A CASE STUDY OF A CORRODED CAST IRON WATER MAIN ON BRIDGE RD, RICHMOND

A.J Spark[1,2], D O'Keefe[3], I Cole[1], A.M Osborn[2], D Law[2] & L.P Ward[2]

CSIRO[1], Melbourne, Australia, RMIT University[2], Melbourne, Australia & City West Water[3], Melbourne, Australia

SUMMARY: Corrosion of cast iron water pipes, particularly localized pitting corrosion, can propagate leaks and bursts of pipelines which can lead to expensive repairs or replacement. One of the primary mechanisms which cause localized pitting corrosion within potable water networks is microbiologically influenced corrosion (MIC) due to the action of biofilms on the pipe surface.

City West Water (CWW), one of the four water companies servicing Melbourne, conducts an ongoing condition assessment program of its potable water pipelines. One of the non destructive testing technologies CWW uses as part of this program on its critical water mains to assess extent of corrosion is magnetic flux leakage (MFL). The information from this program feeds back into CWW's asset management risk model and subsequently the water mains renewal program.

In December 2014, a section of water main located at Bridge Rd in Richmond, Victoria was excavated as part of the condition assessment program. Soil samples and samples of the corrosion product from this in service pipeline were taken for further investigations to identify the microbial species present. From these samples microbial DNA was extracted and amplified which was confirmed via spectrophotometry and DNA gel electrophoresis. There is potential for these techniques to be expanded to a new non destructive testing technique for infrastructure to determine the presence of MIC.

By comparing MFL results, soil analysis data and the early stage microbial data, the aim of this investigation is to give a more complete understanding of the environment surrounding a pipe and how this may contribute ultimately to pipe failure as a result of corrosion. A better understanding of the environment and condition of pipelines through a range of non destructive testing and how this correlates with the corrosion mechanisms occurring could lead to strategies for improved durability design and maintenance.

Keywords: Water pipeline, Localised Corrosion, Soil, Magnetic Flux Leakage, molecular microbiology

1. INTRODUCTION

Many of Australia's potable water pipelines were laid in the late 1800s to early 1900s; with seventy percent made of ferrous based materials (1). Given the length of time these pipes have been in service, the greatest risk to their failure is corrosion. General corrosion along the length of the pipes is a low risk, particularly as the pipe walls would have been originally designed to be significantly thicker than required mechanically. Coatings were unlikely to have been applied during the time period when the bulk of these mains were laid(1), so this protective measure does not need to be considered. However, localized pitting corrosion from the external surface is a significant risk to the integrity of potable water pipelines (2). Such corrosion can propagate isolated leaks and bursts which can lead to expensive repairs or replacement, while the majority of the pipeline remains unaffected. The soil environment, including moisture and oxygen levels which are dependent on the type of soil and the number of pores present, plays a significant role in determining the severity and rate of corrosion that occurs (3). One of the primary mechanisms which cause localized pitting corrosion within potable water networks is microbiologically influenced corrosion (MIC) due to the action of biofilms on the pipe surface.

City West Water (CWW) is one of the four water companies servicing Melbourne with potable water and sewerage services. CWW has approximately 4000 kilometres of potable water pipes and 4000 kilometres of sewer drains throughout its network. In order to prioritise the remediation and renewal of assets, CWW conducts a condition assessment program on both water mains and sewer pipes. As part of the condition assessment program CWW has historically used magnetic flux leakage (MFL) on its critical water mains to assess extent of corrosion and pipe deterioration, especially to determine the levels of localised corrosion occuring. The information from this program feeds back into CWW's asset management risk model and subsequently the water main renewal program.

