, water and sewage pumping stations, sewer vents and other structures, all of which require regular ongoing maintenance and repairs. While all of the maintenance and repair cannot be attributed to corrosion, a significant percentage of it can be.

6. WATER QUALITY

The ADWG provides guidelines for microbiological, organic and inorganic materials, aesthetic, taste and odour qualities. While corrosion of pipes is highlighted as a possible consequence of some water quality attributes, there are no specific water quality requirements for corrosion mitigation; although these are surreptitiously controlled by guidelines for variables including, but not limited to, pH and alkalinity. Where extensive internal corrosion of water mains occurs, taste and aesthetic qualities are compromised (known as red water) which invariably lead to water quality complaints. There are also no specific requirements to treat drinking water with corrosion inhibitors in order to limit corrosion on domestic pipes, such as copper. As such, this practice is not utilised by any Australian water Utility.

7. COST OF CORROSION

The cost of corrosion of the urban water Utilities has been estimated based on data reported in the National Water Commission and WSAA National Performance Report and the supplementary information obtained from a number of water Utilities. The following aspects were considered:

- Cost of water pipe failures
- Cost of loss water due to system leakage
- Cost of lost water from pipeline failures
- Cost of sewer pipe chokes and breaks
- Capital expenditure for new infrastructure replacing existing corroded pipelines
- Costs associated with repair and maintenance of water treatment and sewage treatment plants
- Costs associated with sewerage treatment due to infiltration as a result of sewer pipe corrosion.
- Cost associated with repair and maintenance of other assets such tanks, reservoirs, pumping stations, sewer manholes etc
- Intangible costs or externalities that effect the wider community as a consequence of water and sewer pipeline failures and replacements

The study did not include any water treatment costs as these are generally not carried out specifically for corrosion control; with the exception, however, of lime and carbon dioxide dosing for very soft waters.

These costs were aggregated and costs per person were determined for the population in the supply areas of the urban water Utilities.

7.1 Cost of water pipeline failures

WSAA data provides a breakdown of the number of water main breaks per 100 km of main. Water main breaks when recorded can be anything from a minor leak to a major burst. In some cases the failures may not have been attributed to corrosion, but for water mains corrosion is generally a primary cause of the failure. Often pipe failures are attributed to soil movement or changes in seasonal conditions; however, for brittle pipe materials such as grey cast iron or asbestos cement, these effects are secondary causes after the primary cause of corrosion has weakened the pipe. The available WSAA data for water mains 2008/2009 was used, along with the other supplementary data, to estimate the cost of water pipeline failure which could be attributed to corrosion. These are shown in Table 1, below.

Cost of water pipeline failures	**2008-2009**
Average repair cost per water main break	$4,550
Total kilometres water main	138,698
Average main breaks (per 100 km of water main)	19.2
Total number of breaks	32,944
Total cost of water main breaks	$149,893,483
Percentage of breaks attributed to corrosion	79 %
Costs of water pipeline failures attributed to corrosion	$118,715,639

Table 1 - Cost of water pipeline failures

Two variables, the average repair cost and the percentage of breaks, are not reported and required input from water Utilities. Four water Utilities were consulted and these were able to provide some specific data obtained from their individual data banks.

The average cost associated with repairs, including labour, materials and road restoration, varied from $2250 for reticulation mains (up to DN 300) to $7000 for larger distribution/transfer mains. These were average figures and actual costs can vary enormously depending on the size and pressure of the pipe, and the pipe's location. In some cases pipeline failures have been known to cost between $500,000 and $1M+, but failures of this magnitude are not common. The average of 5 sets of individual water utility data for the repair costs was $4550.

The percentage of breaks attributed to corrosion, as determined by 4 sets of water Utility data, varied from 49 to 100% with an average of 79%.

Using this data, the annual cost to the Australian urban Water Industry due to pipeline failure is approximately $119M per annum.

7.2 Cost of water lost due to system leakage

Leakage of water from pressure mains can be significant and is measured by all water Utilities. Leakage can be the result of factors such as failure of joints, fittings and the pipe itself. Not all leakage can be attributed to corrosion but the average estimate of three Utilities suggested that 49% of the water losses could be attributed to corrosion in one form or another.

Cost of water losses due to system leakage	**2008-2009**
Average water cost per kL	$1.53
Total kilometres water mains	138,698
Average loss kL/km/day water main	2.8
Total loss of water (calculated)	157,904,354
Total cost of lost water	$240,822,501
Percentage of losses attributed to corrosion	49%
System water loss attributed to corrosion	$120,411,250

Table 2 - Cost of water losses due to system leakage attributed to corrosion

Water costs to consumers are generally, but not exclusively, incremental depending on the volume of water used. For this calculation, the cost of lost water was based on the average 2nd step usage for all the urban water Utilities. This was determined as $1.53 per kilolitre.

Using this data, the annual loss of water through leakage due to corrosion costs the Australian urban Water Industry approximately $120M per annum.

7.3 Cost of water lost through pipeline failures

In addition to the water losses identified in 7.2, water lost through water mains breaks was also estimated. . This estimate was based on work carried out by one major water Utility which calculated an average flow rate of 15 L/s during 2 hours of mains shut-down.. For larger mains the flows will be higher and vice versa for smaller mains, but the 15 L/s is considered an acceptable average for the purposes of this study. The percentage of losses attributed to corrosion was the same as that which was determined in 7.1.

Cost of water loss from pipeline failures	2008-2009
Average water cost per kL	$1.53
Total number of breaks	32,944
Average time (hours) to shut down a main break	2.0
Estimated flow (L/s) from a burst	15
Total volume of lost water (ML)	3,558
Percentage of losses attributed to corrosion	79 %
Total cost of water loss from pipeline failures	$4,297,622

Table 3 - Cost of water lost through pipeline failures

As shown in Table 3, using this data the annual loss of water through pipeline failures costs the Australian urban Water Industry approximately $4.3M per annum.

7.4 Cost of sewer pipe chokes and breaks

Sewer pipes in the smaller sizes (up to DN300) are predominately vitreous clay or PVCU, while large larger sizes are traditionally calcareous concrete or normal reinforced concrete pipe. There is a very high number of sewer pipe chokes and breaks and the largest cause of these is tree root infiltration through joints or cracked vitreous clay pipes which ultimately results in the pipe becoming blocked or choked. The major corrosion issues occur with reinforced concrete pipes due to internal corrosive attack from hydrogen sulphide and thus it is only these pipes which have been considered.

Cost of sewer pipeline failures	2008-2009
Average repair cost per sewer main break	$6,325
Total kilometres sewer main	116,901
Average sewer breaks (per 100 km of sewer main)	57.7
Total number of breaks/chokes (calculated)	68,630
Total cost of sewer breaks/chokes	$434,084,914
Percentage of chokes/breaks attributed to corrosion	9 %
Total Cost of sewer Pipeline failures	$39,067,642

Table 4 - Cost of sewer pipe chokes and breaks

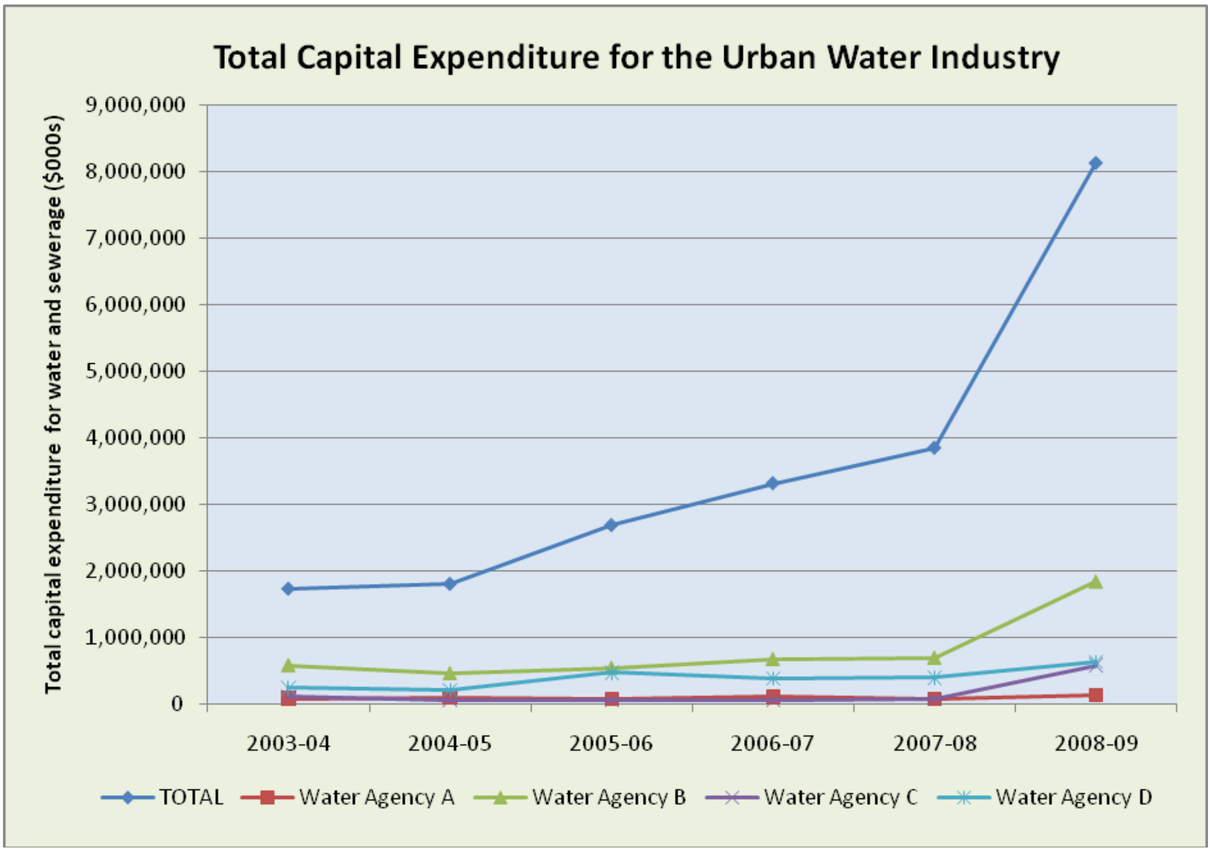
Two water Utilities were able to provide costs associated with the repair of corroded sewer pipe with an average cost of $6325. A third Utility provided some costs of larger diameter concrete pipes and these were in the many hundreds of thousands of dollars. The incidence of these is not high and, for the purposes of this study, only the average costs associated with smaller concrete pipes were used. Similarly, only a relatively small number (9%) of the reported chokes and breaks were attributed to corrosion.

Using this data, Table 4 demonstrates that the repair of sewer breaks costs the Australian Urban Water Industry approximately $39M per annum.

Many, if not most, of the water Utilities have active internal CCTV condition assessment programs for reinforced concrete sewer pipes. The aim of this is to aid prevention of major collapses. The costs associated with the replacement of corroded sewer pipe is reflected in section 7.5.

7.5 Capital expenditure for new infrastructure replacing existing corroded pipes

Significant capital is expended by the water Utilities as shown in Graph 6. As can be seen, there has been a significant increase in capital expenditure from 2004/2005 and a dramatic increase in 2007/2008. Theses rises are associated with the construction of large desalination projects in the Gold Coast, Sydney, Perth, Adelaide and Melbourne.



