CRANFIELD UNIVERSITY

PREDICTING SERVICE LIFE OF STEEL TUBES IN BUILDING
AND INDUSTRIAL SERVICES

SCHOOL OF MANUFACTURING
MRes MANUFACTURING

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Academic Year:2018-2019

Supervisors: Dr S A Impey and Dr J Macadam
                 February 2020

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ABSTRACT

There is a real need to be able to predict the service life of pipework systems taking account the relevant service conditions. The requirement is to translate corrosion control and corrosion behaviour of small-scale coupons representing small parts of pipes to the behaviour of larger pipework systems (for industrial relevance). The research considered a range of factors influencing corrosion and methods currently used for assessing and determining corrosion rates of pipework systems.

Linear Polarization Resistance (LPR) was used to compare results of static and dynamic measurements on carbon steel tubes. The effect of dissolved oxygen, flowrate, surface condition, water chemistry and weld were investigated. Other factors were considered for example; material composition, water (source, composition, hardness), temperature and time.

In order to provide recommendations to accurately predict long service life of metal pipework systems from short duration measurements, a range of relevant service conditions were set up with tap water (from two sources) conveyed in open and closed systems.

Data was assembled from a range of measurement methods and systems in small scale laboratory tests and flow loops to represent pipework systems. The data generated demonstrated correlation and highlighted that dissolved oxygen and flow rate were the main factors influencing corrosion measurement across length scales in static and dynamic environments. A case study was undertaken to consider issues around monitoring a small pipework system in reality.

Corrosion is a dynamic activity and careful attention to a range of influencing factors experienced by a pipe system before and during service and it is important to gather as much relevant information as possible. The use of LPR probes, the probe cleanliness and maintenance, care with handling coupons and a combination of water analysis and LPR measurements are recommended to improve the prediction of service life.

ACKNOWLEDGEMENTS

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LPR   Linear Polarisation Resistance

BIM   Building Information Management

HVAC   Heating Ventilation Air Conditioning

DO   Dissolved Oxygen

1 INTRODUCTION

Pipework systems form the core of most buildings and structures. They bring life to the buildings through the supply of water, heat, air-conditioning, ventilation as shown in Figure 1-1, and are used in drainage to remove material from the building.

Figure 1-1 Illustration of industrial pipework in buildings[Building.co.uk]

The advance in technology offers easier design for buildings with the development of BIM (Building Information Modelling) software [Autodesk]. BIM is said to "be an intelligent 3D model-based process to provide tools for professionals to efficiently plan, design, construct, and manage buildings and infrastructure" [Lorek 2018]. One aspect in which BIM is used is in modelling the pipework systems. With the help of BIM the whole pipework system can be designed and tested. The choice of material for pipes is also made at this stage.

At an early stage, BIM designs might require accurate, representative data which could (it is envisaged) include corrosion rates which depend on the choice of pipework material, pipe dimensions, environment, flowrate, whether a closed or open system. It is imperative to be able predict the service life of the pipework systems at the design stage so that issues such as: additional service life offered by choice of material, keeping uniform material throughout system to avoid

dissimilar metal corrosion and when to maintain, check, repair or replace to avoid failure in service.

1.1 Project Aim

The aim of this research is to provide recommendations to accurately predict long service life of metal pipework systems from short duration measurements, considering the relevant service conditions, when conveying water in open or closed systems.

In order to do this the following objectives were set to:
- assemble data from a range of measurement methods and systems in small scale laboratory tests and flow loops to represent pipework systems and identify contributing factors
- use the data generated to demonstrate correlation and main factors influencing corrosion measurement across length scales in static and dynamic environments
- recommend qualitative and quantitative approaches to improve and predict service life accurately from lab corrosion rates.

2 LITERATURE REVIEW

2.1 Challenges for industrial pipework systems.

Welded non-alloy carbon steel tube is widely used within the building service industry. Termed conveyance tubes, applications include heating, ventilation air conditioning (HVAC), fire prevention and natural gas. Carbon steel is a durable and cost-effective solution when used in a system designed to reduce corrosion risk, if handled, installed, operated and maintained. However, as a metal, it is prone to corrosion when the right steps aren't followed. Section 2.4 outlines the principles of corrosion and many factors influencing corrosion.

There have been further new challenges in the building service sector over recent years, largely aimed to reduce rising costs, but have permitted opportunities to the UK market from many other steel manufacturers which have resulted in concerning issues of corrosion and service life.

For example, for many years UK wall thicknesses of welded non-alloy carbon steel tube (exceeding 2-3 mm) provided a certain corrosion thickness allowance which permitted system testing and commissioning. Over the last 15 years or so, thin walled carbon steel from Europe and tubes of the thicker walled product (over 2-3 mm) from a range of suppliers across the world, have entered the UK market. With the thin walled product, 1.5 mm wall thickness, very little corrosion allowance is available. It is noted that the UK's first major report of internal corrosion in thin walled tubes came when the opening of a new critical care unit at Belfast's Royal Victoria Hospital was significantly delayed after corrosion of pipework was detected in the new heating system during final checks. The project was a PR disaster, coinciding with the rapid rise of social media and unsubstantiated comments about the performance of thin walled carbon steel. The report says the impact of this is still felt today. [Geberit 2019]

Other challenges are increasing steel volumes for single projects which place high demand on single suppliers. Taking London as one example, many high rise

buildings are under construction. The New London Architecture annual London Tall Buildings Survey 2017 reports that were 510 buildings of over 20 storeys planned for London, an increase of 455 buildings when the survey was carried out in 2016. [Mairs 2018]

Previously, it is thought, steel purchase has been, in the main, for low rise and owner-occupied projects. Such tall buildings require enhanced HVAC systems, with associated increase in steel volume. Challenging prices over the past years and lead time requirements for bulk purchase have led to increased supply to the UK of product reported to meet similar standards but from multiple manufacturers, Within the building services industry, it is standard practice for suppliers to obtain carbon steel from multiple manufacturers to reduce lead times and cost. Current national standards for non-alloy steel tubes do not specify a manufacturing method or state test results and inspection certificates are compulsory [Grimmer 2017]. Current national standards for non-alloy steel tubes at ambient operating conditions are EN 10255 and EN 10217-1 [BS EN 10255:2004] [BS EN 10217-1:2002]

The variability within the standards has led to conflicting information within the building service industry. The lack of specific requirements in the standards may have led to contradicting information available in the market, but also a potential for tubes to the same specification to vary considerably from manufacturer to manufacturer. National standards are in place to provide a level of quality and benchmark consistency. However, EN 10255 inspection requirements allow tube to be supplied with only a declaration of compliance. A piece of research to assess tubes from 8 manufacturers showed that tubes of the same standard do vary significantly between manufacturers considerably influencing service life, particularly corrosion. [Grimmer 2017]

Other concerns with multiple storey building are many different tenants with different needs for building service requirements e.g. different technologies for HAVC systems and fixtures (aesthetics). Some storeys may remain largely un-

occupied except for brief periods and issues over commissioning, maintenance repair and ownership, become very complex. Modifications from one tenant could influence an entire building service system.

Antony Corbett, product manager of piping systems for Geberit explains: "Precision carbon steel (i.e. 1.5 mm thick tube) comes with its own considerations. It is only suitable for specific applications, namely in closed water systems where dissolved oxygen levels should be lower than systems with open or vented tanks." [Geberit 2019]

Corbett advises that thin walled carbon steel pipework should not be installed outside buildings without adequate protection, in open systems, or with excessive water treatment. "Simply switching to other materials will not address the problem," he contends. In fact, specifying a material such as stainless steel or other tubes will only move the problem within a system of mixed pipework materials. This is mainly due to pipework corrosion being accelerated through the formation of a galvanic cell and occurs when two metals are physically connected and placed in an electrolyte such as water. Similar issues occur when mixing tubes from different suppliers with different steel chemistries and dissimilar or galvanic corrosion can occur. In such cases there is considerable need for corrosion monitoring as outlined in section 2.2.

2.2 Corrosion Monitoring Principles

Corrosion monitoring (CM) refers to the assessment of metal loss due to corrosion of components in plants or other engineered systems. The loss of metal could be from any number of corrosion mechanisms. The distinction between monitoring, inspection, and field-testing techniques is mainly dependent on if the desired results are quantitative or qualitative. A.K. Agrawal notes a corrosion monitoring technique is one which provides metal loss data to enable corrective action on the system to be undertaken in a timely way. [Agrawal 2001]

Corrosion monitoring is the practice of acquiring information on the progress of corrosion damage to a material on a frequent and regular basis. [Yang 2010]

Corrosion inspection and monitoring are key activities in ensuring asset integrity and control of corrosion. Management decisions on equipment condition, prediction of remnant life and requirements for chemical treating are only as good as the information input provided from field experience [Corrosion Doctors]

Sensitive real-time corrosion sensors can be used to monitor the service life and associated process damage to the system components. A range of methods are available, and some are reported in more detail in Section 2.5. Corrosion inspection and monitoring includes assessment of:

- In-line systems cover installation of devices directly into the process, but which need to be extracted for analysis, e.g. corrosion coupons, bio-studs, etc.
- On-line monitoring techniques include deployment of corrosion monitoring devices either directly into the process or fixed permanently to the equipment
- Off-line monitoring is mainly achieved through the use of inspection and NDT techniques:

2.3 Welded non-alloy carbon steel tube

Although pipes and tubes may look similar, they are in fact different in nomenclature and sizing. Pipes are always round whereas tubes can be square, rectangular or round, Pipes are only provided with an inside (nominal) diameter and a "schedule" (which means wall thickness). As pipe is used to transfer fluids or gas, the size of the opening through which the fluids or gas can pass through is probably more important than the outer dimensions of the pipe. Tube measurements, on the other hand, are provided as an outside diameter and set ranges of wall thickness. Tube is available in cold rolled and hot finished steel. Pipe is typically black steel (hot rolled). Both items can be galvanized. Although this report is mainly concerned with tube, the terms are used interchangeably. [Metal Supermarkets 2014]

Some pipe manufacturing methods include seamless welded, and spiral-welded and schematic illustrations of these are shown in Figure 2.1. [Roy 2012]

Figure 2-1 Manufactured carbon steel pipe

Seam welding is commonly used during the manufacturing of round, square and rectangular steel tubing and is linked to the rolled schematic in Figure 2.1. The steel strip is unwound from coils and side-trimmed to control width and condition the edges for welding. The strip then passes through a series of contoured rollers which cold-form the material into a circular (square or rectangular) shape. The edges are forced together under pressure as a butt joint and then welded by heating the material to temperatures above 1000° C. This is known as electric resistance welding (ERW). The ERW flash weld that has formed is now removed from the outside diameter of the tube. Once the weld has been tested the tube then passes through a series of sizing rolls to attain its precise finished size, after which the tube is then straightened and cut to length.