Two additional methods for determining the likely causes of corrosion present along a pipeline where localised corrosion is suspected are soil analysis and molecular microbiology techniques (4). These also have the advantage of being able to assist in the determination of the mechanism of corrosion present. Soil analysis is a method that has been used for many years to determine the corrosiveness of the environment through which pipes are being laid (1). Many standards are available globally to assist design engineers in determining the most appropriate steps to minimise corrosion in soil, based on soil analysis results. A deeper understanding of the soil structure and moisture content also gives, in addition to information about corrosion potential (5), an indication of what microbial species may or may not be present allowing a more complete picture of the environment along a pipe to be determined (6).

Molecular microbiology is a relatively new field that is beginning to be employed in the study of corrosion. With the advent of new, faster and cheaper DNA and RNA sequencing technologies (7), it is now possible for bacteria and other microorganisms to be identified based on their molecular structure in a relatively short time period. This technique has been used to identify microorganisms in rust tubercles in a marine environment (8) and from this associations drawn between the species present and the potential mechanisms of corrosion. Many further applications of these techniques are possible within the field of MIC including the study of corrosion product on the internal surface of potable water pipes (9), though as yet it has not been applied to the study of corrosion on the external surface of potable water pipes or been achieved without the destruction of the infrastructure component under investigation.

In December 2014, a section of water main located at Bridge Rd in Richmond, Victoria was exposed via excavation of the surrounding soil as part of CWW's condition assessment program (Figure 1). MFL data was collected on site and soil samples taken for soil analysis. Additional soil samples and samples of the corrosion product scraped from the external surface of the in service pipeline were taken for further investigations to identify whether microbial species were present. By comparing MFL results, soil analysis data and microbial data, the aim is to give a more complete understanding of the environment surrounding a pipe, the condition of the pipe and how this may contribute ultimately to pipe failure.

Figure 1: Photo of excavated pipe

2. METHODS

2.1 Magnetic Flux Leakage

MFL is a non-destructive analysis tool which locates defects and corrosion hot spots found on pipes. If underground, the tool requires excavation of the pipe and removal of external coatings and scaling. The method utilizes a large magnet on the external wall of the pipe which magnetizes the exposed steel. A sensor then analyses the magnet field throughout the metal, and where a defect or corrosion is present, a loss or 'leakage' of signal is recorded. Typically a metre length is measured over the circumference of the pipe. The tool can give a high resolution profile of the condition of the pipe.

The technique involves considerable data analysis and interpretation of results to correctly identify faults and regions of metal loss. Whilst providing an overall scan plot, the CWW's service provider also provides location and depth of the ten worst defects in relation to remaining wall thickness.

For the past seven years CWW has utilised this technique as the primary condition assessment tool for the condition of critical assets throughout their potable water network.

2.2 Soil Analysis

Soil analysis testing was conducted both on and off site to CWW's specifications. They were carried out in accordance with standards appropriate to the tests conducted including BS 1377-3 (10); AS 4419 (11) and AS 4454 (12). Moisture content, resistivity (both on and off site), chloride levels, sulphate levels, pH, soil heterogeneity and soil texture were all tested. Soil was collected on site at the mid height of the pipe.

2.3 Molecular microbiology

In order to confirm the presence of bacteria on the surface of the pipe where corrosion was seen, microbial DNA was extracted from three corrosion product samples and three soil samples from along the pipe. A MoBio Power Soil kit was used, following the instructions of the manufacturer except for the final elution step where 100µl of sterile distilled water was used as per a previously established protocol (13). The DNA extracts were stored at -20°C. Bacterial 16S rRNA gene sections of the DNA were then amplified using a single step Polymerase Chain Reaction (PCR). The mastermix used for PCR consisted of 1 unit of 10mM deoxynucleotide triphosphates (dNTPs), 2.5 units of 10x buffer, 1.5 units of 50mM magnesium chloride, 0.25 units of 5U/µl polymerase, 2 units of 10pmol/µl forward (515f) and reverse (806r) primers, 13.75 units of sterile water and 2 units of template DNA. During PCR the protocol listed in Table 1 was adopted and followed.