Graph 6 – Capital expenditure for the urban Water Industry

To normalise the total expenditure and remove the influence of the desalination capital works program, the 2004/2005 expenditure was taken as the base starting point and to this CPI increases were applied to give a level of total capital works expenditure for 2008/2009.

Data from the individual water Utilities indicated that the average amount of capital spend on the renewals of water and sewer mains was 24% of the total expenditure, and of that 61% of the pipes were replaced as a direct result of corrosion.

These estimates, detailed in Table 5 below, provide an estimated capital expenditure for sewer and water pipeline replacement costs of $299M per annum.

Capital expenditure for pipes as a result of corrosion	**2008/2009**
Total Capital expenditure for water and sewerage (2004/05 figure adjusted for CPI)	$2,080,378,000
Average percentage of capital works attributed to renewals	24 %
Annual renewals costs	$492,356,127
Average percentage of sewer and water pipe renewals attributed to corrosion	61 %
Renewal expenditure attributed to corrosion	**$298,696,050**

Table 5 – Capital expenditure costs of sewer and water pipeline replacements due to corrosion

7.6 Costs associated with repair and maintenance of water and sewage treatment plants

Water and sewage treatment plants are also a considerable set of infrastructure assets where there are costs associated with the deterioration of these assets that can be directly attributed to corrosion. Detail of the actual costs associated with the treatment plants was not readily available, so a different approach was taken to determine these costs. One water Utility[2] considered that the annual depreciation allowance in financial accounts is arguably predominantly due to corrosion, particularly in civil works where virtually all of the depreciation can be attributed to corrosion. This Utility was also able to provide detailed depreciation information for 10 water filtration plants where the costs associated with each of the asset classes, of civil, electrical and mechanical were separated. This showed that the civil assets comprised approximately 87% of the depreciation costs for the 10 water treatment plants. Using this data and the premise that all of the civil depreciation was due to corrosion, an average annual depreciation figure of $600,000 per plant was estimated. It needs to be appreciated that these costs are not realised until the actual asset is renewed, but as there is always ongoing replacement and repairs being carried out in these facilities, it was considered a fair assumption that this figure, or a proportion of it, could be used as a representative annual cost of corrosion for each water and sewage treatment plant.

Detailed data for the breakdown of civil, electrical and mechanical assets was not available for sewage treatment plants, but it is assumed that the civil content would be similar to water treatment plants. Sewage treatment plants are considered to be exposed to a more corrosive environment than water treatment plants due to the presence of hydrogen sulphide gas. Many sewage treatment plants are also coastal, or close to the coast, so the marine environment adds to the increased corrosivity of the sewage treatment plant environment. Both these aspects are aggressive to concrete structures.

A conservative approach was taken and an estimated annual corrosion cost for water treatment plants of $200,000 was used and for sewage treatment plants an estimate of $400,000.

Corrosion costs attributed to water treatment plants	**2008-2009**
Total water treatment plants	260
Average cost attributed to corrosion p.a.	$200,000
Maintenance and repair costs of WTP's attributed to corrosion	**$52,000,000**

Corrosion costs attributed to sewage treatment plants	**2008-2009**
Total sewerage treatment plants	442
Average cost attributed to corrosion p.a.	$400,000
Maintenance and repair costs of STP's attributed to corrosion	**$176,800,000**

Table 6 – Annual corrosion costs attributed to the repair, maintenance and replacement of treatment plant assets

These annual costs have been utilised, as detailed in Table 6 above, to determine an estimated corrosion cost attributed to the repair, maintenance and replacement of treatment plant assets. This resulted in a figure of $52M for water treatment plants and $177M for sewage treatment plants.

7.7 Costs associated with sewerage treatment due to infiltration as a result of sewer pipe corrosion.

Infiltration of groundwater into sewerage collection systems places an added burden on the sewage treatment plants and increases overall operational costs. Infiltration occurs mainly as a result of joint failures, particularly in vitreous clay pipes, but also from physical failures of some plastic pipe fittings. Corrosion of cementicious based sewer pipes can also allow infiltration to occur. There is no specific data on this, but estimates in the order of 2% have been proposed.

Sewage treatment costs due to ground water infiltration	**2008-2009**
Total sewerage treatment plants	$442
Total operating costs for sewerage	$1,899,257,768
Percentage of treatment costs as a result of infiltration	2%
Operating costs attributed to infiltration as a result of corrosion of cementicious sewer systems	$37,985,155

Table 7 – Costs associated with sewerage treatment due to ground water infiltration though corrosion of sewer pipe

Using this data, Table 7 shows that the additional costs of sewerage treatment due to infiltration at locations of sewer pipe corrosion is approximately $38M per annum.

7.8 Cost associated with repair and maintenance of other assets such tanks, reservoirs, pumping stations, sewer manholes

There are considerable other assets such as sewer manholes, sewer vents, tanks, reservoirs, and pumping stations associated with water and sewerage systems which also have costs associated with corrosion. Some of these costs can be considerable; especially where repairs and recoating of steel water tanks and other complex steel structure are required. It was not possible to obtain sufficient data for each of these asset groups, so a 5% multiplier was applied to the aggregated costs as determined in sub-sections 7.1-7.7.

Using this approach, the annual cost to the Australian urban Water Industry for the repair and maintenance of assets such tanks, reservoirs, pumping stations and sewer manholes was approx $42M per annum.

7.9 Externalities that effect the wider community as a consequence of water and sewer pipeline failures

During a pipeline failure event, intangible costs or externalities can have a significant affect upon the wider community. These can include disruptions due to flooding, road closures and loss of trade. In the construction of replacement mains there can also be considerable disruption and loss of trade. These costs can vary significantly depending on the magnitude of the corrosion event and have been estimated[2] to range from a factor of 0.1 to 17, which is a very large variation. These intangible cost multipliers are still under considerable discussion, however they are considered to be significant enough to include as part of this study. A conservative multiplying factor of 0.20 has been applied to the costs identified in 7.1, 7.4 and 7.5 was used to estimate these costs.

Using this data, the annual intangible cost to the Australian urban Water Industry was approx $91M per annum.

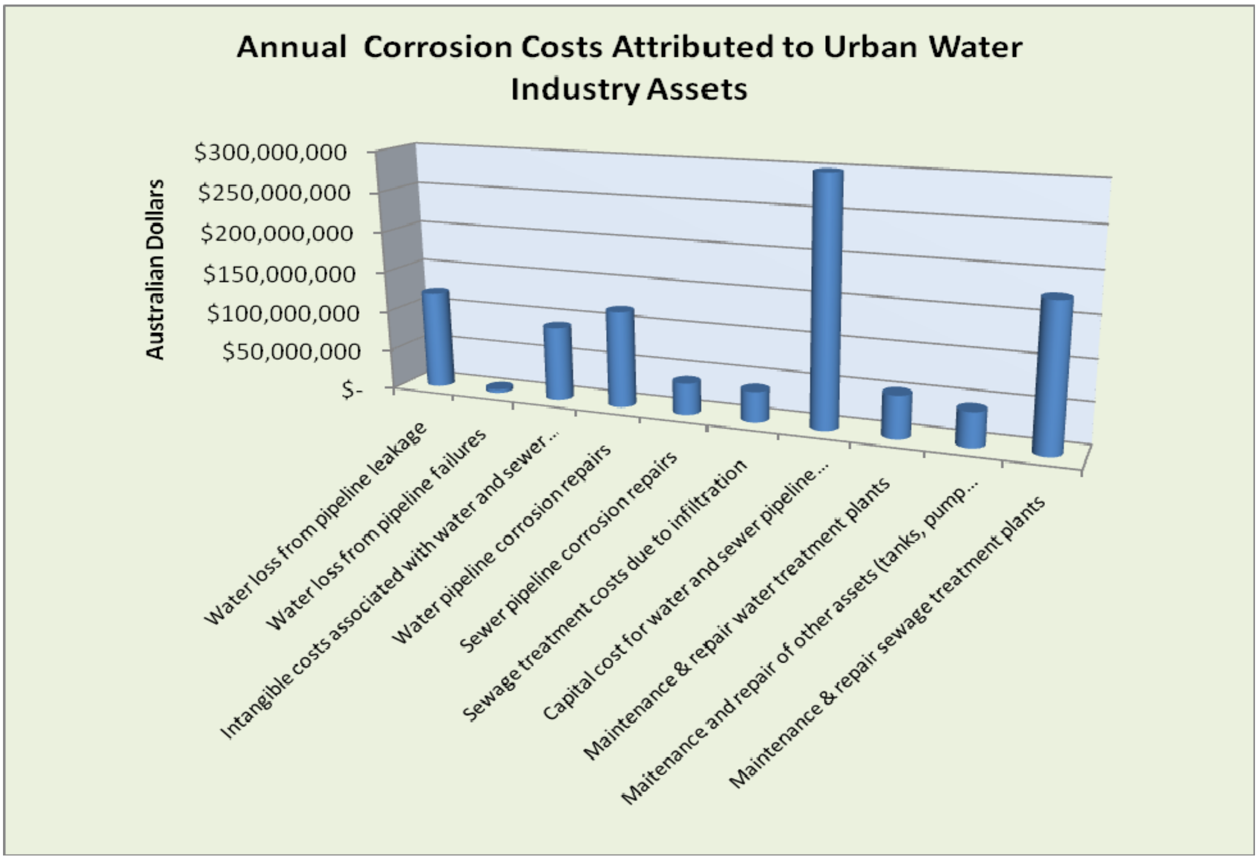
7.10 Aggregated corrosion costs

The aggregated costs of corrosion are shown in Table 8 and Graphs 7 and 8 below. The data in the graphs show the specific and proportional costs in those areas identified in sub-sections sections 7.1-7.9.

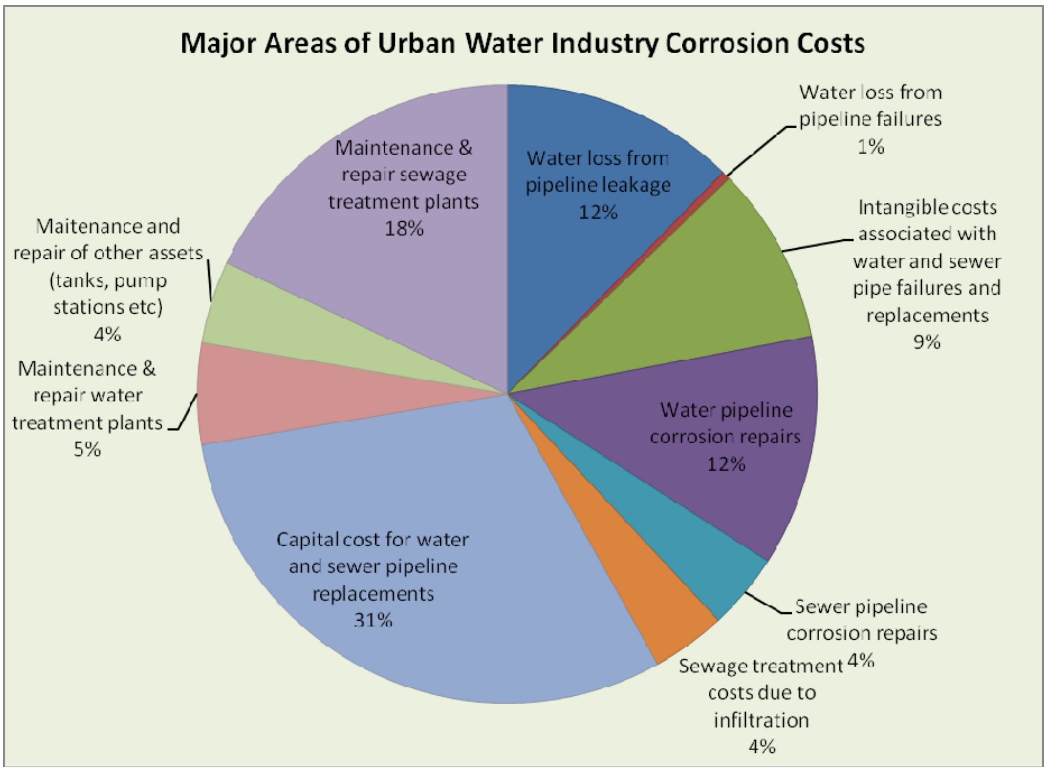
These costs represent the total estimated costs of corrosion in the Australian urban Water Industry which provides water and sewerage services to approximately 16 million people, as well as many of Australia’s larger commercial and industrial enterprises. The remainder of the population are served to varying degrees by local shires and councils but, as the information available on these systems is very limited, there has been no attempt to make any allowances for these other areas. The total estimated annual cost of approximately $AUD982 million equates to a per capita cost of $AUD61 per annum for the population served by the urban Water Industry. The major cost is associated with the capital expenditure required for the replacement of water and sewer pipes once they have reached the end of their useful life, followed by that attributed to the cost associated with the repair and maintenance of sewage treatment plants.