The most significant factor in service life of these tubes is thought by the author to be corrosion and so the following sections will discuss the steel corrosion reaction (section 2.4), types of corrosion (section 2.5) and corrosion monitoring (section 2.7)

2.4 Corrosion reactions and uniform corrosion

Corrosion is the deterioration of a metal as a result of chemical reactions between it and the surrounding environment. The best example is that of steel rusting. When iron metal atoms are exposed to an environment containing water they can give up electrons, becoming positively charged ions, provided an electrical circuit can be completed. This effect can extend across a wide area to produce a general

degraded area or be concentrated locally to form a pit crack or crevice (as described further in section 2.4.1)

The corrosion process (anodic reaction) of the metal dissolving as ions generates electrons, that are consumed by a secondary process (cathodic reaction). These two processes have to balance their charges. At the anodic site the Fe is oxidised (Equation 1) and goes into solution and at the cathode OH- ions are produced. The resultant product Fe(OH)2 goes into solution. The anodic and cathodic sites interchange, and hence you get uniform corrosion on the pipework surfaces. The sites hosting anodic and cathodic processes can be located close to each other on the metal's surface, or far apart depending on the circumstances [Corrosion Doctors]

Some corrosion reactions are outlined below:
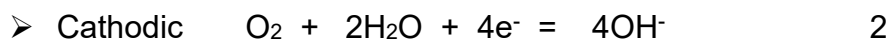
- Anodic $\quad$ $Fe \quad = \quad Fe^{2+} \quad + \quad 2e^-$ $\qquad$ 1
- Cathodic $\quad$ $O_2 \ + \ 2H_2O \ + \ 4e^- \ = \ 4OH^-$ $\qquad$ 2
- In acidic conditions the cathodic reaction is

  $\qquad O_2 \ + \ 4H^+ \ + \ 4e^- \ = \ 2H_2O$ $\qquad$ 3
- The ions then react as follows to give ferrous oxide
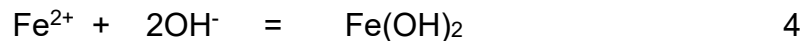
  $\qquad Fe^{2+} \ + \ 2OH^- \ = \ Fe(OH)_2$ $\qquad$ 4
- The ferrous oxide is further oxidised to give ferric oxide [Butler 1978]

  $\qquad 2Fe(OH)_2 \ + \ H_2O \ + \ 1/2O_2 \ = \ 2Fe(OH)_3$ $\qquad$ 5
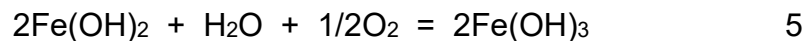
The $Fe(OH)_3$ in turn dehydrates to form rust, Fe_2O_3 [Lambert, 2002]

There should be a flow of electrons from anode to cathode as shown in Figure 2.2 which is a schematic illustration of uniform corrosion, typically taking place on mild steel (Fe). [Robinson 2012]
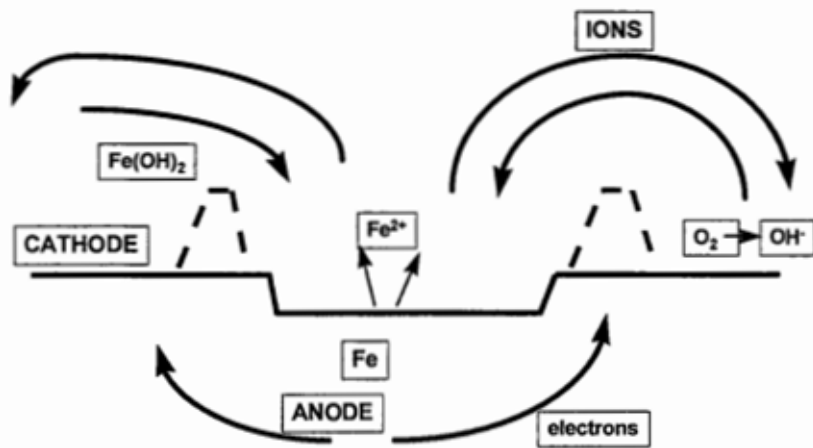
Figure 2-2 Schematic representation of uniform corrosion

The rust formed is insoluble in water and hence it starts collecting on top of the surface.

Some forms of localised corrosion are described in section 2.4.1 below. However, it should be noted that localized forms of attack, tend to occur where there is a breakdown of a surface passive layer. Such passive layers are frequently found in aluminium alloys, stainless steels and chromium alloys. For completeness they are reported here however it is noted that these localised types of corrosion are not often seen in low alloy carbon steel tubes.

2.4.1 Localised Corrosion

2.4.1.1 Pitting Corrosion

Is a form of localised corrosion where the pit diameter is smaller than the depth. It can affect small areas whilst the rest is unaffected. It is difficult to detect because of the pit diameter. Also, the corrosion product collects in the pits and it is not easy to detect and measure them. It appears as several small holes or cavities on the surface and they can come in different shapes and sizes as the pits can be different shapes as shown in Figure 2-3 [Nanan 2019]

Figure 2-3 Some form of pitting on a metal surface[Nanan 2019]

Figure 2-4 Pitting corrosion[Nanan 2019]

Pitting corrosion occurs where surfaces on passive metal or alloy surfaces, where passive layer is damaged or broken, as seen in Figure 2-4. Failure due to pitting can be sudden and catastrophic. Some factors said to affecting pitting corrosion:

- Localised damage to the protective oxide film – this can be either mechanical or chemical.
- Poor coating application – if coating is not properly applied this can leave areas which are not protected and are susceptible to pitting
- Foreign deposits on the metal surface- this introduces a different metal or alloy which leads to galvanic corrosion

2.4.1.2 Crevice Corrosion

Crevice corrosion takes place when water collects in openings which wide enough to allow water in and too narrow to make it stagnant. The most common sites for crevice corrosion are beneath flange gaskets, tube plates in heat exchangers, paint-coating edges overlap in joints. [Bardal 2004]

The reaction taking place are the same as in Equation 5 and this results in depletion of the dissolved oxygen in the crevice, and the dissolving of the metal ions results in chloride ions moving into the crevice and a concentration of chloride ions in the crevice [Lambert 2002]. This leads to this reaction

$$M^+CL^- + H_2O = MOH + H^+CL^- \qquad 6$$
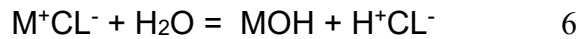
This results in an increased corrosion rate in the crevice compared to the area around it. This protects the area around whilst the crevice gets corroded. This results in the metal or alloy being damaged in the presence of protective layer [Lambert 2002]. The best way to prevent crevice corrosion is to avoid crevices, this will require good design.

2.4.1.3 Under-deposit corrosion

Deposits collecting in cooling water systems contain metal oxides, sulphides, biological material, precipitates and contaminates. These will result in oxygen concentrations in areas covered by the deposit. This will result in localised attack in areas beneath the deposit. [Rithdang]

2.4.2 Erosion Corrosion

This is a combination of erosion and corrosion taking place due to rapid movement and turbulence of the corrosive medium relative to the surface. When the fluid is moving in pipes, the velocity of the fluid and the physical contact of the moving fluid with the pipe combines with corrosion of the metal to result in accelerated metal losses [Lambert 2002].

The presence of burrs or weld beads is sources of turbulence which can cause erosion corrosion. In pipework systems erosion corrosion takes place at bends where water changes direction [Corrosionpedia]. Such events can be minimised:

- Using corrosion resistant material
- Using inhibitors
- Removing burrs throughout the pipework system
- Reducing dissolved oxygen

2.4.3 Galvanic Corrosion

Galvanic corrosion is when two metals with different electrochemical potential are in contact in the presence of an electrolyte. The metal which is more electronegative will form the anode and the other will be the cathode [Christian 2004]. The anodic metal will dissolve whilst the less negative one remains unaffected.

The electronegativity of a metal is shown in the galvanic series shown in Figure 2-5 [Atlas]. The further apart in the series the metals are, the bigger the potential and hence the more likely corrosion. Thus, the presence of other metals in industrial pipework will introduce a galvanic effect to the system. [Francis 2002].
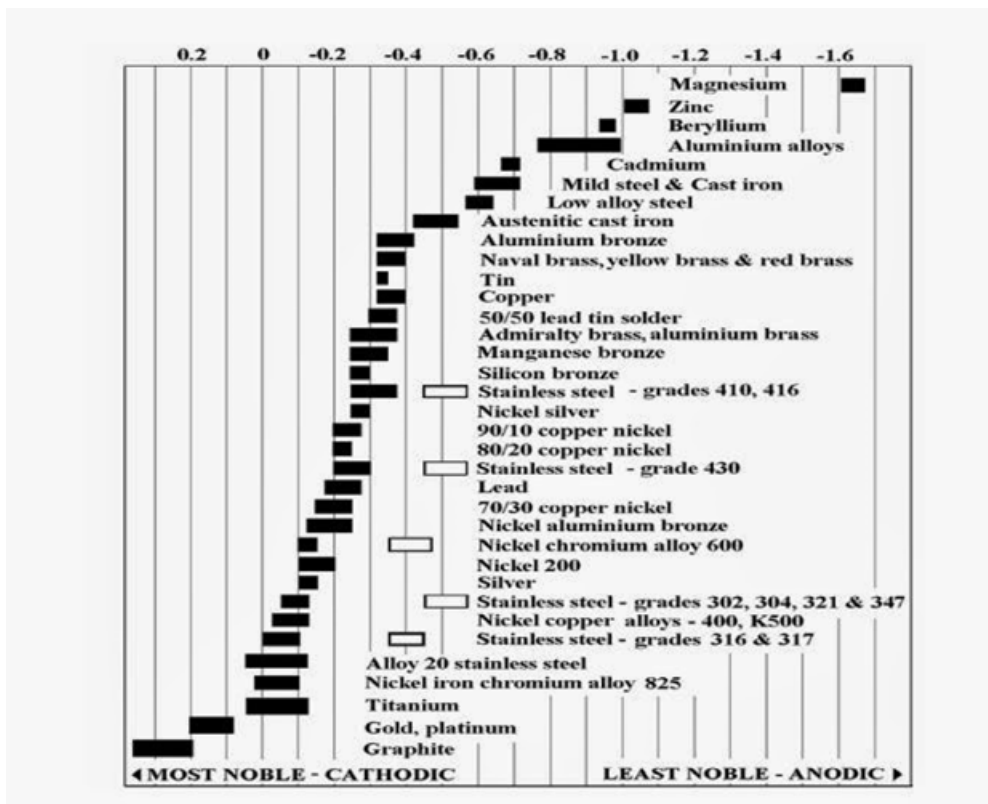
Figure 2-5 Galvanic series [Atlas 2010]

For example, there are three commonly used metals for potable water plumbing pipes, including stainless steel, copper, and brass. These metals are used because of their durability and long-life spans. However, that is not the case if these metals are directly connected. This is because stainless steel and copper are dissimilar metals.

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Similarly substituting a short length of carbon steel in a pipework system for another material like stainless steel 316 is instead likely to move any dissimilar metal corrosion to other parts of the system. Similar issues of dissimilar metal corrosion occur when mixing tubes from different suppliers with different steel chemistries and dissimilar or galvanic corrosion can occur.