Following PCR, the success of the DNA extraction and amplification processes was confirmed with with a NanoDrop spectrophotometer and electrophoresis in 1.2wt% agarose gel.

Table 1: PCR protocol (14). At each step the samples are brought to the given temperature and held at that temperature for the time indicated.

Step	Temperature (°C)	Time (minutes)
1	94	3:00
2	94	0:45
3	50	1:00
4	72	1:30
5: go to step 2, repeat 34 times		
6	72	10:00
7	4	Infinite hold

3. RESULTS

3.1 Magnetic Flux Leakage

Visual inspection showed the pipe to be in good condition, especially for its age, with some faint regions of orange corrosion product present on the external surface. As the pipe had been wiped down prior to the inspection to remove all remnant of soil, it is possible that more obvious signs of corrosion had been removed.

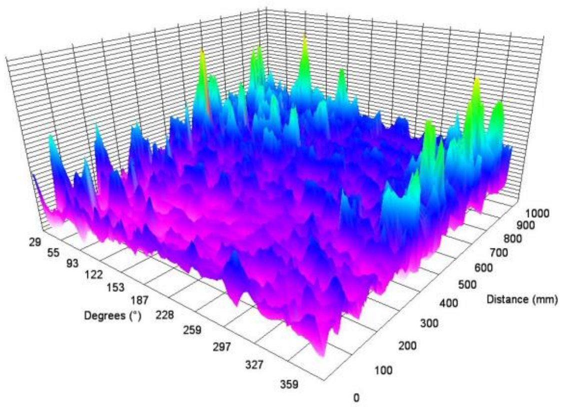

Figure 2: MFL Scan Plot

Results from the MFL scan (Figure 2) show significant pitting corrosion has occurred across certain regions of the pipe section investigated. The most severe pitting all occurs within a 100° quadrant across the pipes circumference as shown in Figure 3 which corresponds with the crown of the pipe, road side. The ten worst defects recorded (Table 2) are all through wall corrosion defects. Axial location refers to distance along the pipe of the one metre section scanned. Orientation refers to position around the pipe with 0° being the top of the pipe.

Table 2: The ten worst defects located in the MFL scan.

Defect no.	Orientation (°)	Axial location (mm)	Defect diameter (mm)	% wall thickness remaining
1	0	432	11	0
2	0	539	11	0
3	29	627	19	0
4	0	815	17	0
5	0	708	12	0
6	0	465	5	0
7	29	69	13	0
8	0	857	17	0
9	0	685	8	0
10	93	598	8	0

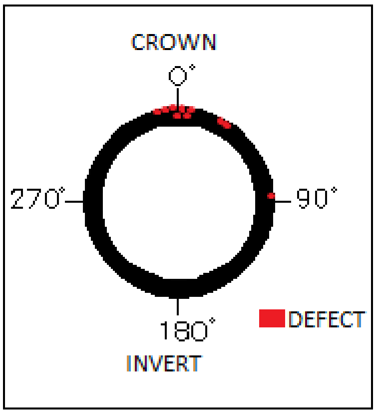

Figure 3: Cross Sectional Area of Pipe Defect

3.2 Soil Analysis

Soil conditions were analysed both on and off site by CWW's contractor. Using the AFNOR scheme (15), which is a French standard, the soil was determined to be highly corrosive. It was a heavy, impermeable, silty clay based soil with a moisture content of 31.5% and resistivity of 500 Ω.cm when measured on site in accordance with BS 1377- Part 3 (10). It also had a pH of 7.2 and a chloride content of 98.6 ppm.

3.3 Molecular Microbiology

Both spectrophotometry and gel electrophoresis were conducted to determine the success of amplification of segments of the extracted DNA with single step PCR. Spectrophotometry results, shown in Table 3, show DNA was extracted and amplified from all six samples sites with quantities ranging from 685±36 ng/µl to a maximum amount of 1002±156 ng/µl.