Aggregated corrosion costs to the Australian urban Water Industry	Annual cost
Water loss from pipeline leakage	120,411,250
Water loss from pipeline failures	4,297,622
Intangible costs associated with water and sewer pipe failures and replacements	91,295,866
Water pipeline corrosion repairs	118,715,639
Sewer pipeline corrosion repairs	39,067,642
Sewage treatment costs due to infiltration	37,985,155
Capital cost for water and sewer pipeline replacements	298,696,050
Maintenance & repair water treatment plants	52,000,000
Maitenance and repair of other assets (tanks, pump stations etc)	42,398,668
Maintenance & repair sewage treatment plants	176,800,000
Total cost	981,667,893

Table 8 – Aggregated annual corrosion costs to the Australian urban Water Industry



Graph 7 – Annual corrosion costs attributed to urban Water Industry assets



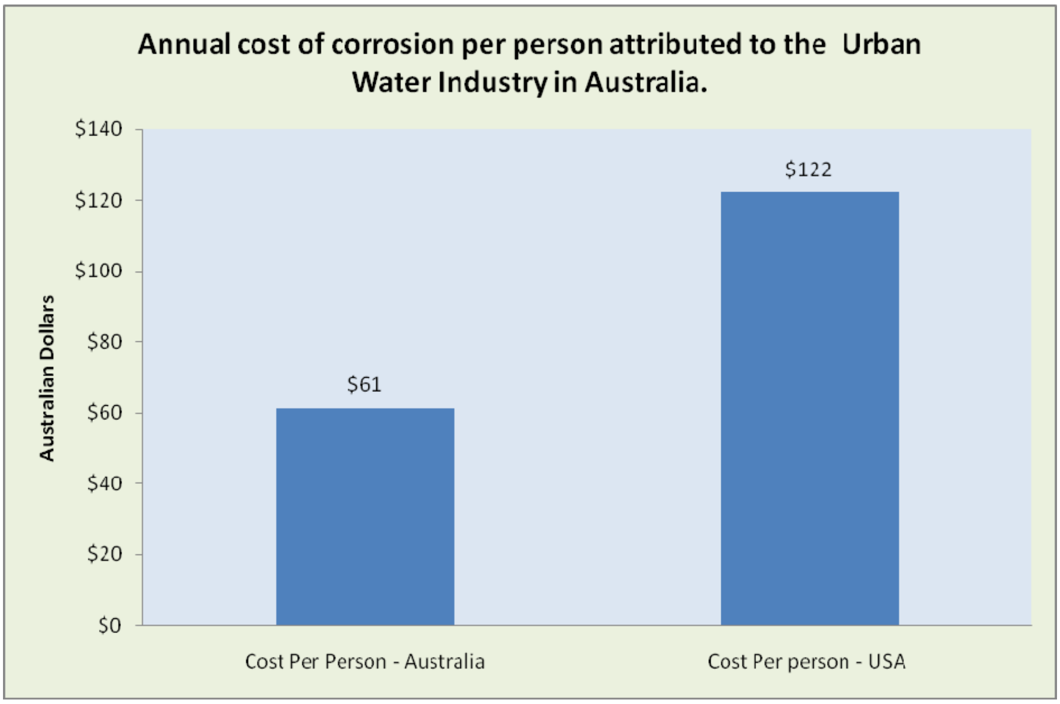
Graph 8 – Major areas of urban Water Industry corrosion costs

7.11 Cost comparisons

The most recent study into the total cost of corrosion was carried out by the US Federal Highway Administration[2] which included a section on the Water Industry. This study estimated the annual corrosion cost to the US Water Industry was $US36B. With a population of 310 million, the annual cost per person is $US116 ($AUD122) compared to a cost of $AUD61 per person in Australia (Graph 9); a difference in the order of 50%.

The reasons for the variation are not obviously apparent, but the US study identified significant problems with internal corrosion of metallic pipelines which resulted in considerable costs for renovation or replacement. In some cases this is due to climatic differences where pipes need to be buried at much greater depths to avoid freezing. By contrast, internal corrosion in Australian pipes is now not a major problem as factory cement mortar lined pipes were widely used from the late 1920's and unlined pipes were cement mortar lined in-situ in the 1950's and 1960's; thus internal corrosion and associated water quality issues were overcome then. External corrosion is the main issue associated with metallic pipes in the Australian water industry.

Water treatment to control corrosion of copper and lead property service pipes (very little lead is present in the Australian system) is not used in Australia and therefore there are no costs incurred due to the use of inhibitors.



Graph 9 – Per capita corrosion cost comparisons

7.12 Accuracy of data

To accurately determine the cost of corrosion is always very difficult and subjective, but in this instance there is considerable usable data that has been collected by water Utilities and reported by WSAA. While there are some limitations and inaccuracies in this data, the analysis used in this paper, including the additional data from water Utilities, has formed the basis of a reasonable estimate of the cost of corrosion. However, like any broad reaching review there will always be areas of inaccuracies which need to be accounted for.

A sensitivity analysis using maximum and minimum extremes of the data was therefore carried out. This gave variations in the aggregated cost of corrosion from $774 million per annum to $1,233 million per annum, so even with what is seemingly good data there is still considerable error. Based on this analysis the cost of corrosion is considered to be $982million ± 30%.

8. OPPORTUNITIES TO REDUCE THE COST OF CORROSION

Part of the study involved the identification of potential opportunities where the costs of corrosion could be reduced by a process of change and review to aspects such as training and management activities.

8.1 Management

8.1.1 Water Mains

One of the practices adopted by the water industry has been to run the pipes to failure; repairing individual pipe failures until the failure rate reaches a predetermined level, at which point the entire section of pipeline is replaced. This is still the case for smaller pipes, but for larger critical pipelines there is now greater emphasis on undertaking pipeline condition assessment to predict when failures might occur. In some cases, where the consequence of failure is very high, condition assessment is used to evaluate replacing the pipeline before any failures have occurred. The reactive process of running the pipes to failure may not be seen as "best practice", but the nature of the assets themselves, ie buried where they are out of sight and mind combined with large variations in corrosion rates, does make it difficult to proactively maintain such assets. There are a number of ongoing activities, however, where this reactive process is being changed to a proactive approach. These include but are not limited to:

- Retrofitting of cathodic protection (CP) systems to pipelines which are economically amenable to this method of corrosion control and life extension. These pipes are usually continuously welded steel, cement lined pipes. While there is considerable application of CP in some Utilities it is likely that a greater use of this technology could be made to mitigate external corrosion of steel mains. However, CP of other metallic pipe such as cast iron or ductile iron (sleeved or un-sleeved) is not a viable application of this technology.
- Condition assessment of critical mains within the limitations of existing technology.
- Application of structural or semi structural linings to extend the life of critical pressure water mains.
- Ongoing leak detection programs
- Active electrolysis testing and corrosion mitigation where stray current corrosion from traction systems is likely.

New pipeline infrastructure generally requires a minimum design life of 100 years which is achieved by the selection of appropriate corrosion resistant materials (often non metallic materials) and improved construction and installation practices.

8.1.2 Sewer Mains

Most Utilities have active CCTV inspection programs where internal corrosion of non-pressure sewer pipes can be assessed, particularly reinforced concrete pipes. The industry is now at a point where such assessments are used to implement repairs, renovations or replacements of these sewers before major collapses occur. This proactive approach is now well defined and structured and, in this case, the condition assessment technology is effective in determining when action is required to prevent major failures. A raft of repair and renovation techniques is available for these assets.

8.1.3 Data Collection

The industry is very conscious of the requirements for management of its assets and the majority of water Utilities are actively involved in the many aspects of Asset Management. Data is collected by water Utilities and provided to WSAA to enable benchmarking. It has been recognised that there are some deficiencies in the collection of data; specifically in the case of water mains failures. This aspect has been recognised by WSAA and they recently reported:

> *"One of the projects commenced in 2008–09 is the development of a National Water Mains data base, based on that used in the United Kingdom but tailored to address the Australian context. This data base allows the upload, collation and anonymous comparison of water pipe data between water Utilities. The benefit is that it identifies issues in the quality of data collection and provides guidance on what data is important and should be collected. It will also provide a large dataset of pipe failure events. This data base is the crucial first step in creating pipe deterioration curves and improving estimations of failure events, remaining life and the optimum time for replacement or rehabilitation."*

This initiative will improve the quality of data for water mains failures and will also open up some training opportunities in this area (see sub-section 8.2).

While the Water Industry collects a large amount of data, it became apparent that there was no direct emphasis on measuring the cost of corrosion. As highlighted in this paper, if some additional information can be obtained and reported, a more accurate estimate of the cost of corrosion to this industry would be obtainable. This would require a re-think of the data collection for other assets within the industry where corrosion has a bearing on performance. It is likely that a focus on this type of data collection would highlight other areas of cost which have perhaps haven't been previously considered but should be reported as corrosion costs. These aspects should be considered and would provide a management tool which can then help justify actions to reduce the overall corrosion costs and improve asset management.

8.1.4 Design Accreditation

WSAA has recently implemented a Design Assurance Scheme which focuses upon ensuring that designers and design auditors have the skills required for competent use of the Sewerage Code of Australia and the Water Supply Code of Australia. The objective of the scheme is to:

- Improve the competency of the designers and auditors

- Set a minimum standard of competency for designers and auditors
- Encourage a national approach to the development of competencies in water supply and sewerage reticulation design
- Ensure the portability of design competencies between states and between water Utilities

These Codes cover the design of water and sewerage reticulation schemes and aspects of materials and corrosion prevention. However, in discussions with water Utilities[2], it was felt there was an opportunity to provide some more detailed information and training on corrosion prevention, and that it was worth closer investigation. Such training could be included as part of, or as a separate requirement for, the Design Assurance Scheme.