A summary of the various types of corrosion that can be observed with a range of metal systems is summarised in Figure 2-6
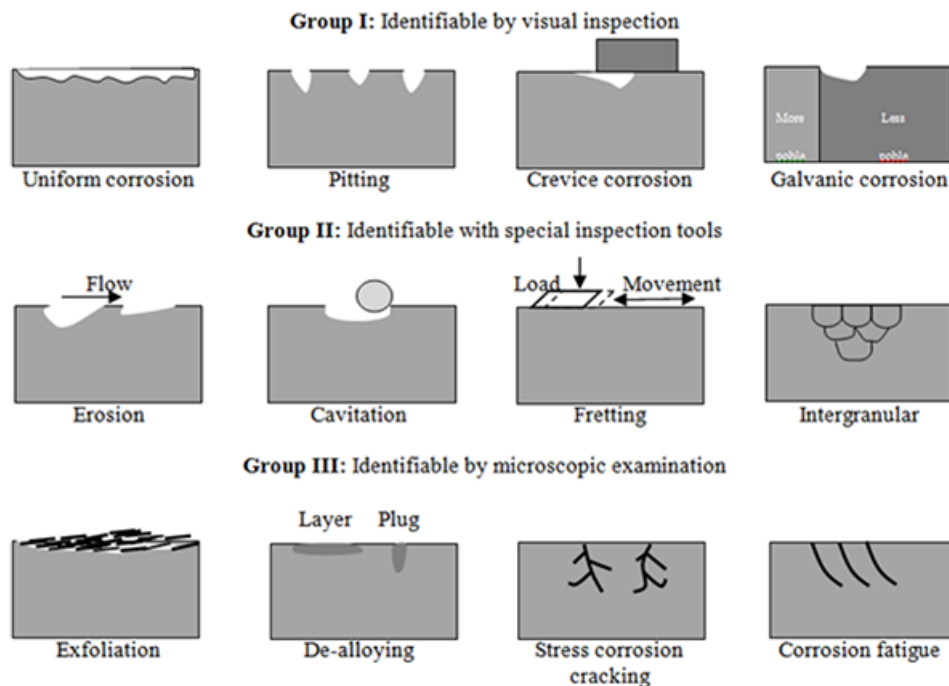
Figure 2-6 Main groups of corrosion grouped by ease of recognition [Anaee 2016]

Having considered some of most frequently found corrosion mechanisms, it is relevant to consider a few factors that influence corrosion rates apart from the material itself.

2.5 Factors Affecting Corrosion

2.5.1 Dissolved Oxygen (DO)

DO is the said to be one of the most influential factors in corrosion of steel pipes in water [Gupta 1994] In work in which corrosion behaviour of mild steel was evaluated dipped in water samples of different amounts of dissolved oxygen from

1.4 mg/L to 5.7 mg/L). It was found, initially corrosion of mild steel is directly proportional to the DO concentration then this rate diminished over a period of days because of formation of oxide film on the samples. [Gupta 1994] As the oxide layer builds up the effect of dissolved oxygen diminishes. Oxygen in oxidises the Fe to $Fe^{2+,}$ and iron ions produced will go into solution as iron(II)hydroxides. This accelerates the corrosion reaction. The oxygen also oxidises the Fe^{2+} to Fe^{3+} (equations in 2-1 above).

The effect of DO on the corrosion of low-carbon steel in tap water at different temperatures is shown in Figure 2-6 [Corrosion Doctors]
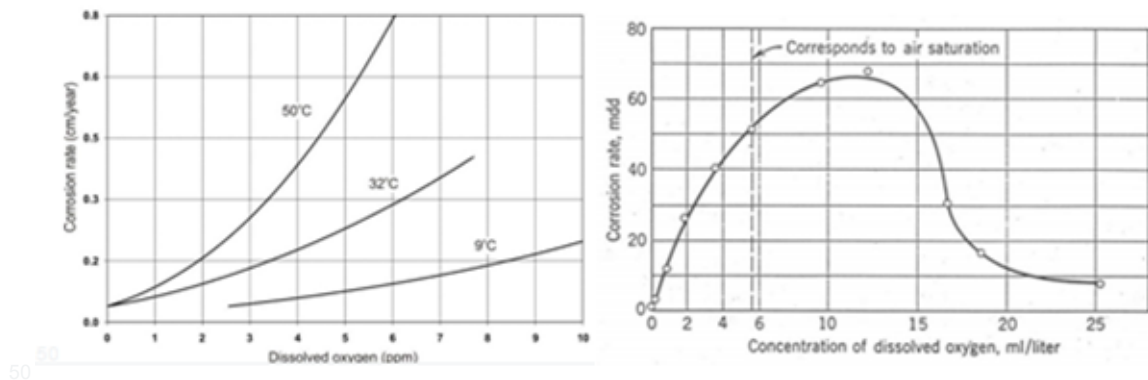
Figure 2-7 (a) , (b) Effect of dissolved oxygen on corrosion (a)[Corrosion Doctors] (b) cited by [Robinson 2012]

Oxygen is a cathodic depolarizer that reacts with and removes hydrogen from the cathode during electrochemical corrosion, thereby permitting corrosion attack to continue. The graph shows that the corrosion increases with dissolved oxygen. In the initial stages all the oxygen is consumed in the corrosion equation. However, as Figure 2-6b shows then it reaches a point where not all the oxygen is used in the corrosion, part of the excess is used to form the oxide layer [Winston 2008)], [Gupta 1994]

2.5.2 Effect of inhibitors

Corrosion inhibitors are substances that effectively reduce or prevent the corrosion of exposed metal in a corrosive environment. Inhibitors in small concentrations can be added to cooling water, acid, and steam to maintain an inhibiting surface film. Different mechanisms inhibit corrosion. They can enhance

barrier properties of the oxide layers present on the metal surfaces. This mechanism is based on decreased oxygen transport to the metal by the formation of thin passive films. As shown in Figure 2-7 [Nathan 1973] inhibitors affect the corrosion rate can:

- Increase polarisation of the anodic reaction (anodic inhibition)
- Increase polarisation of the cathodic reaction (cathodic inhibition)
- Form a deposit on the metal or increase electrical resistance
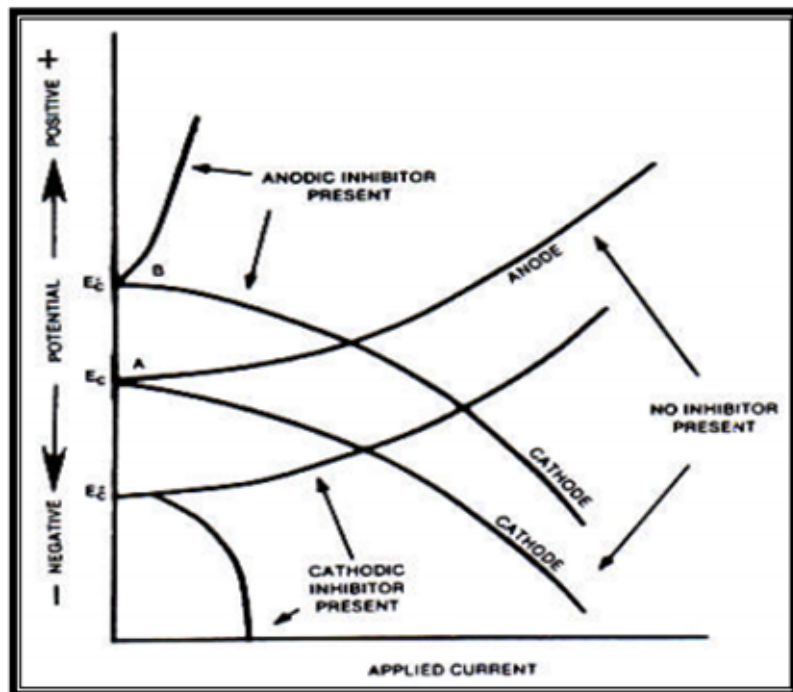
Figure 2-8 Effect of inhibitors on polarisation curves[Nathan 1973]

2.5.3 Temperature

Temperature will affect the corrosion reaction itself. It also affects the other elements consumed in the reaction like oxygen and hydrogen. The reaction under non-equilibrium conditions increases with temperature. Where there is free air access, the corrosion rate reaches a maximum at 80°C before coming down. This is because the rate of oxygen dissolving reduces at temperatures above 80°C. In the absence of oxygen, in hydrogen rich environments, the corrosion rate increases with temperature [Huckerman1952]

2.5.4 Surface Condition

Surface roughness has significant influence on pitting corrosion. A rough surface is more susceptible to pitting corrosion. A smoother surface has less possible sites for pitting corrosion [Burstein 1995].

2.6 Effect of water quality and flowrate

Values of pH below 7 occur in water of low dissolved solids and low alkalinity and result in uniform corrosion attack. In the absence of pitting, the corrosion rate as total weight loss is high but the surface will last long. [Carson 1968].

The presence of calcium or magnesium compounds in the water determines its hardness. These form scales which collect at the metal surface and this layer reduces the rate of corrosion because it shields the surface from corroding medium.

A little motion can result in more uniform corrosion than stationary conditions. [Carson 1951]. If the velocity is too high, it will result in erosion corrosion which is not uniform. It was also discussed that the effect of water flow on corrosion rate depends on what is dissolved in the water, if the water contains dissolved oxygen the corrosion rate will increase. If there is inhibitor the corrosion rate goes down. This is due to water transporting the respective chemicals to the interface. [Carson 1951]

Rabald, reports that the corrosion rate of flowing tap water is 0.25 mm/yr [Rabald 1968]. The flowrate or steel type is not specified. Corrosion rate in aerated flowing water increases to certain levels before decreasing. [Fredj 2012]. The decrease is due to passivation, oxygen potential increase as oxygen is transported to the surface and it forms an oxide layer.

Any corrosion products formed could be washed away, and hence fresh surface is exposed, and this increases corrosion as well. The presence of dissolved solids can also damage the surface film resulting into further corrosion.

2.7 Corrosion Monitoring Techniques

There are a number of techniques for monitoring corrosion. In contrast, corrosion sensors can provide day-to-day and even minute-to-minute real-time corrosion rate information for metal components in a system, without the need to retrieve the sensors within a closed system. However long term variations are not picked up unless monitored very regularly. Both techniques are responsive and not predictive if changes to the system occur.

2.7.1 Corrosion Inspection and monitoring via non-destructive evaluation

Non-destructive techniques (NDT) that monitor and measure material responses that reported to be are also helpful for corrosion are [Corrosionpedia]

- Visual inspection
- In this process the insultation of the pipe is removed and the pipe is inspected, and the insulation is replaced. The limitation is that the external surface is only assessed. It is expensive because the insulation is replaced in most cases. There is an additional risk of contamination as well.
- Radiographic inspection (X-ray and gamma ray)
- This operate on the principle of the X-rays producing a diameter profile showing corrosion product accumulation and/or pipe thickness changes. The insulation does not need to be removed because X-ray will pass through. The use of advanced software and digital imaging makes it possible to have real-time images. Main advantage is that it is portable, fast, traceable and can have digital images.
- Eddy current inspection

- Electromagnetic waves are used to determine the thickness of the pipe. This gives an average of wall thickness and hence is used for screening but not for detecting isolated areas of corrosion. It can only be used on carbon steel or low alloy steel only.

- Ultrasonic thickness measurement

- This uses the principle of movement of ultrasonic waves and can be used through a variety of linings and coatings. It only needs access to one side of the pipe. It is effective, accurate and can be used remotely. It is the widely used in many industries.

- Thermographic inspection

- A component is thermally excited, and its response is observed under infrared camera. With conventional methods, it was used to measure average surface temperature. Active thermography uses the variations in surface temperature over time to detect subsurface features through coatings or lining. In this way any corrosion taking place is measured.