Table 3: Spectrophotometry data following amplification

Sample	Average mass of DNA (ng/µl)
Corrosion product (CP) 1	1002 ±156
CP 2	865 ±160
CP 3	685 ±36
Soil (S) 1	837 ±91
S 2	936 ±195
S 3	730 ±166

Each of the amplicon solutions were verified by gel electrophoresis. When matched against sizing ladders (HyperLadder 1kb plus and HyperLadder 100bp plus) the amplified DNA were shown to be in the range of 300bp, as expected. There was also no contamination of the amplification process. This indicates DNA was successfully extracted from both the soil samples and, more uniquely, the corrosion product scrapings.

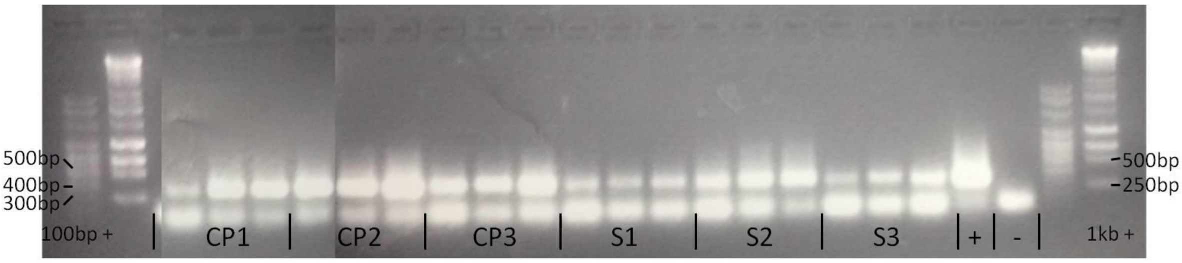

Figure 4: Image of gel electrophoresis results showing consistently sized amplicons and no contamination

4. DISCUSSION

4.1 Magnetic Flux Leakage

Considering the age of the main, there were no visual signs of weeping or leaks discovered during the excavation. There was however, evidence of localised corrosion in the form of regions of corrosion product on the external surface. A precursor ultrasonic scan at key intervals including the crown of the pipe identified major pits, albeit not through wall corrosion.

The report identified the ten worst defects along the pipe interface all of which were through wall pits. Many of these defects were concentrated on the crown of the pipe along the 1m length, with the only one not on the crown of the pipe being located at 93°. The disparity in defect size detected between the precursor ultrasonic scan and the MFI scan suggests a limitation in one or both techniques and that multiple techniques should be used to get an accurate understanding of the condition of an asset. The finding that all ten of the worse defects in the pipe are on the top half of the pipe and that the bottom of the pipe is relatively free of significant pitting suggests that there has been water flow on the bottom of the pipe (16, 17). Due to compaction of the soil directly below a pipeline, the bottom of a pipe is an area where water will collect as it struggles to flow further down, especially after heavy rain fall. This would reduce the oxygen concentration along the bottom of the pipe and also decrease the number of triple phase boundaries along this section of the pipe leading to a decrease in corrosion rate (3). While there was no visual evidence of this during the site inspection, the pipe was excavated below the level of the pipe so this may have been missed. The soil above the pipe where the worst defects are clustered would be the least compacted, so that this area would have the most porous structure allowing water to flow freely through the soil, leading to oxygen levels being readily replenished (18). This would increase the corrosion rate on the crown of the pipe.

Given the age of the pipe, there were no standards to describe how the soil should be replaced around a pipe. Disturbed soil is more porous than undisturbed soil and generates a higher risk of corrosion (16). It is also likely that there would be a higher concentration of bacteria present, as more pores in the soil allows more water to flow and it is with water that bacteria are able to move through soil (6). MIC is a possible cause of the pitting corrosion observed along the top of this pipeline.