8.2 Training – Corrosion and Corrosion Prevention

The Water Industry utilises the skills of a wide range of staff to manage, operate and design water and sewerage systems, including management, operations staff, professional and technical staff and support staff (Administration etc). Extensive training is available for water and sewerage operations (Government Skills Australia, NWP07 Water Training Package), programmes which incorporate a large number of competency requirements. While there are some requirements in these competency units to enable identification of corrosion, there are no competency units that specifically relate to corrosion. Professional and technical staff may receive some corrosion theory during the course of their professional training, but most of the expertise in corrosion lies with specialist groups within some water Utilities. While specialist groups are not unusual, and in most cases are effective, there are opportunities where additional instruction on corrosion would be of benefit to the industry at large. Some specific areas identified in this study include, but are not limited to:

- Collection of reliable data, as aimed for in the National Water Mains Failure Data Base (8.1.3), is reliant on the interpretation of pipeline failures by operations staff. To ensure operations staff are suitably equipped to undertake this role, specific training in some basic corrosion theory and pipeline failure identification would be beneficial, and would provide greater support and credibility to that scheme.
- Requirements are being introduced for designers and design auditors to show competency in using the Water Supply and Sewerage Codes of Australia. These Codes cover aspects of materials and corrosion but the main focus is on design. A specific accreditation for materials and corrosion mitigation requirements was considered to be a useful training prerequisite for water and sewerage infrastructure designers.
- There are no specific corrosion courses aimed at the water industry and opportunity exists to develop such a training course for water industry personnel. Such courses would cover the previous dot points and could include others including but not limited to:
    - Corrosion basics for the water industry
    - Materials and corrosion control for use in conjunction with the Water Supply Code of Australia and the Sewerage Code of Australia
    - Identification and assessment of corrosion and pipeline failures in the water industry
    - Retrofitting of CP to aged steel water mains (supplementary CP course)

The above training courses could form part of training initiatives for WSAA and Government Skills Australia, as well as general training for Water Agencies.

8.3 Regulatory – Legislative requirements which can influence corrosion performance

There are no specific regulatory or legislative requirements that could be directly linked to any factor which may exacerbate corrosion, or any factor which would hinder measures implemented to mitigate corrosion. Many Australian Standards and legislative and regulatory requirements give due consideration to corrosion and its consequences; for instance health and safety regulations, and the requirement for regular corrosion inspections of pressure vessels. In some instances the local EPA may become involved where there are odour complaints from sewerage reticulation systems or sewerage treatment plants. This can result in an accelerated concrete corrosion through closing off sewer vent pipes or enclosing treatment facilities to prevent the escape of hydrogen sulphide gases. This practice can and does have severe effects on the infrastructure, particularly where concrete pipes or structures are exposed to higher levels of hydrogen sulphide gases.

9. CONCLUSIONS

The cost of corrosion to the Australian urban Water Utilities has been estimated by considering the costs associated with:

- Cost of water pipe failures
- Cost of water lost due to system leakage
- Cost of water lost from pipeline failures
- Cost of sewer pipe chokes and breaks
- Capital expenditure for new infrastructure replacing existing corroded pipelines
- Costs associated with repair and maintenance of water treatment and sewage treatment plants
- Costs associated with repair and maintenance of sewage treatment plants
- Costs associated with sewerage treatment due to infiltration as a result of sewer pipe corrosion.
- Cost associated with repair and maintenance of other assets such tanks, reservoirs, pump stations etc

- Intangible costs or externalities that effect the wider community as a consequence of water and sewer pipeline failures and replacements

This analysis provided estimated annual cost to the industry of $982million ± 30%.

The investigation also highlighted opportunities for a number of training issues which would be supportive and complementary to the initiatives of the National Water Mains Data Base, the Design Assurance Scheme being implemented by WSAA and Government Skills Australia, NWP07 Water Training Package.

Training courses could include but are not limited to;

  - Corrosion basics for the water industry
  - Materials and corrosion control for use in conjunction with the Water Supply Code of Australia and the Sewerage Code of Australia
  - Identification and assessment of corrosion and pipeline failures in the water industry
  - Retrofitting of CP to aged steel water mains (supplementary CP course)

There is also an opportunity to report on a regular basis upon the cost of corrosion to the urban water industry by reviewing the existing data collected for the WSAA Annual National Performance Report. Such an indicator would provide management and asset managers with a greater appreciation of the influences and impacts of corrosion. With that knowledge, a more proactive role in corrosion mitigation with scope for considerable savings to the industry as a whole is possible.

The Australian Water Industry faces ongoing challenges in future years in many areas, but in particular the asset management of ageing infrastructure. Pipe materials of grey cast iron and asbestos cement make up the largest proportion of reticulation pipes and many of these are reaching a time where replacement will be required. The cost attributable to the maintenance and repair of sewage treatment plants is also considerable, with ongoing significant repairs and remedial works required.

Where possible the industry is moving from a reactive to a proactive approach to corrosion management, but there will always be difficulties in any proactive approach to manage buried assets where there is limited technology to carry out condition assessments.

10. RECOMMENDATIONS

It is recommended:

- that this report is used to raise the awareness in the water industry of the impact of corrosion on infrastructure, and the associated direct costs that result.
- that the additional training identified be further investigated in conjunction with key stakeholders.

11. ACKNOWLEDGMENTS

Special thanks to the support of the Water Services Association of Australia and their foresight into the generation of the National Performance Report which has made this review possible. Thanks also to water industry personnel from Hunter Water Corporation, Sydney Water, Water Corporation and South Australian Water Corporation.

Annexure A

Corrosion in the Water Industry

This annex provides a brief summary of the major pipe materials used for water and sewerage reticulation systems in Australia, focusing only on pipes which are used in significant quantities and which are susceptible to internal or external corrosion.

1. METALLIC PIPE MATERIALS

1.1 Cast Iron Pipes

Cast iron pipes were the first metallic pipes used for water supply. The earliest cast iron pipes were first produced in Europe and the first cast iron pipes used in Australia were imported, generally from the UK. In the late 1800's many foundries started to produce cast iron pipes in Australia. These were supplied to local markets and in the absence of any standards were often made to local requirements. It was not until 1903 that cast iron pipes were standardised in the UK with the publication of BS 78, Cast iron pipes (vertically cast). The production of these pipes resulted in thick walled grey cast iron with an internal lining and external coating of Trinidad tar or bitumen for both internal and external corrosion control. The deficiencies of this basic corrosion protection soon showed up – initially internally where the coating broke down resulting in extensive internal corrosion – Figure A1. Many of these pipes in Australia were then cement lined in situ which overcame the majority of the internal corrosion problems. Cement mortar lining has proven to be a very effective lining for internal corrosion protection, with the dual benefit of a lining which provides a physical barrier and the secondary effects of producing and maintaining a high pH environment at the cast iron surface which places the cast iron in the passive or non corroding condition. The performance of cement mortar linings has recently been reviewed[3] and concludes:

"This work has shown that the performance of CML cast iron and ductile iron pipes for use in potable water carriage is exceptional. A survey of the water industry has found few cases of failure in CML cast iron and ductile iron pipes, with problematic failure cases being attributed to poor installation procedures".

External corrosion is by far the most prevalent form of failure of cast iron pipe (Figure A2) due largely to corrosive soils, but the thick walls of the early vertical or horizontally sand cast pipes provided in many cases a large corrosion allowance which afforded longevity of life which otherwise would not have been the case . Some of these pipes with only the original bitumen external coating are still in use today after 100+ years of service, but these are generally in areas of low soil corrosivity and are probably the minority at this point in time. The introduction of spun cast iron pipes in 1929 in a steel mould process resulted in thinner pipe walls. The absence of a high silica surface layer formed in the sand casting process which anecdotally provides greater corrosion protection was also removed with the introduction of spun cast iron pipe.

Figure A1 Internal corrosion of an unlined cast iron pipe

Figure A2 External corrosion of cast iron pipe

Cast iron pipes are generally one of the larger groups of pipes in a water Utility's reticulation system.

1.2 Ductile Iron Pipes

Ductile cast iron pipes were first introduced into Australia in 1973. The mechanical properties of this material with higher tensile strength and ductility compared to grey cast iron meant that the wall thickness was able to be reduced for equivalent pressure ratings. It was recognised that external corrosion prevention required enhancement and at this time the use of loose fit polyethylene sleeve became more wide spread to provide protection. This technique has in most cases provided good performance but like all techniques has its limitations. Where problems have been experienced these have been related to galvanic corrosion of the ductile iron due to the use of un-insulated copper water services, poor installation or use in situations where this form of protection is inappropriate (i.e. anaerobic saline ground conditions). Internal corrosion protection is in the form of cement mortar lining, applied by the centrifugal process, which provides a dense high quality lining and excellent corrosion resistance.

1.3 Steel Pipes

Steel pipe, sometimes incorrectly referred to as wrought iron pipe, was first introduced in Australia in 1885 by Mephan Ferguson. At this time welding of steel had not been perfected, so the steel pipes were either riveted (figure A3) or joined using an innovative locking technique using longitudinal bars (figure A4). Not surprising this Australian invention was known as locking bar pipe and was used extensively from 1895 – 1925. The most famous pipeline constructed using this pipe was the Perth – Coolgardie pipeline which was 560 km long and constructed in 1898 – 1902.[4] However, like the early cast iron pipes, internal and external corrosion protection was limited to either a tar or bitumen coating.

Figure A3 Riveted steel pipe

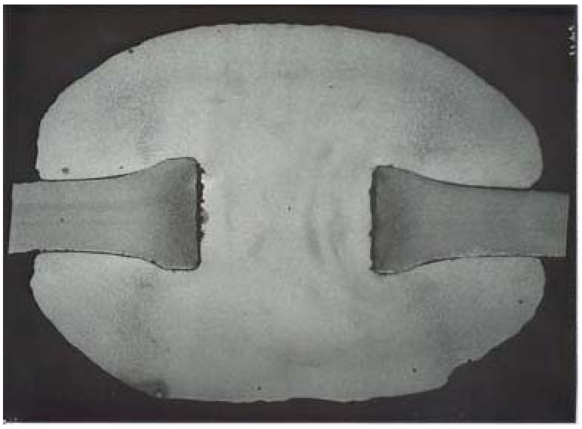


Figure A4 Cross section of locking bar joint

These pipes were usually larger diameter and in most cases were lined in situ with cement mortar lining which overcame the internal corrosion issues. External corrosion protection was hessian reinforced coal tar or bitumen, and provided some external corrosion prevention for buried pipes. Inevitably this failed, allowing external corrosion to progress. The different mechanical properties of the steel compared to cast iron generally resulted in the formation of leaks which in many cases could be effectively repaired. This was in contrast to grey cast iron pipe which generally fails catastrophically.

While steel has been used for over 100 years, today's steel pipe has had many improvements and developments in corrosion protection, and in recent times has provided the industry with a high performance product. Fully welded steel pipe, externally coated with fusion bonded polyethylene and centrifugally lined with cement mortar lining, can provide the 100 year life as demanded by the industry. Some manufactures have recently promoted epoxy or other organic linings as an alternative to cement mortar lining, but these will not provide the long term performance required by the Water Industry. Prior to the introduction of fusion bonded polyethylene, external coatings of reinforced coal tar enamel were widely used. While this provided improvements over the very early tar and bitumen coatings, it was susceptible to deterioration; particularly by soil stresses which resulted in splitting of the coatings and subsequent exposure of the steel to soil corrosion as shown Figure A5.