Selection of inspection methods are best if based on good knowledge of process conditions, materials of construction, geometry of the system, external factors and historical records. Although each method is based on different principles, an understanding and control of a range of factors that influence corrosion is important. Reported influencing factors are

- Material composition (magnetic, non-magnetic, metallic, non-metallic)
- Part thickness, size and geometry
- Material condition (heat treatment, grain size)
- Inspection scanning rate
- Fabrication route (casting, forging, weldment or brazed)
- Surface condition (rough, plated, bright, scaled)
- Nature or use of the part (critical, non-critical, high or low stress)
- Human factors

2.7.2 Electron migration techniques

The main reaction in corrosion is the reduction of the iron from Fe to $Fe^{2/3+}$, this involves transfer of electrons from anode to cathode. A group of measurement techniques are based on the movement of electrons. The resistance of the material to this electrical flow, or the number of electrons flowing per unit time and area can be used to determine corrosion.

These techniques can be used on both laboratory and industrial scale. The main advantage with this group is that corrosion is measured instantly, and any variations can be observed.

2.7.3 Solution based techniques

As corrosion take place there is a change in solution chemistry. This is due to the metal or alloy dissolving into the solution or some dissolved elements or ions in the solution being used up. This group of techniques are based on measuring the changes in the levels of the elements or ions in solution. Thus, information can be gathered from water itself. For example, in industrial boiler systems, corrosion information is available regarding the formation of deposits and scale from [Amtec]

1. Accumulation of corrosion products mostly consisting of iron oxides introduced in the boiler from feed water and condensate systems
2. Contaminants present in the make-up water
3. Contaminants introduced to the condensate return from process equipment.
4. Solids introduced from leakages

Thus, it is important to consider both metal surfaces and the electrolyte conveyed within.

2.7.4 Weight Loss Techniques

In this technique a coupon of the same material as the surface being investigated is exposed to the same corrosive environment over a period time. The corrosion

test coupon method has been a simple and long-established method for evaluating corrosion or corrosion monitoring. A uniform corrosion rate is usually obtained from the weight loss or weight gain measured before and after the exposure to the environment of interest and the duration of the exposure. The coupon method is also widely used to evaluate localized corrosion such as pitting corrosion and crevice corrosion. More detail is given on localised corrosion mechanisms in section 2.4.1. If properly implemented, coupon methods are the most reliable method for corrosion monitoring. However, this method is slow; it usually requires an exposure time of 6 weeks to three months or longer. The evaluation of coupons is also labour intensive and the coupons must be taken out of the monitoring environment before the evaluation can be performed.

2.7.5 Hydrogen release techniques

This technique is used where the hydrogen atom produced from corrosion reaction dissolved into the steel surface. This technique uses the amount of hydrogen atom dissolving as an indicator of the rate of corrosion.

A number of possible corrosion monitoring techniques have been summarised as part of the literature survey in Figure 2-8 [adapted from Sahal 2018]

CORROSION MONITORING TECHNIQUES

Corrosion rate monitoring via released hydrogen (product):
1) Hydrogen flux monitoring (hydrogen monitoring probes)

Corrosion monitoring via dissolved solids:
1) Concentration of dissolved solids (TDS)

Corrosion rate monitoring from electron flow:
1) Linear Polarisation resistance (LPR)
2) Zero-resistance ammeter (ZRA)
3) Impedance spectroscopy (IES)
4) Electrochemical Noise

Corroded Spot

OH

Ionic movement

Fe²⁺

Electron Migration

Cathode

2e-

Anode

Techniques of Corrosion monitoring/control by water analysis:
1) Metal ion probes
2) Dissolved oxygen probes
3) Conductivity probes
4) PH sensors

Non-Destructive Testing
1)Ultrasonic Testing   4) Thermography
2) Radiography   5) Intelligent pigs
3) Eddy current/magnet flux

Corrosion rate monitoring by material loss:
1) Corrosion coupons
2 Electrical resistance probes (ER)

Figure 2-9 Corrosion monitoring techniques [adapted from Sahal 2018]

2.8 Corrosion monitoring practice

There is huge difference in emphasis for corrosion monitoring in oil and gas industry or offshore structures and the building services pipework systems. This is mainly because the other environments are by far more corrosive than domestic water and critically corrosion is a safety and environmental issue in offshore structures and oil and gas sector.

In domestic water there is no direct regulation to cater for corrosion, but the Drinking Water Inspectorate specifies the maximum levels of metal ions acceptable.

After commissioning and the start of service, the maintenance of heating and cooling systems is usually given to a water treatment contractor. This contractor measures and monitors the system for the corrosion rate or water constituent variables such as iron or inhibitor levels.

Routine inspections are carried out with greater frequency immediately after commissioning as inhibitor levels may drop quickly as they are consumed to control any initial corrosion or on surfaces. Once the system has been stabilised then the conditioned water and good system design, should result in the system reaching its design life (typically of 25 years) without problems.

Initially, a few small leaks or drips from joints, flanges and valves may be expected due to poor fitting or minor equipment faults.

Corrosion failures taking place more than six months after the commissioning stage should be viewed with concern. If red rust appears at sites, it can be assumed that air has entered the system and that the inhibition provided by the water treatment chemicals is insufficient. Rapid corrosion due to air leaks in closed systems is a common problem. Water leaks can often result in inhibitor depletion and loss of protection.

Indications of corrosion in heating systems are rapid inhibitor consumption, the need for excessive inhibitor dosing, the presence of debris at the lowest point, the presence of slimes and biomass from microbial corrosion and changes in the colour of any water drawn from the sampling point.

Corrosion that leads to leaking radiators, pipe work or fan coil units should be reported. Increasing numbers of leaking components associated with poor water quality should trigger a review of the whole system by either a corrosion engineer or a maintenance and equipment engineer in combination with a corrosion engineer. [Amtec]

Having considered a range of issues, apart from the guidance provided in the previous section, there is little to guide users on corrosion monitoring for predicting service life. A range of techniques that are used generally are after the effect and not predictive unless used over a long period of time. The more dynamic the system the more challenging the prediction of service life.

Some laboratory tests and medium scale testing (on a system when available) have been explored to see the suitability of service life predictions from lab scale corrosion tests. These are described in section 3.

2.9 Literature review conclusion

Literature review showed that corrosion was dependant on different conditions in the corroding system. There was limited or no data on how these conditions will affect corrosion in welded mild steel pipes in tap water. This necessitated designing appropriate laboratory experiments to generate data.

There was no relationship between laboratory test work and large-scale pipe work systems in literature. A case study was carried out on an industrial scale pipework system to establish this relationship. This is key in using laboratory results to predict service life.

There was nothing in literature on predicting service life in mild steel welded pipes in tap water and hence there was a need to carry out this research. It is important to highlight all the factors which need to be considered in considered when making accurate service life prediction.

3 METHODOLOGY

The aim of this research is to provide recommendations to accurately predict long service life of metal pipework systems from short duration measurements, taking into account the relevant service conditions, when conveying water in open or closed systems. In order to do this the following objectives were set:

- To assemble data from a range of measurement methods and systems in small scale laboratory tests and flow loops to represent pipework systems
- Use the data generated to demonstrate correlation and main factors influencing corrosion measurement across length scales in static and dynamic environments
- Recommend qualitative and quantitative approaches to improve and predict service life accurately from lab corrosion rates.

Thus, small scale laboratory experiments were carried out to investigate the extent to which different factors affect corrosion that may impact service life. One case study of a pipework system was used to support work on techniques with laboratory experiments, as far as possible.
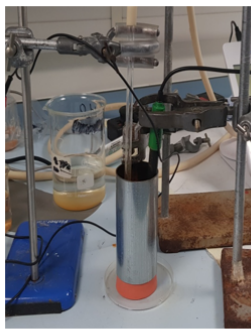
Experiments in static
conditions
-short term on thin
walled cold formed tube
-both Cranfield and
Loughborough water

Experiments in flowing water in
plastic pipes

Case studies
- B57 Cranfield cooling system

a) Effects on flowrate
b) Effects of mixed material

Figure 3-1 Overview of tests at lab scale LHS and for larger pipework system RHS

3.1 Methods and Materials

Tests were undertaken (as detailed below) across length scales: from small coupons to small mocked up pipework systems, in static and dynamic conditions (to show influence of flow rate and movement of ions from surface), in open and closed systems (to show influence of oxygen).

Materials:

Cold formed carbon steel welded tube (EN10305; 0.06%C, 0.35%Mn, 0.025%P, 0.025%S), 31 and 50 mm outside diameter and 1.5mm wall thickness. The tube had been produced by a strip forming process and induction welding the seam. Samples were cut 100 mm in length for the corrosion studies and tested in the as-received condition.

Thus, similar behaviour for:

- material composition
- material condition (heat treatment, grain size)
- fabrication route (ERW welded)
- Surface condition (Zn coated on outer layer)
- Nature of part (tube)

Water was taken from two locations to compare (Cranfield and Loughborough University water -at the time the plan was to compare data).

Techniques for Corrosion Measurement.

The schematic in Figure 2.9 was compiled to show the range of corrosion measurement techniques requiring determining changes both metal and electrolyte (water) as a result of corrosion. In this work two techniques were used on the tube surfaces and water analysis taken:

- Metal/pipe surfaces (mass loss and electrochemical measurements using LPR with a Gill AC instrument)
- Water analyses (pH, dissolved solids, conductivity, iron ions, dissolved oxygen)

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Factors	Detail	comments
Tube thickness, size and geometry	31 mm and 50 mm OD diameter cut into 100mm lengths also cut into coupons (4-6mm strips 14mm long)	EN10305; 0.06%C, 0.35%Mn, 0.025%P, 0.025%S), 1.5 mm thickness. Manufacturer Geberit Coupons were cut from 31mm diameter tube some without the weld and some with) The back and sides of the strips were painted with vanish. The surface area for each strip was calculated.
Water	Water parameters Cranfield and Loughborough tap water	LPR measurements in static water in 100 mm stopped long tubes, and corrosion monitored over 14 days Mass loss in static conditions coupons in glass beakers with Cranfield tap water for 4 weeks
Dissolved oxygen (DO)	Closed system Minimal dissolved oxygen	
	With added oxygen (air, 20 O_2)	(a) Air added for 5 mins after steady state conditions maintained
	Continuously added oxygen	(b) Air added continuously after steady state conditions maintained
surface cleanliness		(a) as received condition, no cleaning (b) dry cleaned using a tissue (c) cleaned with deionised water (d) cleaned using deionised water and then isopropanol
Temperature	Fixed at room temperature	
use of inhibitors	Not assessed in lab Case study only	
Galvanic corrosion	Presence of weld Case study	
Water flow	Three systems set up for different flow rates	(a) Flow loop in a beaker (b) PVC flow loop

Table 3-1 Summary of factors used for testing

3.2 Summary of tests in static conditions at room temperature using LPR technique

Detailed Laboratory experiments to determine effect of different conditions on corrosion rate

a. To determine changes in corrosion rate over 14 days - corrosion in static conditions using LPR and weight loos,

- LPR measurements in Cranfield tap water in 31 and 50 mm pipes, and corrosion monitored over 14 days

- Weight loss in static conditions coupons in glass beakers with Cranfield tap water for 4 weeks

b.   To determine effect of dissolved oxygen, corrosion with air (20% oxygen) addition

- Oxygen added for 5 mins in 31mm pipe when corrosion rate reached steady state. Air is added using an air bubbler and dissolved oxygen measured with a Hanna system.
- Oxygen added continuously in a 50mm pipe from the beginning of the experiment

c.   To examine effect of surface cleanliness. Four 31mm diameter pipes are cut and each tube was cleaned differently:

- in as received condition, no cleaning
- dry cleaned using a tissue
- cleaned with deionised water
- cleaned using deionised water and then isopropanol

d.   To determine effect of weld on corrosion rate - LPR measurement on 2 coupons, in glass beakers in tap water were monitored in static conditions over 14 days with and without weld
SEM and EDX analysis to characterise surface and determine changes in corrosion on the weld

e.   To determine corrosion rate in dynamic conditions (LPR, mass loss and water quality)

- LPR measurements, coupons in beaker in a flow loop and another with metal pipe in a PVC pipe flow loop
- Mass loss in dynamic conditions, coupons in beaker flow loop wighed before and after experiment

f.   To determine the effect of water quality on corrosion rate
Selected experiments repeated with Loughborogh water

3.3 Set up of tests in static conditions
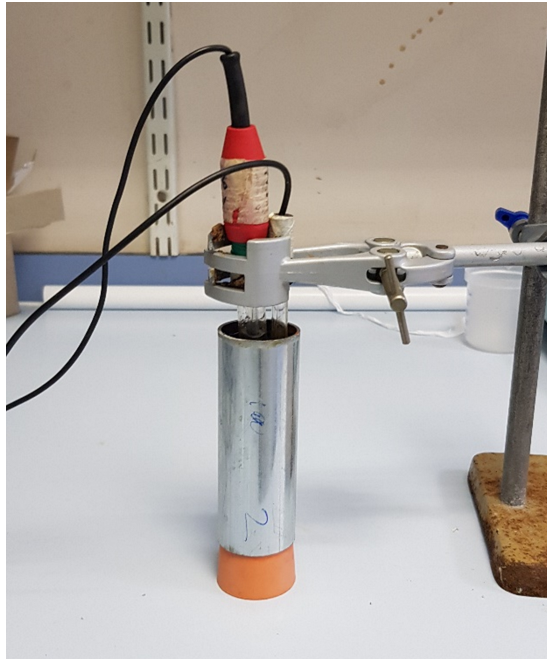
Figure 3-2 Static test in a pipe for LPR measurements, showing reference electrode (SCE) and platinum auxiliary electrode

For most static tests, experiments were set up as shown in Figure 3-2 above. A rubber stopper was inserted at the bottom of a tube, so that it just fits tight with minimum height of the stopper protruding into the pipe. The vertical height of the stopper is measured before it is inserted into the pipe (S_t) and height outside the pipe (S_o) is measured. The height of the stopper protruding into the pipe (S_p) is calculated subtracting S_o from S_t

$$S_p \quad = \quad S_t \quad - \quad S_o \hspace{4cm} 7$$

Cranfield water was added to the tube and Pt reference and auxiliary electrodes are suspended in the in the water for LPR measurements. Care was taken to make sure that they were not touching, and both are not in contact with the pipe. Air was added to the system via a bubbler. DO at 68% was measured.

The height of the pipe at the top not covered by water (P_t), was measured using Vernier callipers. The height of the pipe in contact with the water was calculated using the following equation

$$P_t = 10 - S_p \qquad\qquad 8$$

The area of the pipe in contact with the water P_A is calculated using the area of cylinder formula

$$A = \pi dh \qquad\qquad 9$$

where d is diameter of pipe and h is P_t and the units used is cm. This area is input in the Gill AC instrument for measuring LPR corrosion. Details on using GillAc machine are in Appendix A1.

3.4 Set up of tests in dynamic conditions

It is widely acknowledged that flowing water and flow rate is a key contributing factor to service life. However, at the time of setting this project up, no dynamic systems were available to investigate. Two flow loops were built. One using a peristaltic pump in a beaker (beaker flow loop) and a second larger one of PVC using a submerged pump for circulating the water (PVC flow loop).

3.4.1 Beaker flow loop

The experiment is set up as shown in Figure 3-3. A peristatic pump is connected to beaker, with a water inlet and outlet. The water flowrate of 16ml/s measured. A coupon of 3.7×13.8 mm strip was cut from a 50mm pipe, its back painted with vanish. It was then suspended in tap water in a reservoir in front of the water inlet.

GillAC LPR reference and auxiliary electrodes are suspended in the water. The working electrode terminal is attached to the metal sample. An oxygen probe is also suspended in the water. Corrosion rate, potential and dissolved oxygen levels are recorded after every 24hrs.
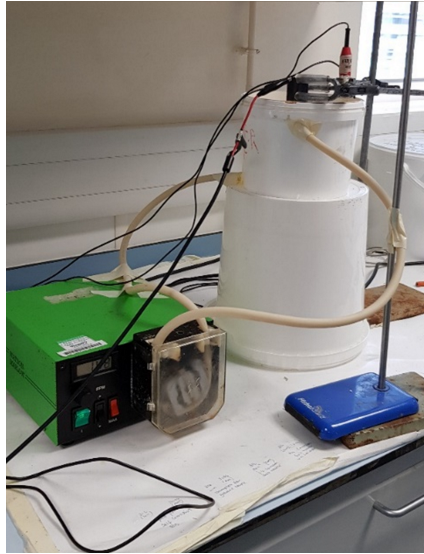
Figure 3-3 Beaker flow loop set up

3.4.2 PVC flow loop

A flow loop to circulate water was built from scratch using PVC tubing. The initial design was a little more elaborate than the final version with T pieces and ends to house 2-4 coupons were designed with and a tap to change the flow of the water (in conjunction with the pump controller). During designing reference was made to an online flow loop by Pavlo Ostreyko [Aqua] Appendix A2 The plan was be able to move this flow loop, as a 'mobile unit' and integrate this into any heating or cooling system such as used in the case study (Chapter 5). Due to high pressure in the larger cooling system, this was not undertaken, but LPR probes and pipe coupons were placed into the case study.
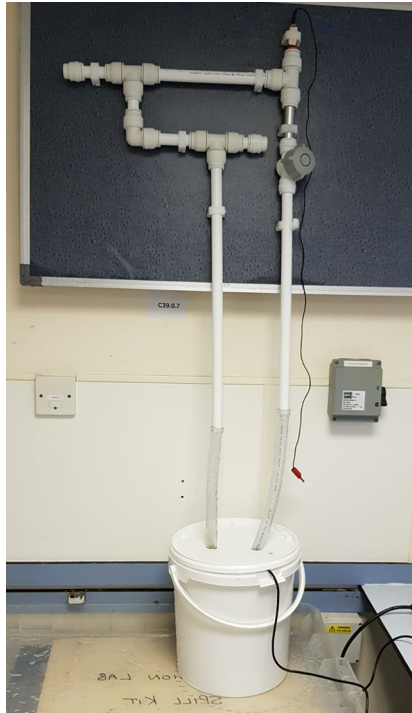
Figure 3-4 PVC flow loop with steel pipe foe corrosion measurement built for this research

Figure 3-5 Part of the flow loop with LPR probes

To measure the corrosion, rate an LPR measurements were taken using Pt wire and a saturated calomel reference electrode. Platinum wire is wound together and attached to a saturated calomel reference electrode as shown in Figure 3-4. This in then inserted into one end of PVC T- joint and connected such that the reference electrode enters one end of the 100 mm long 22 mm OD, 1.5 mm thick metal pipe used as the working electrode as in Figure 3-3. A submerged pump is

placed in the water reservoir, and circulates the water in the system at 127 l/h.. This was the slowest rate.

Coupons could also be inserted into the coupon holder, marked in Figure 3-3, left for a period and reweighed to determine the corrosion rate.

Once first set up, as it was an open system a considerable amount of dissolved oxygen entered the system (81.2% DO). This was much higher than expected due to turbulence and air around the coupon system and the filling method. Attempts were made to reduce the DO in the system to 69.4% DO as this was still felt to be very high unrepresentative with inaccuracies due to the high volume of air bubbles.

Calculation of corrosion rates using LPR measurements.

LPR measurements were taken after every 24 hours. A GillAC measures the resistance R_p and the corrosion current I_{corr} is given by the formula

$$I_{corr} = \frac{B}{R_p}$$

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 where B is the proportional constant expressed in mV and is dependent on the corrosion system under consideration, R_p is the polarisation resistance in

The corrosion rate is given by this equation

$$C = \frac{I_{corr} \times E}{A \times D} \times 327.2 \qquad\qquad 12$$

Where

      C =   Corrosion rate in 'mils per year'(mm/yr)

      I_{corr} =   Corrosion current(A/m^2)

      E =   Equivalent weight of corroding metal(g)

      A =   Area of corroding material(m^2)

      D =   Density of corroding metal(kg/m^3)

      Kp=   327.2 mm.kg/(A.m.yr)

Three readings are made each time, and the corresponding average corrosion in mm/yr is plotted against time in hours. Experiments were carried out under the same condition to check repeatability.

4 RESULTS AND DISCUSSION

4.1 Laboratory Technique Assessment

In this Chapter the results of tests undertaken in static then dynamic conditions will be assessed and discussed.

4.2 Static Conditions

4.2.1 Cranfield Tap water in static condition
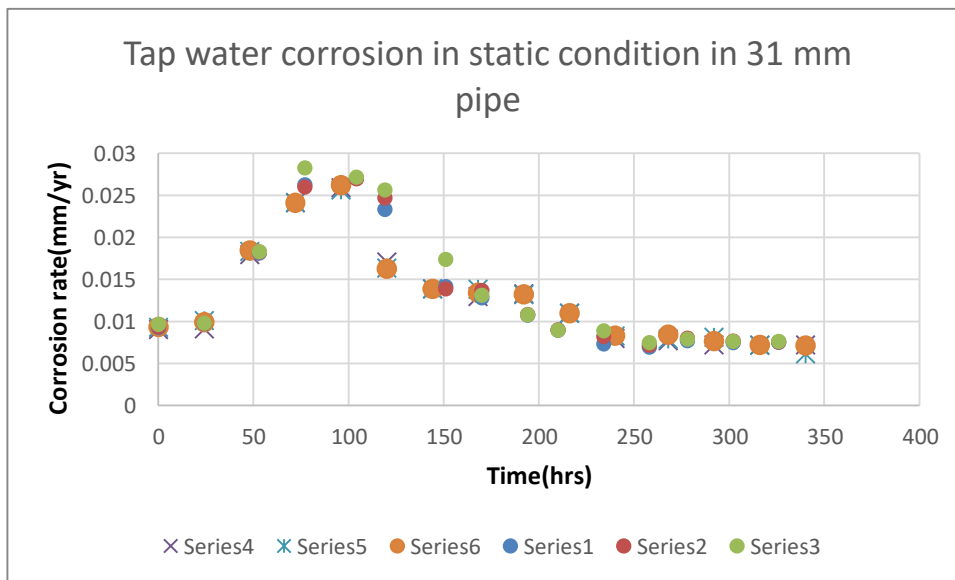
Figure 4-1 Cranfield tap water corrosion in static condition in 31 mm pipe

In this experiment, Cranfield water was placed in a 31mm pipe at room temperature and left to corrode under static conditions. Two experiments were carried out, series 1 to 3 was one and 4 to 6 was another. In each instance 3 readings were taken at a time. The graph proves the repeatability of the experiment. Figure 4-1 shows that the corrosion rate increased in the first 100 hours before decreasing steadily until reached a steady rate of corrosion after 250 hours. The increase is due to the initiation of the corrosion reaction on the surface of the pipe.