Another potential cause of the pitting corrosion observed is stray current corrosion. It has been well documented that stray current from the DC train and tram networks has an effect on Melbourne's underground metallic assets (19). Stray current passes through the soil to pipelines where, if it discharges from the pipe, rapid corrosion can occur. A City West Water investigation was undertaken recently along the length of the pipeline under study to determine how 'active' the pipeline was in relation to stray current. It was found that this particular piece of pipeline showed very little evidence of the phenomena. More testing is required along the length of the main to determine if stray current corrosion is contributing to degradation of the whole pipe.

4.2 Soil Analysis

Defining the corrosivity of a soil environment is a difficult endeavour, especially along a pipeline as the soil environment is likely to change over the length of the pipe. The most commonly cited values when considering soil corrosivity are the pH of the soil, chlorides, the resistivity of the soil and the type of soil. According to the Australian Standard, AS 2159, which deals with the exposure classification for steel piles in soil; a resistivity of less than 1000 Ω.cm in a low permeability soil such as silts and clays indicates a soil of moderate risk for corrosion (20). However, given that the soil along a pipeline is disturbed, the risk category for this type of soil is severe. The pipeline under investigation was buried in a silty clay soil and a resistivity of 500 Ω.cm was measured on site. Resistivity is commonly regarded as the most important condition to consider, though there is some debate as to whether this is a good indication of corrosivity in soil and whether other factors should be considered in more detail (1). A pH of 7.4 would suggest that the soil is non-aggressive, especially with chloride levels as low as those found in the soil along this pipeline as the 98ppm found is well below the 10000ppm in groundwater that is considered to be aggressive. This inconsistency between suggested corrosivity levels dependent on the condition investigated is one of the reasons determining the risk of soil is highly subjective.

The composition of the soil gives several indications as to the likelihood of corrosion. Clay based soils are more likely to be corrosive than sand based soils as the smaller pore structure of clay traps moisture within the soil (18). In sand based soils water runs through the large pores rapidly. Clay based soils also have more triple phase boundaries due to the smaller pores which increases corrosion (3). Increasing moisture levels in soils increases corrosion rates until an optimum moisture content of 60-65% is reached as the more moisture there is the higher the chance that buried metal will come into contact with water in the soil allowing corrosion to occur, if there are aggressive ions present to initiate corrosion. However, as moisture increases, aeration decreases as they compete for the same space, so that above the 60-65% level there the reduced oxygen levels present begins to reduce the rate of corrosion. This pipe was buried in silty clay soil with a moisture content of 31.5% so the corrosion rate could be predicted to be moderate to severe.

Considering the resistivity measured of the soil surrounding the pipe, as well as the moisture content and type of soil the environment the pipe is exposed to should be classed as a moderate to severe corrosion risk, as determined by the contractor. Given the pipe has survived since 1865 with, at least on this section, no major maintenance work or failures, this suggests that there is a need for a greater understanding of the contributing factors of corrosiveness in the soil environment.

4.3 Molecular Microbiology

Bacterial DNA has been successfully extracted from both the soil samples and corrosion product samples obtained from along the pipeline. Both the spectrophotometry and gel electrophoresis results demonstrate this as they show that there has been DNA of sufficient quantity and of the correct size been produced. They also demonstrate that an appropriate PCR protocol has been chosen for the number and types of bacteria present which, given the novelty of extracting DNA from corrosion product, is important.

This is the first instance we know of where bacterial DNA has been extracted from corrosion samples taken in a non-destructive manner from a piece of buried metallic infrastructure that is still in service. The potential for this to be explored further as a non-destructive testing technique to determine the likelihood and contribution of MIC to corrosion in a system is vast and would have a wide range of applications. As molecular sequencing gets cheaper it will become more widely available and more accessible for non-biologists.