Figure A5

Longitudinal splitting of coal tar enamel external coating exposing the underlying steel to external corrosion

External corrosion of steel pipes is the major cause of pipeline failure. Welded steel pipes and their jointing technology are suitable to the application of cathodic protection (CP). This has allowed CP to be retrofitted to these pipes and this has been shown to be a very successful life extension technique for these types of pipes. The use of CP has not been effective on the very early steel pipes which were lead jointed, which created high resistance joints and prevented sufficient electrical continuity.

2. NON METALLIC PIPES

Plastic pipes such as PVC and PE do not suffer from conventional corrosion and are therefore not considered any further. Asbestos cement and reinforced concrete pipes are susceptible to corrosion and are considered in the overall scheme of this review.

2.1 Asbestos Cement (AC) Pipes

The first AC pipes were manufactured in 1916 in Italy and were first imported into Australia in the 1920's. AC pipes were one of the first composite pipes and are generally composed of approximately 10-15% asbestos fibres in a matrix of ordinary Portland cement, or Portland cement and finely ground silica. During the manufacture of the pipe, the Portland cement reacts with water to form calcium hydroxide and calcium silicate/aluminate hydrates. The physical binding of these hydration products cures the cement mortar and, together with the formation of lime ($Ca(OH)_2$), determines the structural integrity of the final product

Manufacture commenced in Australia in 1926 and these pipes were used extensively by some water Utilities in Australia up until 1986 when manufacture ceased due to the health and safety issues associated with asbestos. The use of these pipes was limited by water quality and was not generally used in waters which were soft and low in pH. However, in some situations bitumen coating of the AC was available to provide additional protection in soft or aggressive water situations. In harder water AC pipes were promoted as having exceptionally long life and large quantities were laid. In some Utilities, this type of pipe makes up more than 50% of pipeline assets.

AC pipes do not corrode in the way that steel and cast iron pipes rust, but instead it undergoes chemical conversion of the cementitious binder. There is often no discernable change to the dimensions as a result of this change, but the loss of binder or its replacement by a weaker product forms a weak material that, when damp, has mechanical properties that have been called (unfavourably) by water maintenance servicemen as wet cardboard.

Originally it was thought that AC pipes would not corrode, and life expectancies of the order of 80 -100 years were regularly quoted. This was found not to be the case in some situations where the pipes were buried in aggressive soils or where they conveyed aggressive water.

AC pipe deterioration can occur at both the internal and external surfaces of a pipe. Due to large quantities of AC pipe that have been used in water supply systems in Australia, New Zealand and many other parts of the world, the deterioration of AC pipe has been extensively studied [5,6] and is well understood. The deterioration is effectively a result of two processes[5]:

- Weakening of the cement matrix through attack by aggressive soils and aggressive water
- Weakening of the hoop strength of the pipe through saturation of the asbestos fibres

The resulting loss of strength begins to compromise the structural integrity of the pipe making it progressively more susceptible to failure due to internal pressure loads.

The common method used to assess the depth of deterioration or degradation of an AC pipe wall is staining with phenolphthalein indicator[5,7]. Phenolphthalein is a weak acid indicator that changes to a progressively deeper magenta colour from a pH of 8.3 to 10.0. This colour change and can be used to highlight the difference between the alkaline areas, where the cement matrix is sound, and the lower pH areas where the $Ca(OH)_2$ has been leached away (Figure A6).

Figure A6

Cross section of AC pipe showing internal and external deterioration. Un-deteriorated portions of AC show up as the coloured areas. (Courtesy Opus International Consultants)

2.2 Reinforced concrete pipes

Reinforced concrete pipes are used for some pressure applications but these are a minority compared to non-pressure sewer pipes. In most cases conventional reinforced concrete pipes manufactured with normal Portland cement were used, but in some areas calcareous aggregate was used to allow for a more uniform corrosion rate of the concrete. Hydrogen sulphide is particularly aggressive to concrete and severe corrosion can result in the vapour zone or the crown of the pipe (Figure A7). Ultimately the corrosion can be such that the structural strength of the pipe is severely compromised which usually ends in a collapsed sewer. Similarly, where odour control initiatives have been introduced in sewage treatment plants by covering tanks, very severe concrete corrosion can result (Fig A8).

Figure A7 - Relining of a corroded reinforced concrete sewer pipes shows the crown of the pipe has been severely corroded leaving only the base of the pipe and the collars at the joints where they were provided with some protection by the spigot of the other pipe.

Figure A8 - Severe corrosion of concrete in an aeration tank covered to reduce odours. The corrosion was up to 75mm in 3- 4 years despite the use of an extraction system.

CORROSION CHALLENGES – NAVAL DEFENCE

Graeme Emerton
Defence Materiel Organisation, Sydney

1. INTRODUCTION

Many studies into the cost of corrosion have been undertaken with the aim to demonstrate the benefit of preventative maintenance strategies; yet within the Naval environment repeated instances of unscheduled or ill defined corrective maintenance still exist. Of greatest impact, from the perspective of both cost and vessel availability, is corrective maintenance where the extent of repair is not fully defined prior to the commencement of repair. Case studies in this report will examine contributory factors to such situations on both aging and newer vessels. Extensive data analysis by the US Department of Defence has provided methods and metrics by which to measure corrosion prevention; not as a cost but as an investment which is measurably more effective than a programme of corrective maintenance. This report aims to assess the various systems and structures that exist within the Australian Defence Naval sector, evaluate how they influence the management of corrosion and use selected case studies to assess the potential for more effective expenditure by prevention of deterioration.

1.1 Naval Technical Regulation

Australian Defence Naval Assets are subject to an extensive regulatory regime, as articulated in the Naval Technical Regulations Manual[8] (NTRM). Compliance with NTRM is imposed through an extensive certification regime with a combination of Independent Third Party and Naval certification. In the context of this study, the importance of Naval Technical Regulation and the associated certification regime is the manner in which they influence the maintenance of Naval Assets through a series of Sustainment Organisations. Independent Third Party certification is most commonly provided by Classification Societies (Class); these societies have become increasingly active in the Naval sector over the last 10-15 years. This reflects a worldwide trend of Navies experiencing difficulty in the resource and development of their own discreet sets of regulations for the design, construction and maintenance of Naval assets.

Despite considerable resource being applied to education of Naval personnel, there remains difficulty in understanding and implementing Class requirements; in particular defining and integrating the Vessel Owner's maintenance requirements to ensure the stated aims:

> *"To efficiently and effectively maintain materiel so that:*
>
> *a. An optimum balance between availability and asset preservation is achieved during peacetime to meet operational readiness requirements without compromising fitness for service, safety or environmental compliance.*
>
> *b. Availability is optimised during a contingency to meet operational requirements, realising that safety margins and mission worthiness may be varied in a pre-planned manner."*[9]

Maintaining Class certification requires a structured survey regime, incorporating a system of "Conditions of Class" (Condition, or similar terminology depending on the Class Society). Conditions are imposed where survey items are found to be below the minimum baseline agreed between the Class Society and Vessel Owner, with the Condition being a formal notification of requirement for corrective action to be addressed within a specified timeframe. A key point to understand in the context of this study is that Conditions are always corrective, not preventative. The Condition itself results in additional expense to the Vessel Owner for the Class Society's costs associated with Independent Validation and Verification, ensuring the Owner's repair actions comply with applicable standards.

In Merchant shipping terms, imposition of Conditions allows a vessel to remain operational whilst remedial action is progressed, thereby allowing the Owner to keep to schedule and minimise the impact to business. In Naval terms this process is not well understood with some organisations relying solely on Class in order to determine through-life maintenance requirements; in effect being reliant on reactive decision making and corrective maintenance. If the business analysis has been undertaken to support such an approach, it's possible that reliance of corrective maintenance on a 'best case' scenario might be viable, however this study will demonstrate that a lack of consideration for contingent requirements will invariably result in cost, schedule blowouts and safety impacts where originally low risk safety issues are elevated to a higher level of risk.

1.2 Naval Personnel Training and Experience

Essential to the maintenance of Naval assets are the Engineering personnel; Marine Engineering (ME) Officers and Marine Technician (MT) Sailors. Over the last two decades the focus on training and development of personnel, particularly for MT sailors, has been as generalist operator technicians rather than specialist maintainers. This is particularly significant in the context of this report given the expertise required to prevent asset deterioration. Research has indicated that existing training modules for ship's husbandry have fallen into disuse. These will require resurrection and review in order to ensure future generations of ME & MT personnel have the requisite training and experience so to reduce through-life maintenance burdens.

Searches of Naval training courses for junior sailors found that courses such as Spray Painting and Ships Preservation are inactive, whilst Basic Corrosion Control is about to become inactive. This leaves the only active course Bosun's Mate (BM) Corrosion Control. Within the MT branch there are course modules on welding, fabrication, ship's stability and construction, however there are no modules on protective coatings or corrosion. In practical terms, the MT branch is responsible for managing the condition of the vessel whilst those in the BM branch are charged with ship's husbandry. The method of training within each branch ensures that neither branch relates the importance of these complementary roles for surface cleanliness, preservation and corrosion control. The operator technician training focus over a prolonged period has produced Senior Sailors who lack the underpinning experience of maintaining a Naval Asset. As mentors to and leaders of the Junior Sailors, it is this sort of information which is crucial to pass on to the Junior Sailors so their skills can be practiced and improved.

The deficiency of knowledge and its transfer has resulted in even greater reliance on contracted labour to perform tasks that could have been conducted by Naval personnel. Processes to engage contracted labour result in a 'report and forget' approach where the condition is not reviewed once a work request has been sent from the ship. More time is then taken to prepare work instructions, and estimate and schedule repairs with significant resource and cost expended in this process, further increasing the overhead cost of maintenance.

1.3 Maintenance Engineering

Maintenance of Royal Australian Navy (RAN) vessels is based on two facets; those of Organic Maintenance and those of External Maintenance. Organic maintenance is that which is undertaken on board by RAN personnel, whilst External maintenance encapsulates all other work undertaken by RAN personnel and contractors during scheduled maintenance periods. The RAN operates on a structured regime of External Maintenance Availabilities which should enable work requirements to be properly defined, scoped, scheduled and costed. Critical to the case studies herein is the requirement that:

> *"Maintenance planners and managers are to be aware of the consequences of maintenance items being omitted or deferred from work lists and ensure that financial or operational constraints do not impact on technical integrity."*[10]

Systems Engineering principles, as advocated within the NTRM, stipulate that continuous improvement by review of "lessons learnt" is a necessary requirement. Case studies within this report, together with review against United States Navy (USN) practices to measure corrosion by Return on Investment (RoI), will seek to demonstrate how existing engineering policy and direction can be adapted to provide greater assurance of technical integrity in conjunction with sound economic judgement.

1.4 Case Studies

As with other corrosion studies, this study confirmed the difficulty in collating a detailed cost breakdown of corrosion repairs. Whilst researching information for this report, data for the Amphibious vessel (section 3) represented total costs for labour, materials and 'other' due to the inability to pre-plan repairs. In the case of the Surface Force vessel (section 4) the detail appears to be available during tendering activities, and only the total base price plus growth on the base price and manhours are recorded for historical reference. Such limitations of data records make it difficult to isolate and analyse corrosion costs amongst other repair activities.