The decrease is due to the depletion of the dissolved oxygen in the system, and this continues until the corrosion rate reaches a steady state of 0.007mm/yr . This condition exists in the pipework systems, under two circumstances. The first

being after a building has been completed and water is pumped into the system to test the system and is left in static condition until occupation. The longer the length the building is left before occupation, the more this condition prevails.

The second situation is during occupation, when the water taps are turned off and these relatively short periods

4.2.2 Influence of oxygen addition

4.2.2.1 Intermittent air added
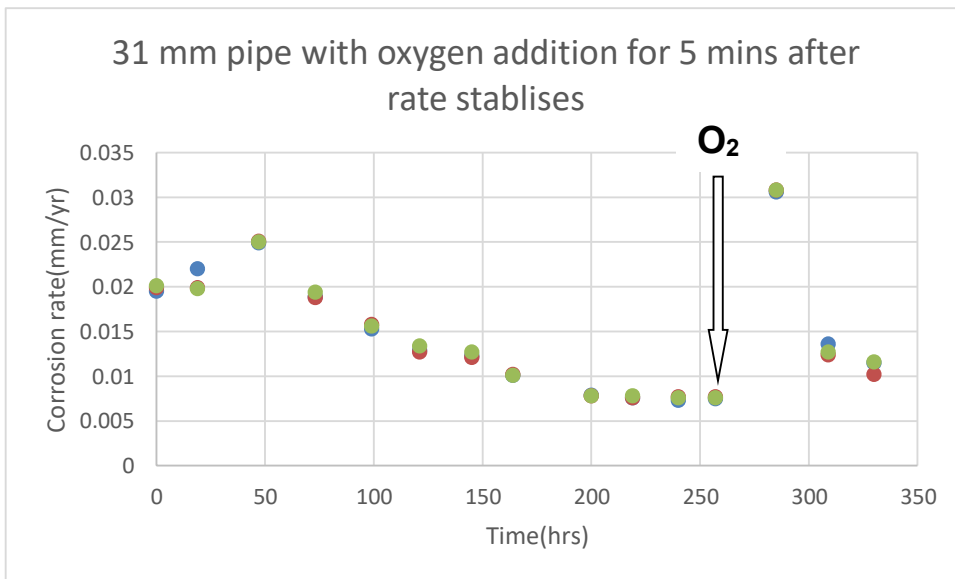
Figure 4-2 31 mm tube with oxygen addition for 5 minutes after rate stabilises

This experiment was carried out using Cranfield water under static conditions and at room temperature in a 31 mm pipe. Three readings were recorded at each instance. The graph shows very small error in the 3 readings. Figure 4-2 shows that after the corrosion rate reached steady corrosion rate of 0.0075mm/yr after 9 days, air (20%) was added for 5 minutes.

At the beginning of the experiment the dissolved oxygen level was 68.2%, this reduced to 2.4% at constant corrosion rate. After oxygen addition the oxygen increased to 18.6%. At the same time the corrosion rate increased to 0.03 mm/yr. The corrosion rate then started decreasing steadily. The drop in dissolved oxygen levels from 68.2% at the start of the experiment to 2.4% at steady state corrosion rate confirms the consumption of oxygen in the process. After adding air (20%

oxygen) for 5 minutes, the increase in both oxygen levels and corrosion rate shows that dissolved oxygen is the rate determining factor in this situation. It confirms that the gradual decrease in corrosion rate after day 4 is mainly due to oxygen depletion rather than accumulation of corrosion product on the surface as reported by Sarin et al., [Sarin 2004].

4.2.2.2 Air added continuously
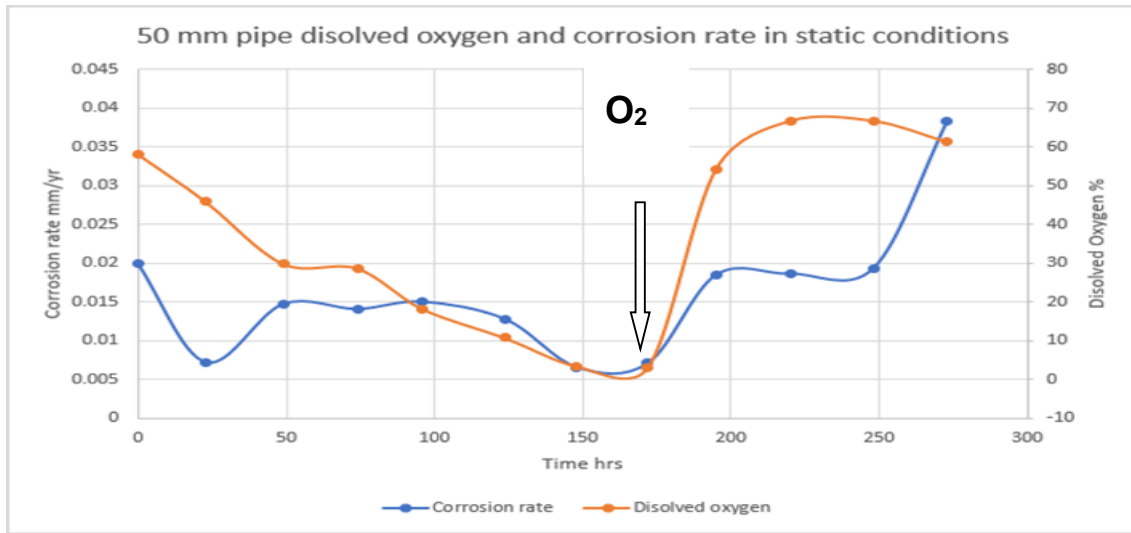
Figure 4-3 Oxygen added continuously after reaching constant corrosion rate in a 50 mm pipe

This experiment was carried out using Cranfield water in 50 mm pipe under static condition at room temperature. Figure 4-3 shows that after the corrosion reached constant rate of 0.007mm/yr, oxygen was added continuously. In the first 50 hrs there is an increase in corrosion rate whilst there was a decrease in the dissolved oxygen, after that it is the relationship is fairly proportional. This is because in the initial stages of the experiment the dissolved oxygen levels are higher than the amount needed for the corrosion reaction, hence the rate increases whilst the dissolved oxygen levels decrease.

After 50 hrs the corrosion rate depends on the dissolved oxygen levels. The dependence of the corrosion rate to dissolved is confirmed as above.

4.2.2.3 Variation of potential with oxygen ingress (monitoring corrosion)
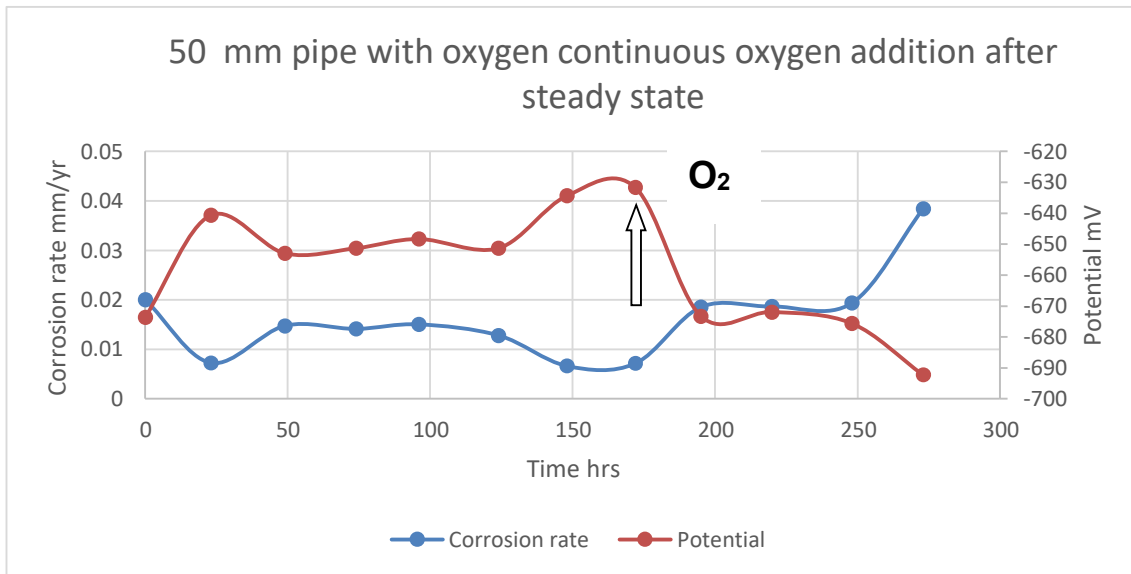
Figure 4-4 Effect of oxygen potential

Figure 4-4 shows that ingress of air increases the electro-negativity of the potential. The more electro negative the system, the higher the corrosion rate. As the negative potential was linked to the increase in oxygen, and associated increase in corrosion rate.

Effect of Dissolved Oxygen Level

The majority of aqueous solutions will be in contact with oxygen in the air, therefore any corrosion taking place within the solution will have oxygen acting as a cathodic reactant. This is due to the dissolution of oxygen within the water, the extent of which varies from liquid to liquid. The saturated solubility of oxygen within pure water is 10^{-3} mol dm^{-3} however, in regard to other solutions, any slight increase in temperature or salt concentration will notably decrease this value [Shreir, 1963].

Various studies have concluded that a greater concentration of dissolved oxygen, within the solution surrounding a corroding metal sample, is likely to cause an increase the rate of corrosion of that sample. This can be explained by considering the Nernst equation:

$$E = E_o + \frac{RT}{nF} + \frac{[Ox]}{[Red]}$$

Equation 13

Dissolved oxygen is known as the oxidising agent in aqueous corrosion, as it is itself reduced in the process. The Nernst equation shows that if the concentration of the oxidising agent increases then the electrode potential increases. A graphical representation is in the following Evan's diagram of Figure 4-5.
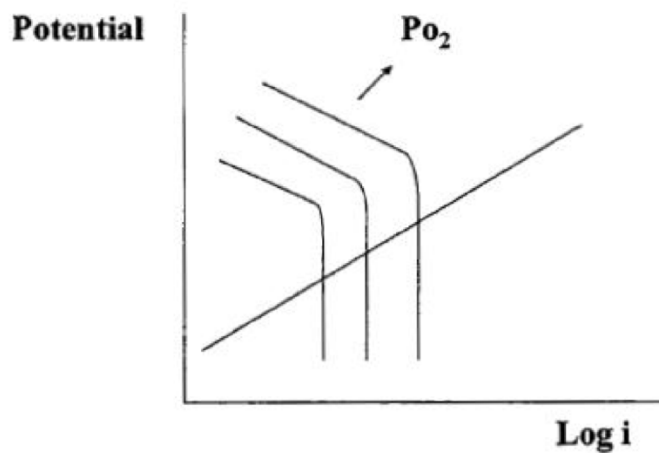
Figure 4-5 An Evan's diagram displaying the effect of the concentration of dissolved oxygen on the corrosion rate of a metal[Robinson, 2012]

The Evan's diagram typical of this phenomenon shows an example of corrosion under cathodic control; with increasing levels of dissolved oxygen, within the solution, the corrosion rate increases. A specific case can be clearly seen for mild steel in water in Figure 4-5. As depicted in Figure 4-5, the point at which the anodic and cathodic curves intersect increases with increasing O_2 levels.

Removing dissolved oxygen from water (de-aerating) practically halts all corrosion of mild steel under pH neutral low temperature conditions, therefore highlighting the importance of oxygen in the corrosion process.