4.4 Summarising Remarks

The pipeline under investigation has been in functional operation for 150 years so some corrosion is expected. At this stage in the pipe's life it is still in good condition over the bulk of the surface examined, with only the crown of the pipe experiencing major pitting. The pits at the crown of the pipe have penetrated the surface of the pipe, but yet there was no visible water loss. Taking into consideration the soil environment surrounding the pipe, pitting is expected though pits would be expected along the sides of the pipe as well as the crown. There were no chemically corrosive substances detected in the soil in sufficient concentration to have contributed to the pits, suggesting an alternative cause. MIC is known to contribute to pitting and localised corrosion of buried infrastructure, such as pipelines. Bacterial DNA has been extracted from both the surrounding soil and corrosion product found on the pipe and given the pitting observed is in a specific region of the pipe, there is potential for MIC to be involved.

5. CONCLUSION

Over the one meter section of pipe studied, pitting defects were detected in fairly even distribution across the crown of the pipe. Taking into consideration the soil type, chemical composition, moisture content and resistivity of the soil it can be determined that there are likely to be other factors involved in the pitting corrosion observed, especially as it is unusually limited to the crown of the pipe. Bacterial DNA has been successfully extracted from scrapings of corrosion product from an in-service pipe, which with future work could prove a significant new non-destructive technique to test for MIC. A detailed understanding of the pipe environment has been obtained through this case study; however more research is required to determine how the environment, especially any microbial communities, may contribute to the pipe's failure. It would also be of benefit to compare samples of corrosion product taken from different places along the same pipe and to other pipes of comparable age and material.

6. FUTURE WORK

Following on from the successful extraction of bacterial DNA from soil and corrosion product samples from the pipeline, analysis of the bacterial components of the community can be undertaken to contribute to the understanding of the environment surrounding the pipeline. The bacterial 16S rRNA gene sections will be sequenced on an Illumina platform. Bioinformatics analysis of the sequencing data can then be used to identify the composition of the bacterial communities present in the soil samples and on the corroded pipe surface via comparison with online databases. Both soil and corrosion product samples were taken to enable comparison of the bacterial communities to determine if there were species present that were more attracted to or flourished more next to the metal surface than in the bulk soil. The species more attracted to the metal surface can then be analysed and used in lab based testing to determine whether they play a role in corrosion.

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AUTHOR DETAILS

Amy Spark is in her third year of a PhD with RMIT University and CSIRO, focussing on the electrochemical mechanisms of MIC at the steel/soil interface of carbon steel water pipes. She graduated from Monash University in 2012 with a double degree in Materials Engineering and Biomedical Science. Previously she has worked in water treatment for Goulburn Valley Water and in advanced materials and asset management with AECOM. In 2014 she was awarded the ACA's Marshall Fordham Award for Best Research Paper.

Dylan O'Keefe is a corrosion engineer in the Asset Performance Department at City West Water. He graduated from RMIT in 2010 with a degree in chemical engineering. He has worked at City West Water for the last five years in various roles and is currently responsible for the condition assessment and cathodic protection of City West Waters metallic assets.

Dr Cole is a Program Director in the Manufacturing Flagship at CSIRO. His depth of expertise in material science and mathematical modelling allows him to work in areas such as manufacturing and aerospace alloy corrosion protection. He was awarded the Silver Medal, BAE Systems Chairman's Award for Innovation and the Guy Benough Award throughout the course of his career.

Dr Law is currently a lecturer at RMIT University. His research interests are in the durability and performance of reinforced concrete structures. Particular areas of research are in electrochemical monitoring and protection, the use of sustainable materials and material properties of concrete.

Dr Ward currently holds the position of lecturer within the School of Civil, Environmental and Chemical Engineering, RMIT University, since 1996. His background is in Metallurgy and Materials Engineering, having obtained his Ph.D. in the development of PVD coatings for orthopaedic applications from Newcastle Polytechnic, UK, in 1991. Research interests are focussed predominantly in the area of surface engineering, specifically structural characterisation, corrosion and wear behaviour and surface modification using ion implantation.