In order to minimise the impact of such a shortcoming, the selected case studies relate to corrective maintenance solely attributable to corrosion damage. Given this limitation, it was crucial to seek to conduct a broad and balanced review without a perception of bias for age or type of vessel. The following case studies examine both aged and relatively new maritime assets and analyse Amphibious and Surface Force assets which have a differing design ethos; the Amphibious vessel is designed and constructed using Merchant rules with higher damage tolerances, whilst the Surface Force vessels are designed and constructed to Naval rules with less damage tolerance. The significance of these differing design/construction philosophies is the impact upon maintenance strategies; the less the margin for damage or deterioration, the greater potential for loss of operational capability if a preventative strategy is not implemented.

2. ASSESSMENT BASIS

A US Department of Defence (DoD) report[11] illustrated the proportion of corrosion costs as shown in Figure 1. This report advocated a structured approach to recording corrosion costs as either preventative or corrective, utilising definitions from ISO 9000:2000 (such definitions are still valid in AS/NZS ISO 9000:2006). This cost ratio is used as a basis to work from in the absence of a similarly detailed study of corrosion costs by the RAN. The aforementioned US report notes that it's not simply a case of spending more on preventative maintenance, but establishing the correct balance, as Figure 1 illustrates. For example, renewal of protective coatings on a time based routine could result in excessive expenditure in the absence of wear rates or test methods to objectively assess deterioration rates.

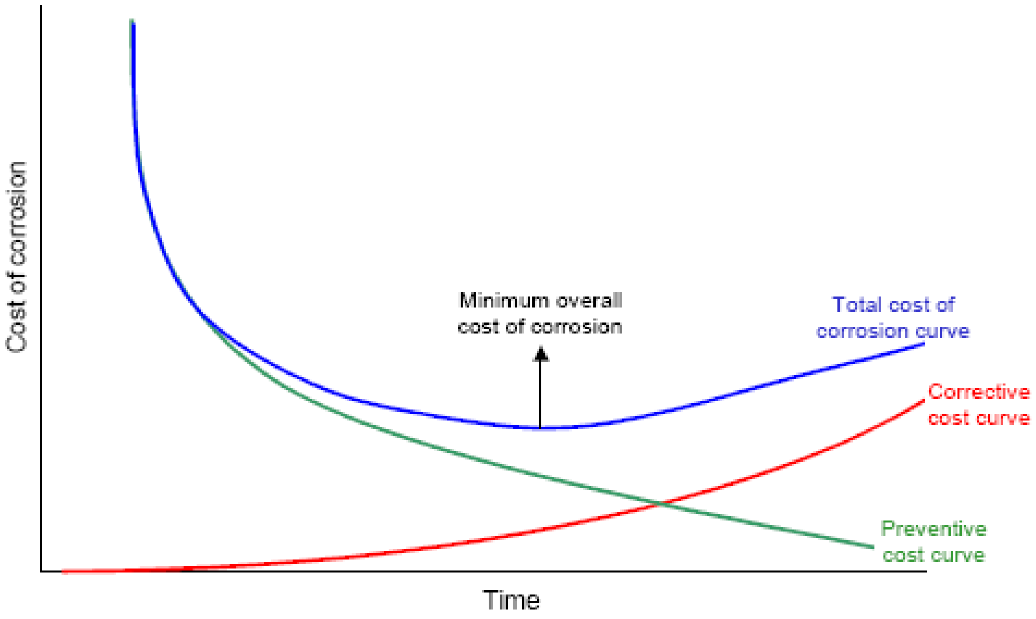


Figure 1 Preventive and Corrective Corrosion Cost Curves

Further USN research and analysis identifies that up to 30% of DoD corrosion cost could be avoided through investment in sustainment, design and manufacture[12]. Supporting this assertion are the data in Figure 2 which illustrate the cost impact of deferring repair. This is particularly relevant in an RAN Risk Management context. Cost when discovered is preventative maintenance whereas cost after 2 or 4 years is corrective maintenance.

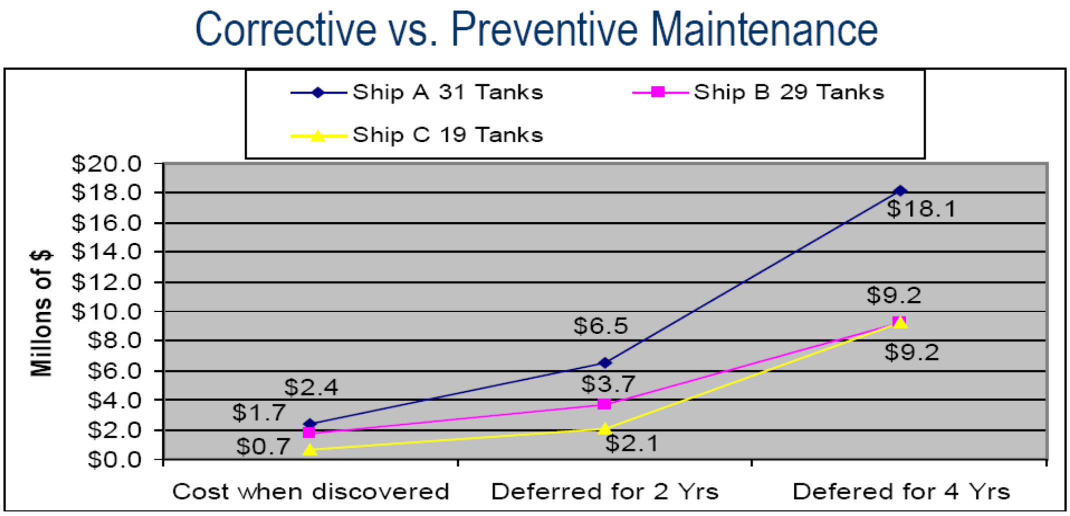


Figure 2 Corrective versus Preventive Maintenance

3. AMPHIBIOUS VESSEL

Current RAN Amphibious vessels are old and scheduled for replacement by the new Canberra Class LHD (Landing Helicopter Dock) in the first half of the current decade. Meanwhile, significant challenges have been experienced in sustaining the current amphibious assets with considerable cost and schedule overruns in maintenance availabilities; the consequence of which is disruption to scheduling individual vessels for operational deployments. This particular case study will use the example of a vessel with multiple areas of corrosion which resulted in extensive steelwork renewal. It will seek to analyse the cause of the corrosion and the cost of repairs, and will discuss the maintenance routines that could have minimised corrosion severity and the cost effectiveness of the alternative routine. Also of relevance is the emphasis on technical regulation and the role of Classification Societies providing Independent Validation and Verification, and how these influenced the decision making processes. It should be noted that routine husbandry and preventative maintenance tasks are not requirements of Classification Society, but a prudent Ship Owner's obligation. Through analysis of this case study it has become evident that Classification Society's role and value is not properly understood in Naval applications.

3.1 Vessel Design

The subject vessel has a service life of 30 years and was designed in accordance with merchant ship rules with generous scantling allowances. These typically allow for wastage between 25-30% of nominal plate thickness (NPT) before steelwork renewal is required. Such margins are reflected in the RAN's survey and repair policy and procedures[13] which also provides guidance on appropriate repair methods relative to the loss of plate thickness. An acknowledged difficulty with Naval operations, as distinct from Merchant operations[14], is that the service life and replacement of vessels is determined by Government policy. This results in differing influences upon decisions as compared to merchant vessels where an owner can determine vessel replacement at an optimal economic service life.

3.2 Corrosion Areas

Deep corrosion, requiring steelwork renewal, occurred in the following areas:

- After Peak Tank shell plate and watertight bulkhead to the Auxiliary Machinery Room
- Auxiliary Machinery Room shell plate
- Foredeck Cargo Hatch supporting structure
- Bow shell plate and supporting structure

The cumulative effect of the corrosion and immediacy of repair necessitated an unscheduled period of dry docking and attracted a total repair cost of approximately $1.9M of unplanned expenditure. Over the last decade the focus on sustainment of this vessel had been to reduce total expenditure due to its pending withdrawal from service in 2-4 years, however these savings have been on preventative maintenance with an increasing likelihood and consequence of corrective maintenance. Predicted cost savings were based on avoidance of steelwork renewal, with direct reductions on material and labour costs which could have been achieved through appropriate maintenance.

In the absence of a detailed breakdown of costs, estimations of cost savings are given as a rough order of magnitude. Each of the following examples represents worst case corrective maintenance expenditure and, relative to Figure 2, these examples typify the exponential increase in cost of repair due to deferral.

3.3 After Peak Tank

Structural Function:	Nominally a dry tank but can be used for ballasting if required.
Corrosion Protection:	Primarily by preservation (coal tar epoxy given the age of the vessel) with secondary protection provided by sacrificial anodes.
Damage Susceptibility:	Corrosion from immersion or atmosphere.
Planned Maintenance:	30 month survey interval. Deficiencies identified are planned and scheduled for subsequent maintenance periods.
Damage:	Corrosion in this tank, in a localised area, resulted in general wastage exceeding 80% of NPT. The area of corrosion was rendered inaccessible for purposes of routine inspection and maintenance due to obstruction by a section of pipework. Coating repairs indicated this section of pipework had previously been removed for access to conduct maintenance. Examination of survey records showed coating repairs were undertaken the following survey period, i.e. 2 years after defect identification, as they had been perceived to present a low risk to the integrity of the tank. Patch repairs of coatings throughout the tank showed signs of corrosion indicative of inadequate surface preparation and/or film build of the coating. Figure 3 shows the configuration and condition in this area.

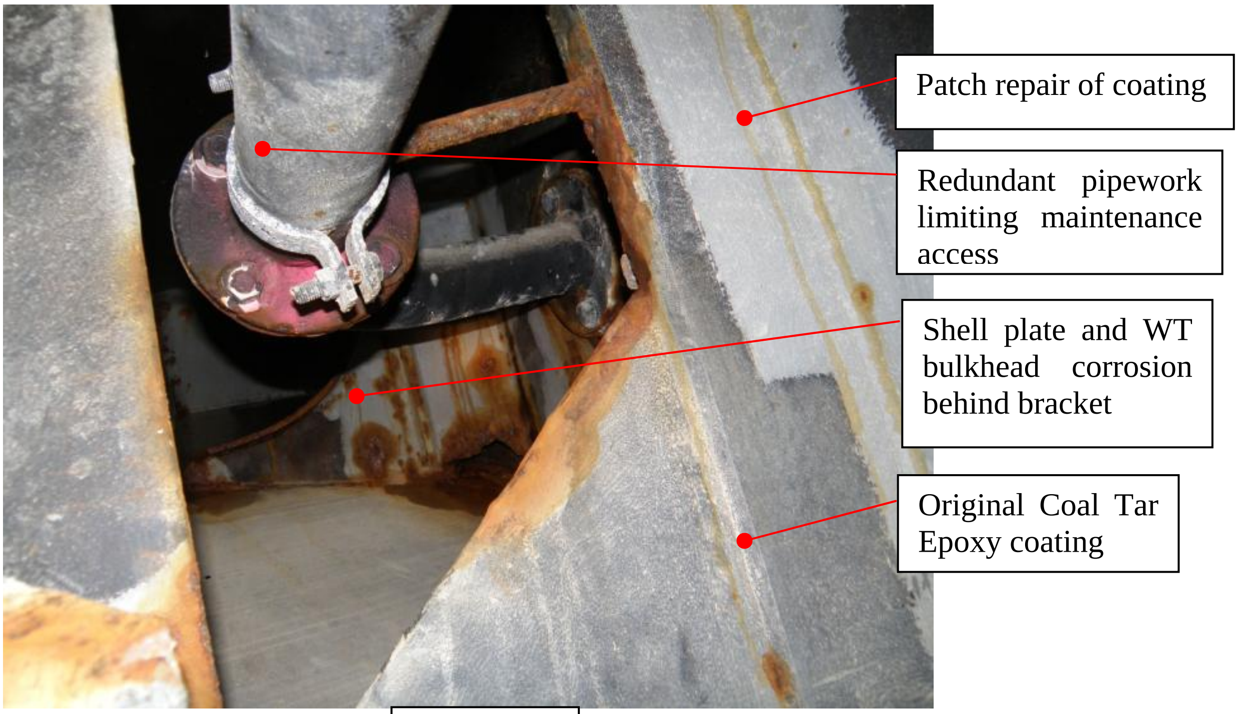


Figure 3

Repair Costs: Direct repair costs were dominated by labour which accounted for 89% of the total, with materials representing 8.7%. As the pipework was redundant, costs included removal of the redundant system. Indirect repair costs include a proportion of the unscheduled docking component, Project Management, the time the vessel was unavailable for operations and the time other vessel's operations were extended at short notice. Other costs not identifiable in the data include initial repairs undertaken in late 2009 which resulted in a Condition of Class being imposed due to the manner in which the repair was undertaken.