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4.2.3 Effect of surface condition
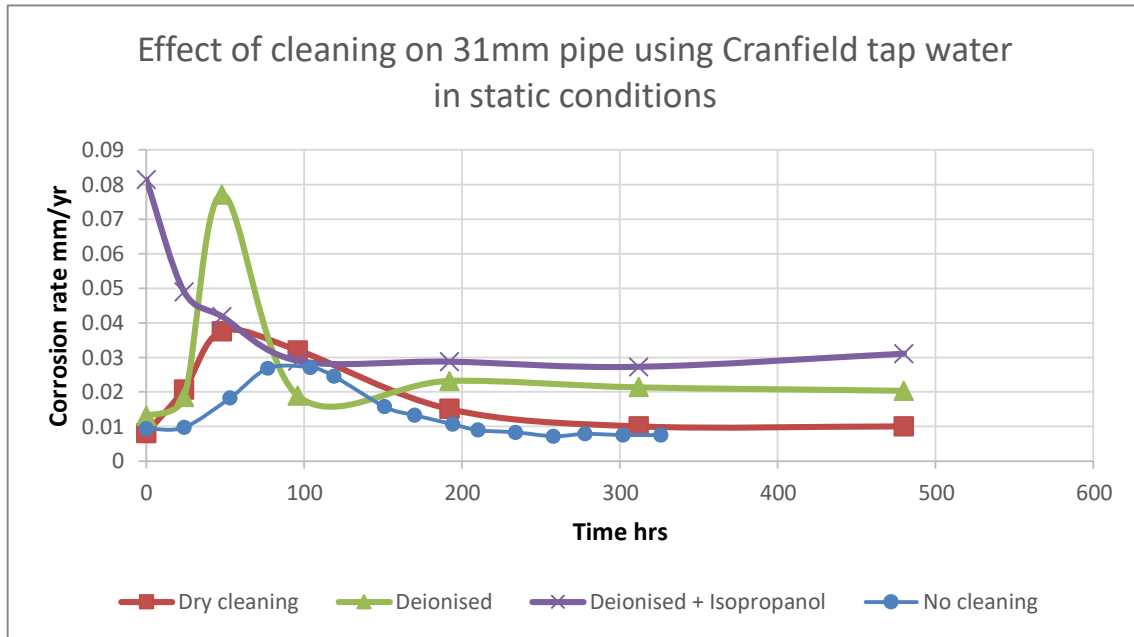
Figure 4-6 effect of cleaning on 31 mm pipe using Cranfield tap water in static conditions

In this set of experiments the influence of the cleanliness is assessed. For all plots in Figure 4-6, except where both deionised and isopropanol were used, the graphs follow a similar trend where the corrosion rate increases sharply before decreasing gradually. With the use of deionised water and dry cleaning (tissue), a peak is reached in the same period within 3 days. In the 'no cleaning' experiment there is a shift of the graph to the right with the peak reached later in 4 days. Where both deionised and isopropanol were used, the high corrosion rate is observed initially, decreasing with time.

Generally, the individual plots in Figure 4-6 show that cleaning had an effect on the corrosion rate profile over a period of time. This implies that there is something on the surface inhibiting the corrosion. This is confirmed using dry tissue, water and the surface inhibition is completely removed with water and alcohol. Mertzdorff notes this in her work on similar tubes and argues that the effect of the inhibitor in dynamic conditions lasts a few days. She reports that a water-based inhibitor was sprayed onto the internal surface during manufacturing

(specifically on cooling the weld after formation) to give short term corrosion protection [Metzdorff 2015].

The cleaning experiment confirms that an amount of residual inhibitor will affect the corrosion profile and hence it is important to (a) clean consistently or (b) check surface products e.g. inhibitor before comparing corrosion behaviour of different materials.

4.2.4 Effect of the weld
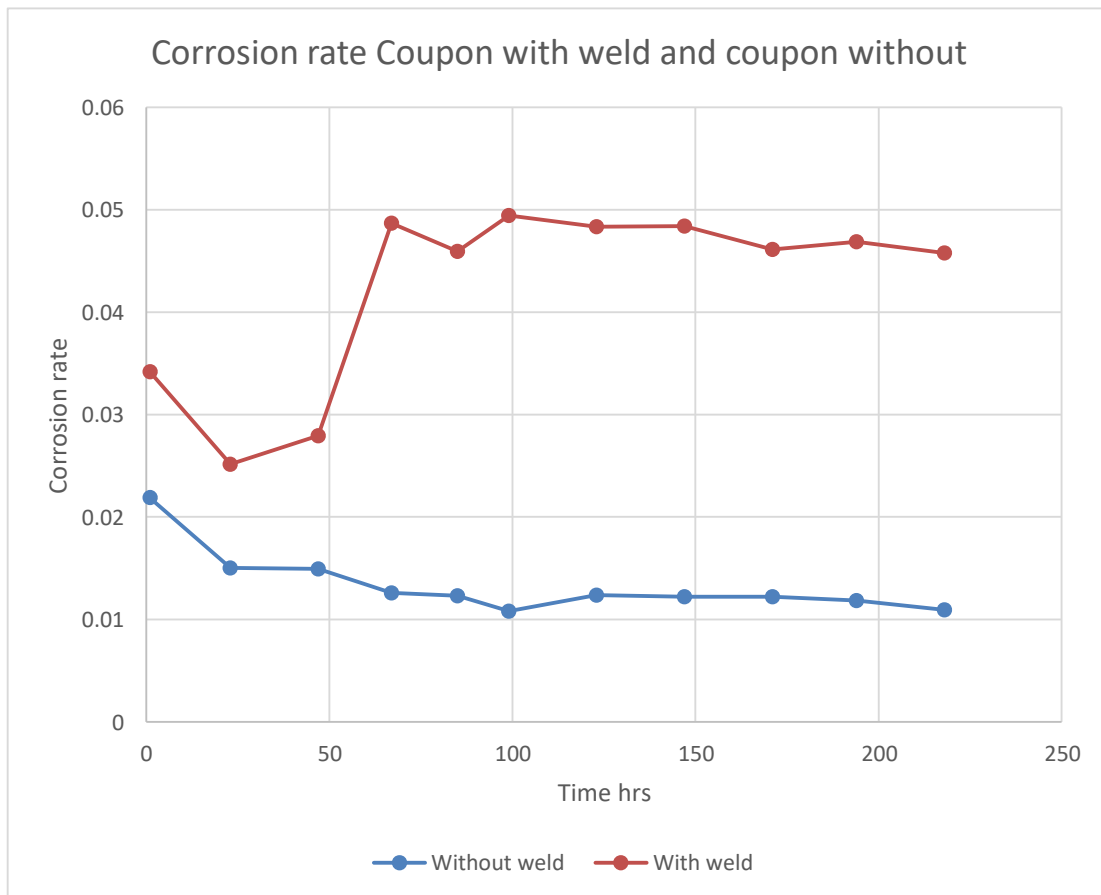
Figure 4-7 Corrosion of coupons with and without welds

One other surface feature to consider is the presence of a weld. Figure 4-7 shows that in the coupon with weld present, the corrosion rate of the surface is almost 5 times than that without the presence of the weld. To see what impact the weld might be providing, some cross sections were prepared, and SEM images taken on the internal surfaces of the weld bead.

(a) Polished sample of weld at top showing possible crevices and small cracks

(b) higher magnification of polished sample of weld at top showing possible small cracks

(c) higher magnification of oxide at surface of the weld

(d) surface image in SEM of cracks in oxide at surface of the weld
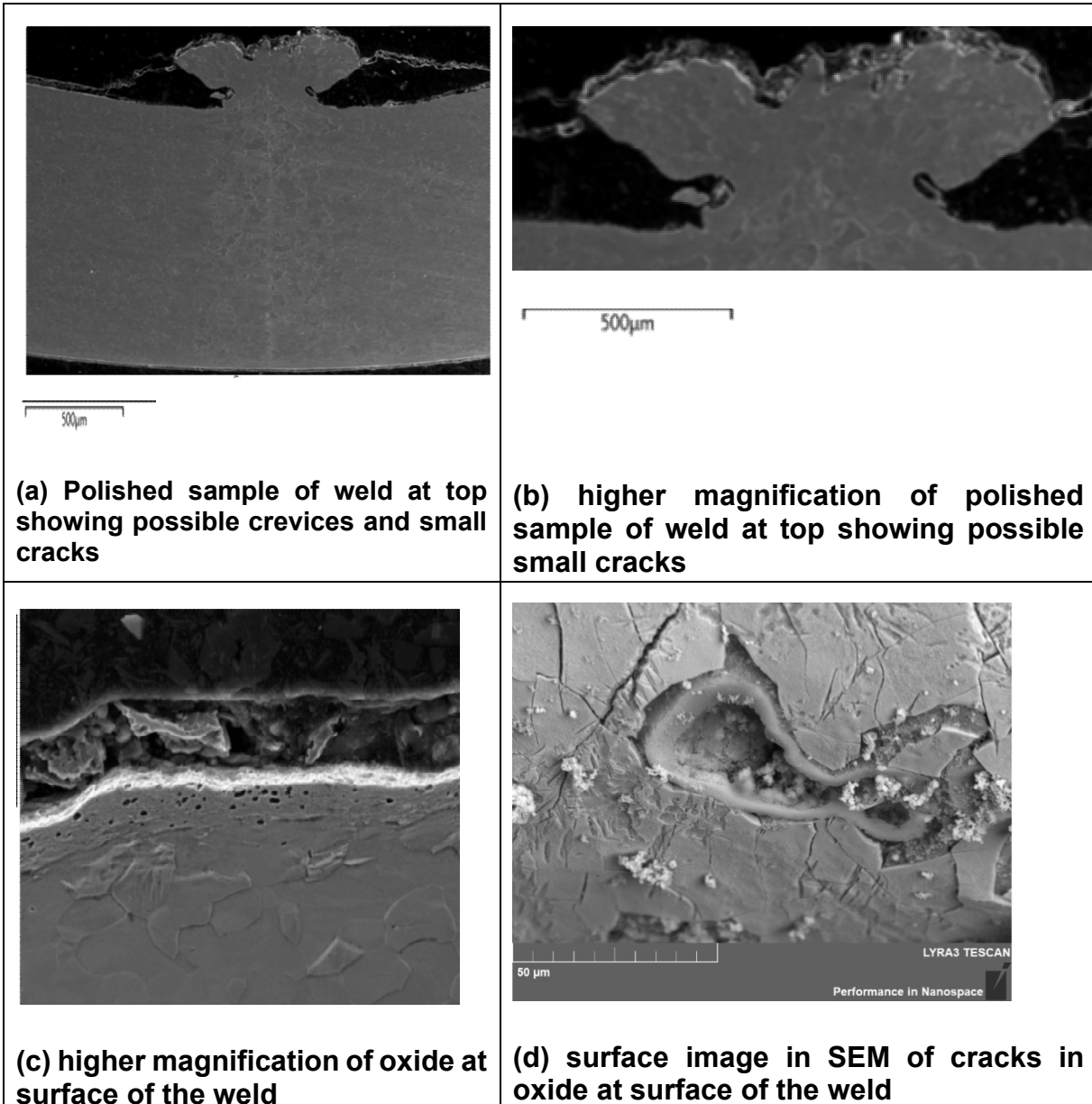
Figure 4-8 Images of weld showing cracks and crevices

The images taken in Figure 4-8 show that there are modifications observed at the weld compared to tube surface without the weld. Cracks and surface oxide are observed. This is likely to be oxide or millscale as the weld area used together is at much higher temperature (greater than 1000 °C) than the unwelded surface. This, in uncontrolled environment, is likely to result in the formation of an millscale or an oxide layer on the weld. It is reported that mill scale, a related material containing magnetite and various other oxides of iron, proves disadvantageous against corrosion. Its flaky nature causes areas of concentrated local corrosion

and eventually pitting [Shreir, 1963]. Additionally, in research by Metzdorff, she reports the weld surface has a 30mV potential difference from the rest of the surface, (Metzdorff 2015). This introduces a galvanic effect to the surface. The fast cooling of the weld results in the formation of cracks. Water could be trapped within the crevice and cracks (shown in Figure 4-8) and hence a combination of these factors may result in high corrosion on the weld.