Review: A preventative strategy would be to address the removal of redundant material or infrastructure at the time of redundancy and improve upon the quality of coating repairs. Neither would have been a requirement of the Classification Society and therefore both are at the Vessel Owner's discretion. The pipework removal represents a one-off cost, whilst the life of coating repair is subject to preparation and application procedures which are well defined in specifications, but with reliance on a resident quality assurance system.

Detailed cost breakdown was unavailable (consistent with USN experience where quality of data was a limitation of analysis), however the direct cost of coating repairs is estimated at 10-15% of material and labour costs. Note that this approximation allows for costs associated with emptying, gas freeing and cleaning the tank; such costs are acknowledged as a significant contributor to routine maintenance costs. Offsetting the routine cost is the saving from a preventative strategy which mitigates against foreseeable eventualities such as unscheduled docking, with consequential savings to fleet scheduling and operations.

3.4 Auxiliary Machinery Room

Structural Function:	Hull shell plating and machinery support platform.
Corrosion Protection:	Protective coating.
Damage Susceptibility:	Corrosion from bilge lines draining directly onto shell plate.
Planned Maintenance:	60 month survey interval.
Damage:	Whilst repairs to the Aft Peak Tank were being undertaken, further deep corrosion of shell plating was evident underneath a machinery flat in the Auxiliary Machinery Room. Detailed inspection and thickness testing showed corrosion in excess of 50% NPT with the subsequent plate renewal extending the duration of the unscheduled docking period. Figure 4 shows the underside of the machinery flat, the related piping and shell plating. The cause of corrosion was attributed to drain lines plumbed under the deck, out-letting directly onto the shell plate and not into a drain tank.

Figure 4

Repair Costs: Material cost represented 12% of the direct repair costs with labour accounting for 83%. Indirect repair costs include a proportion of the unscheduled docking component, Project Management, the time the vessel was unavailable for operations and the time other vessel's operations were extended at short notice.

Review: A preventative strategy would address correct detailing and installation of drain lines to a holding tank. A detailed cost breakdown was unavailable, however the direct cost of coating repairs is estimated at 10-15% of material and labour costs. Noting that the paint specification is for a high performance polyurethane coating, there is already a commitment to prevention which should be supportable by appropriate organic maintenance (ship's husbandry) to extend coating life and minimise the onset of corrosion.

Whilst a machinery space is difficult to maintain over a 30 year service life, the margin of acceptable plate wastage is such that identifying the onset of coating breakdown or surface corrosion would provide adequate time to plan, cost and schedule coating repairs. Requirement for coating repairs is identified as low technical risk and therefore subject to continual review, but it does not consider coating deterioration leading to corrosion which can result in the proportionately higher cost of steelwork renewal.

3.5 Foredeck Cargo Hatch

Structural Function: Wheeltrack rails to support cargo hatch when sliding clear of opening. Wheeltrack has a local strength function, however it is attached to a main structural girder that compensates for the structural discontinuity in the main deck created by the hatch.

Corrosion Protection: Protective coating.

Damage Susceptibility: Corrosion from accumulated residue; lesser corrosion margin due to compromise on material thickness at build.

Planned Maintenance: 60 month survey interval.

Damage: The ship raised a work request for a survey and repair of the wheeltrack; however, work instruction was prepared without conducting the survey. Whilst repairs were being undertaken, "fractures" were identified in the repair area (Figure 5) and it was at this point a detailed survey was undertaken.

Wheeltracks are welded to a main structural girder either side of the cargo hatch opening (Figure 6); corrosion to the girder exceeded 50% of NPT over the length of wheeltrack under the Superstructure. Fractures resulted from extensive wastage of fillet welds to the main structural girder.

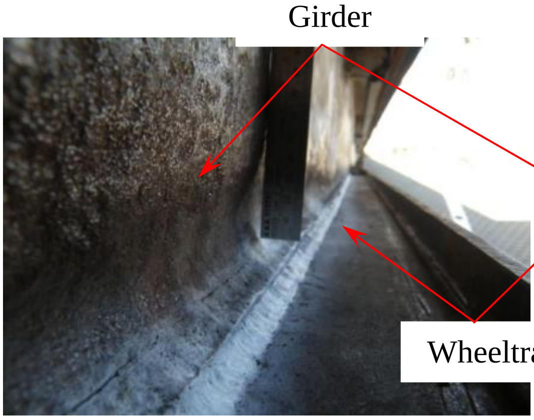


Figure 5

Figure 6

Repair Costs: The initial repair represented futile expenditure as all work had to be removed and the new repair required considerable increase in work scope. The final repair cost represented 650% of the originally budgeted repair; in addition to lost expenditure. Material cost represented 4.7% of repair costs with labour accounting for 78%. Scaffolding to the repair area impacted on indirect repair costs, and these also included Project Management, the time the vessel was unavailable for operations and the time other vessel's operations were extended at short notice.

Review: The manufacturer of the cargo hatch stipulated 12mm thick mild steel for the wheeltrack, however the ship's drawings identified it as being constructed at 10mm thick. The normally accepted corrosion margin is 25% NPT which would equate to 3mm for a 12mm thickness. As 2mm had, effectively, been 'removed' at point of construction, the result was that only a 1mm margin remained. Thickness testing of the wheeltrack showed diminution to 7.5mm, or 37.5% loss of NPT relative to the design requirement. Had the vessel been constructed under Class survey, the reduction in material thickness at build would have been subject to specific approval and a more rigorous through-life inspection regime.

The minimal corrosion margin necessitates a high level of ship's husbandry to keep the wheeltrack clean and prevent accumulation of debris. This would be supplemented by periodic renewal of coatings. Routine husbandry could be achieved from a mobile working platform with coating renewal necessitating scaffolding for the production period. Such preventative measures would not have been a requirement of the Classification Society and therefore are at the Vessel Owner's discretion. Such a strategy may not have prevented renewal requirements for the wheeltrack but would almost certainly have prevented corrosion of the girders. Based on a tonnage rate for steelwork renewal, replacement of the wheeltrack would be approximately 20-25% of the cost of girder renewal with coating replacement estimated at up to 10% of the cost of girder renewal.

3.6 Bow Structure

Structural Function: Shell plating and supporting structure at the bow.

Corrosion Protection: Protective coating (high build polyurethane).

Damage Susceptibility: Corrosion from accumulated residue.

Planned Maintenance: 30 month survey interval.

Damage: An accumulation of debris and visible corrosion around the site of debris lead to conducting a thickness test of the shell plate. Readings indicated localised wastage in excess of 50% NPT, with general wastage between 30-50%. A resurvey undertaken after the thickness testing indicated a high risk of excessive corrosion to internal stiffeners. The extent of wastage necessitated immediate repair due to the resultant loss of strength in the bow region. Once plating was cropped away, cleaning of internal framing revealed extensive deep wastage of web frames with some sections holed (Figure 7); a total of 8 web frames required repair on both the port and starboard sides of the bow, together with approximately 12m^2 of shell plate. Figure 7 shows how localised and severe the corrosion was, with the section marked up to be cropped back 350mm.

Example of internal web plate corroded & holed

Figure 7

Repair Costs: Material cost represented 2.8% of repair costs with labour accounting for 67.6%. The requirement for scaffolding, to enable the repair to be completed both in dock and afloat, impacted upon "other" costs which totalled 29.6%. Indirect costs included Project Management, the time the vessel was unavailable for operations and the time other vessel's operations were extended at short notice.

Review: Structure within the forepeak region of this vessel is a safety climber system that enables access from main deck level down to the equivalent of the 4th deck. Access to the port side of the structure is compromised by fitted hydraulic lines, the original installation of which could have been optimised (at additional cost to design and install) to improve maintenance access for routine cleaning and/or coating renewal.

Of the direct costs, labour could have been reduced dramatically and scaffolding avoided altogether if removal of accumulated debris had been routinely undertaken as part of a maintenance plan. A combination of an appropriate ship's husbandry preventative routine and preservation renewal as a corrective routine would have addressed through-life maintenance for the 30 year service life. This combination of preventative maintenance and condition based coating renewal, based on a square metre rate for abrasive blasting and preservation, is estimated at 10% of the cost of the immediate repairs described above. Neither routine would have been a Class requirement.

3.7 Return on Investment

In each case study, the necessity for corrective maintenance would have been avoided by conducting preventative maintenance at an appropriate time. The difficulty is in Naval sustainment organisations seeing the value in the cost of such maintenance when it's not required to maintain Classification Society certification. In essence, the Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR), as conventional maintenance engineering terms applicable to machinery systems, are not readily adaptable to the MTBF of hull structure designed for a 30 year service life with periodic thickness testing and a pre-determined allowance for wastage. Furthermore in a Naval context, whilst the cost of operating a vessel on a daily basis is known, this is not articulated in such a way that lost days of operation is measured in dollar terms against the cost of preventative or corrective maintenance.

In simple terms the cost of routine husbandry to remove accumulated debris or setup and conduct of preservation repair is significantly cheaper than steelwork renewal. Whilst a commercial ship operator can measure cost effectiveness of maintenance strategy against vessel unavailability and the resultant direct impact upon the income and expenditure necessary to keep the vessel operational, equivalent performance metrics are not visible in a Naval context.

With the next generation of amphibious vessels due for introduction into Naval service within the next 5 years, measures to define RoI have significant potential to ensure the value of preventative maintenance is properly defined. Such definitions also need to articulate the RoI from ensuring personnel on board have the competencies to undertake basic ship's husbandry, particularly in the areas of surface cleanliness, preservation and corrosion control.

Expenditure on the series of problem areas defined in the preceding sections is at the extreme end of the corrective cost curve in Figure 1 and consistent with the exponential increase in cost from deferral represented in Figure 2. In the absence of a detailed cost analysis, but noting the veracity of information from USN experience, a RoI for preventative maintenance in the selected examples of between 10:1 and 7:1 would appear plausible. Hence the $1.9M cost could have been avoided by expenditure of $0.19M to $0.27M in preventative maintenance over a period of time.

4. SURFACE FORCE VESSELS

Current RAN Surface Force vessels reflect a Military Off The Shelf (MOTS) design solution typified by the Adelaide FFG class frigates of USN origins, Anzac class frigates of the German Meko 200 design and the future Air Warfare Destroyers from Navantia. MOTS designs, from a hull and structural perspective, often have far more optimised scantling tolerances and are therefore more reliant on preventative maintenance to achieve the balance of asset preservation against asset availability.

4.1 Sea Inlet Tube Design

The ANZAC Class frigates have an extensive number of sea inlet tubes, underwater hull valves and overboard discharges; around 150 in total. These are designed to enable the valve to through-bolt to a flange which is in turn welded to the sea inlet tube in the ship's hull - all quote-conventional ship design. The intention is not to analyse the design detail in this report but focus on consequences of the design. However, it is worth noting that the ANZAC class design could be manufactured and installed at lower cost than that of the Navantia design to be used on the RAN Air Warfare Destroyers; hence the influence of through-life costs in the initial design can also impact on RoI.

4.2 Corrosion Areas

The design of tube connection results in a "shoulder" from the flange/sea tube to the valve and turbulent water flows around this interface. Erosion corrosion was evident at the first scheduled docking of HMAS ANZAC and has been a continual problem for RAN ANZAC class vessels since. This problem also highlights limitations with sustainment organisations focused on a single class of vessel, as this pattern of wear was not initially seen as unusual whereas specialist engineers with experience across many classes of vessels recognised the design limitations.

In order to ensure serviceability of the sea inlet tubes between scheduled dockings, a procedure was developed to remove the valves, document damage and set defect limiting criteria for localised weld repair or complete renewal of the sea inlet tubes. An example of wastage experienced can be seen in Figure 7 which amply illustrates the extent of wastage at the connection site of tube (40NB) and flange.

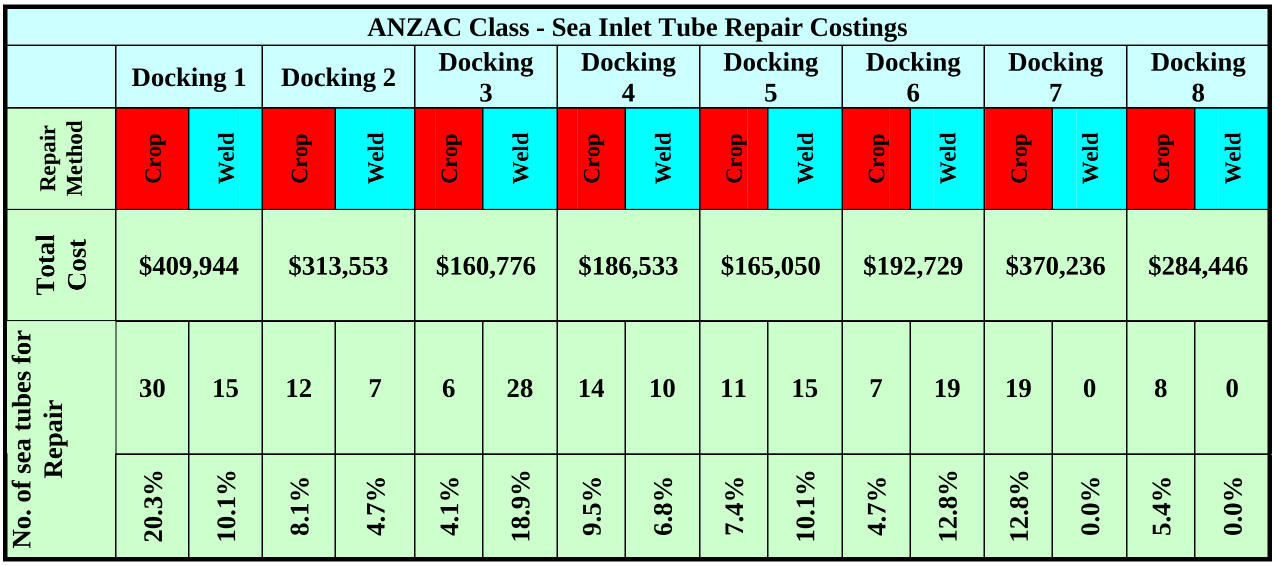
Example of erosion of sea inlet tube and flange; 40 NB tube

Figure 8

4.3 Corrosion Records

With the extent of corrosion increasingly impacting upon ship repair activities, additional rigour was applied to documenting necessary repair actions. These data were initially used to trace the rate of damage across the ANZAC class as a trend analysis. This enabled potential repairs to be more easily identified as an initial phase to predict likely replacement rates in order to pre-plan labour and material requirements. This lead into a second phase of pre-emptive action where it is determined which sea inlet tubes require targeting for an improvement to design, thereby preventing wastage. Recently it has been possible to verify the cost of repair of the sea inlet tubes across a selected number of docking periods. Repair method data, as tabulated against costs, is shown in Figure 9.

Figure 9



ANZAC Class - Sea Inlet Tube Repair Costings																
	Docking 1		Docking 2		Docking 3		Docking 4		Docking 5		Docking 6		Docking 7		Docking 8	
Repair Method	Crop	Weld	Crop	Weld	Crop	Weld	Crop	Weld	Crop	Weld	Crop	Weld	Crop	Weld	Crop	Weld
Total Cost	$409,944		$313,553		$160,776		$186,533		$165,050		$192,729		$370,236		$284,446	
No. of sea tubes for Repair	30	15	12	7	6	28	14	10	11	15	7	19	19	0	8	0
	20.3%	10.1%	8.1%	4.7%	4.1%	18.9%	9.5%	6.8%	7.4%	10.1%	4.7%	12.8%	12.8%	0.0%	5.4%	0.0%

The data available totals $2.08M for these 8 dockings, averaging $0.26M per docking. With eight ANZAC class vessels, based on a 30 year service life and three years between docking periods, a simple extrapolation indicates likely expenditure of $20M (excluding inflation) over the life cycle of the ANZAC Class. Whilst such potential expenditure warrants closer analysis, available data does not facilitate further breakdown of costs.

An unfortunate conclusion to be drawn from available data is that variability in base cost, growth on base cost and manhours (not presented in this report) is such that the real cost of these repairs is not fully understood; nor is how repair requirements influence each of these key measures. As a result of such variation, establishing measures of RoI or developing a business case to support redesign of the sea inlet tubes relies on average costs and the broad assumptions as discussed above.

From the tabulated data of sea inlet tube repairs, it's also evident that 59% have no recorded repair action beyond preservation; hence there may be an argument that too much maintenance is being undertaken. This would correlate with the preventative/corrective cost curves in Figure 1. Therefore whilst the second phase of trend analysis identified those sea inlet tubes warranting redesign, thereby reducing through-life repair costs, a third phase to confirm those with no corrective repair requirements may yield further reductions in cost by extending the inspection intervals.

Reference to industry guidelines[15] suggests that for the pipe sizes and schedules routinely being replaced, the manhours required to replace each sea inlet tube would be between 10-20 hours, excluding maintenance on the valve itself. Establishing manhour requirements against the list of sea inlet tubes on the ANZAC class would be a more accurate method of quantifying likely costs and qualifying the resultant business case to support redesign. RoI could then be measured, with the design costs amortized across the ANZAC Class, and initial replacement of sea inlet tubes with high rates of failure and replacement of other sea tubes could be dealt with on an "as needs" basis.

Implementation of a redesign is aimed at approximately 20 sea inlet tubes all of which have a clear history of excess wastage across the ANZAC Class. For the purposes of this study we can assume 10 are around 50mm diameter and 10 around 100mm diameter and both are equivalent to a Schedule 80 wall thickness. Based on these examples and using industry guidelines, replacement would take approximately 11 hours per smaller sea inlet tube and 20 hours for the larger tubes. This results in a total of 310 hours, per docking availability, expended on replacement of the sea inlet tubes. A further 6 to 9 hours per valve would be estimated for removal, servicing and reinstallation.

Based on the historical rate of repair and costs associated with such repairs, a possible RoI for redesign of sea inlet tubes and related maintenance processes on the ANZAC Class would reasonably exceed 10:1; however this is highly qualitative. Again, the lack of detail in costing data limits detailed analysis so to derive quantitative results.

5. CONCLUSIONS

The selected case studies presented in this report draw very similar conclusions to early US DoD studies where the quality of data was a key limitation. Such limitations prevent a full quantitative analysis at this time.

Case studies illustrate that the cost benefit of preventative maintenance over corrective maintenance is not fully understood by Naval agencies responsible for vessel maintenance. The Amphibious ship examples represent short term savings in preventative maintenance resulting in an exponential increase in corrective maintenance work scope, costs and impact on vessel availability for operations.

The role of Classification Societies and how they relate to a Ship Owner's maintenance requirements is not clearly understood in a Naval context. Independent Validation and Verification is not a function intended to remove the obligation of a Ship Owner to manage the condition and residual value of maritime assets.

Application of Naval Technical Regulatory requirements appears inconsistent with the intent. Whilst an overarching requirement of maintenance is to achieve a balance of asset preservation against availability, application of technical risk in isolation of cost and schedule risk is apparent. This requires further study in order to improve processes so that judgements achieve the required balance.

Shortfalls in training are now becoming apparent in the experience of personnel charged with operational level maintenance. This has resulted in a greater reliance on resources external to vessels in order to undertake maintenance that, whilst a 'low level' task, have the potential for considerable long term savings.

The ANZAC class example demonstrates the importance of higher quality data for deeper analysis in order to support more timely decision making processes. It further illustrates the importance of critical design reviews in order to address through-life support costs.

An absence of methodology to predict time, effort and resources required for corrective maintenance impacts on the ability to ascertain value for money. In addition to achieving the balance between preventative and corrective maintenance, the Return on Investment could also be enhanced through a shared knowledge base of ship repair cost estimation.

6. ACKNOWLEDGMENTS

Resources, reports and data available through the US Department of Defence Corrosion Exchange are specifically acknowledged.

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AUTHORS

Greg Moore - Principal, Moore Materials Technology Pty Ltd

Greg's career encompasses materials and corrosion prevention technology, durability and technology management. He has had 33 years of experience related to the durability and performance of materials and products in the Water and Wastewater Industry, initially with the South Australian Water Corporation and more recently as an independent consultant to the Water Industry. His field of expertise includes durability studies, metallic, plastic and other non ferrous pipe failure analysis, protective coatings performance and assessment, soil corrosivity, corrosion of stainless steels and other materials used in the water and waste water industry. Greg has also represented the Water Industry on numerous Australian Standards Committees and has provided significant input to the Water Services Association of Australia Infrastructure and Products Network.

Graeme Emerton – Hull Survey Manager, Centre for Maritime Engineering, Defence Materiel Organisation.

Involved in Naval Engineering for 28 years as a Naval Architecture engineering technologist, Graeme has worked the last 13 as a hull maintenance specialist with oversight of hull maintenance and repair across the RAN surface fleet. This role is uniquely positioned to share information and experience between RAN support systems around Australia and making effective use of the research being undertaken into corrosion by people and organisations both within Defence and associated with the Australasian Corrosion Association. Hull maintenance specialisation includes contributing to policy and standards development and implementation. This has included development specific maintenance plans for the hull and structure of RAN vessels, assessment and accreditation of Surveyors and conduct of surveys. Experience has also included damage assessment and supervision of repairs on RAN vessels deployed overseas.