4.2.5 Effect of sample geometry (or influence of weld)
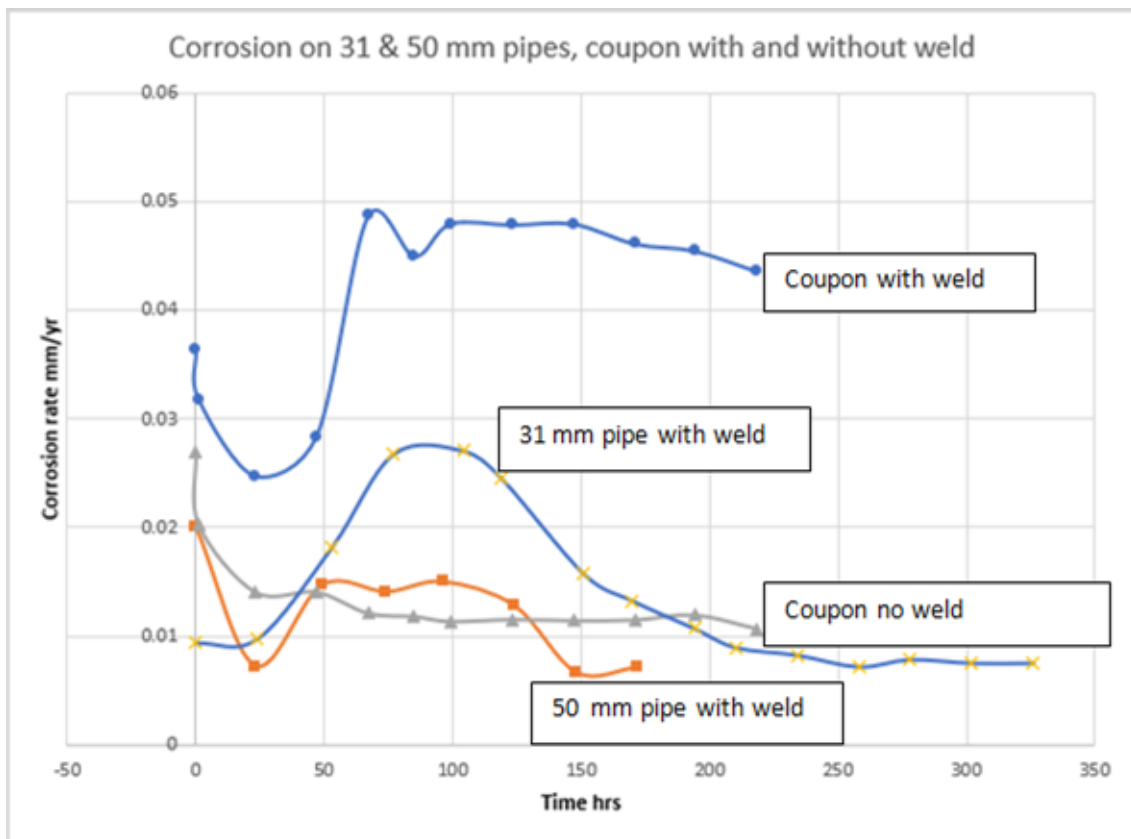
Figure 4-9 Effect of sample geometry (or influence of welds)

Comparison of the corrosion rate as influenced by the diameter of tubes is given in Figure 4-9, normalised for the surface area. It appears that the smaller tube diameter (31 mm) has a faster corrosion rate. This is counter intiutive as expectations might be that the larger tube diameter might have greater dissolved oxygen and faster corrosion. However when adding the corrosion rates for coupons with and without welds, the influence of the weld appears to dominate. corrosion rate starts high and and comes down quickly and reaches steady state

after 60 hrs. The coupon with weld corrosion rate starts low and and increases quickly. Whereas the larger tube diameter has more similarities in terms of corrosion rate to the coupon with no weld. Thus the effect of the weld is implicated. A comparison of the areas associated with the weld was undertaken.

The area covered by the weld is approximately 2h mm^2. Where 2 is the width of the weld and h the height. For a 31mm diameter tube with height h the total tube area is given by:

$$\text{Area }_{31 \text{ mm}} \quad = \quad \pi dh$$
$$= \quad 97.428 \text{ h mm}^2$$

The percentage area covered by the weld to the total area is given as:

$$\% \text{ Area with weld} = (2h/97.428h) \times 100$$

$$= \quad 2.05\%$$

In the 50 mm diameter tube the weld area is estimated as:

$$\% \text{ Area with weld } = (2h/157.14h) \times 100$$

$$= \quad 1.27 \%$$

Thus, the ratio of weld area-to-total surface area is twice that on the 31 mm tube than the 50 mm diameter tube. This means the influence of the weld is twice that in the smaller tube. This is perhaps why the corrosion rate is greater on the 31mm diameter tube to the 50mm diameter

In support of the observation of the welds contributing negatively to service life, it has been reported that corrosion rates of carbon steel samples containing welds were found to be notably higher than samples that did not contain welds [Anquetin, 2010].

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4.2.6 Effect of water quality
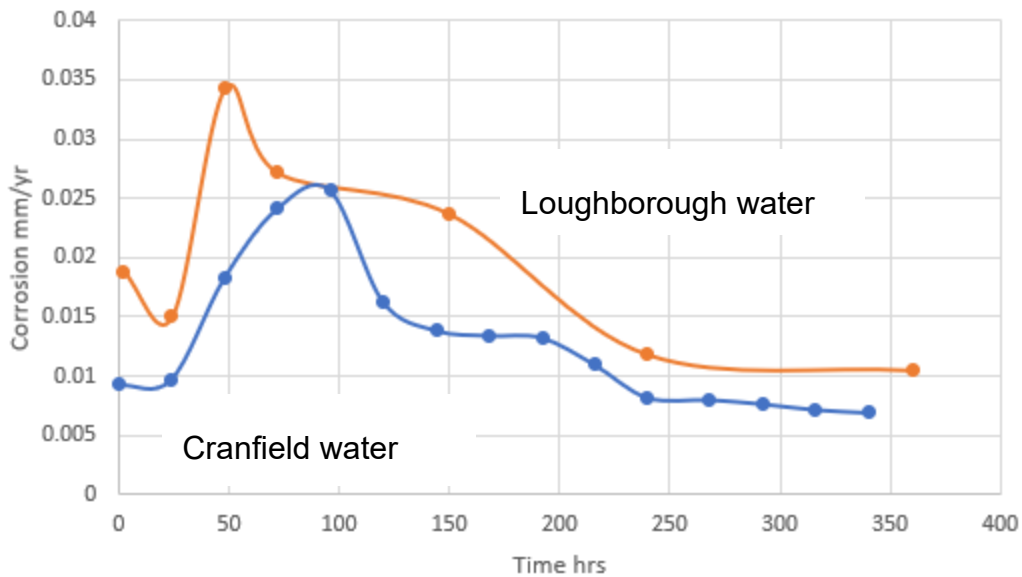
Figure 4-10 Corrosion of 31mm pipe under static conditions using both Loughborough and Cranfield water

One further influence that was assessed was that of water quality. Specifically if the same experiment was carried out with different tap water, would the corrosion rate be any different? Figure 4-10 shows that the corrosion profile of the water from Cranfield and Loughborough in a 31mm pipe under static conditions is very similar. However the profile with Loughborough water is shifted a little to the left and after 250 hours they both reach steady state corrosion rate.

WATER ANALYSIS REPORT

Sample Point	pH	Cond. (µS/cm)	TH	p-Alk	m-Alk	Cl⁻	Fe*	Cu*	Amine
			(ppm CaCO3)			(ppm)			
L'BRA B4	7.5	589	290	0	180	50	0		
Cranfield B4	7.2	324	150	0	45	30	0		

Table 4-1 Analysis of Loughborough and Cranfield water(GEMchem 2019]

The water analysis shows that the pH of the both water sources not too dissimilar although the hardness reported for Loughborough water is twice that of Cranfield water and may be classified as hard water. The results are very similar to that published by the water authorities, Severn Trent and Anglian Water respectively.

Higher hardness levels imply that there will be more scale formation and perhaps eventually the corrosion will be lower. Figure 4-10 does not show this, possibly because of the short term impact over 350 hours. In Figure 4-10 the corrosion rate for Loughborough water is a little higher than the Cranfield water corrosion rate. The possible reason for this is that the effect of conductivity is prevailing after 350 hrs. However, over a longer period of time it might be expected that the scale will prevail.

Water hardness is described by categories given in Table 4-2 after Shrier [Shrier 1963]. Thus, Loughborough water is 'Hard' corresponding to the water containing over 200 mg/l $CaCO_3$ and the Cranfield water is slightly or moderately hard.

Hardness Category	Hardness (CaCO3 ppm)
Soft	<50
Moderately Soft	50-100
Slightly Hard	100-150
Moderately Hard	150-250
Hard	250-350
Very Hard	>350

Table 4-2 Hardness categories defined in terms of CaCO3 content [Sheir 1963]

In terms of the hardness, previous work at Cranfield has been undertaken on corrosion of carbon steel in different water sources, although at this time the Cranfield tap water was reported as moderately soft – Hardness 100mgL^{-1} as $CaCO_3$, Alkalinity 50mgL^{-1} as $CaCO_3$, Conductivity 281µS cm^{-1}

Water	Average Titre (cm^3)	Calculated Hardness (CaCO$_3$ p.p.m)	Category of Hardness [Shreir 1963]
Birmingham	1.93	38.63	SOFT
Nottingham	3.5	70.06	MODERATELY SOFT
Cranfield	4.16	83.27	MODERATELY SOFT
East Haddon	6.7	134.12	SLIGHTLY HARD
Derby	9.4	188.16	MODERATELY HARD
Corby INDUSTRIAL	9.55	191.17	MODERATELY HARD
Corby TAP	12.66	253.43	HARD
Newport Pagnell	13.13	262.84	HARD
Bedford	13.76	275.45	HARD
Ipswich	17.66	353.52	VERY HARD

.

Table 4-3 Table displaying the average titre and calculated hardness for a range of UK collected waters[Whittaker 2012]

D Whittaker determined corrosion rates in for a range of static tap waters with carbon steel cold formed welded tube coupons (with no weld present on the coupon) [Whittaker 2012],. Waters with equivalent hardness to that of the Loughborough water (290 CaCO$_3$ ppm) are Newport Pagnell (263 CaCO$_3$ ppm) and Bedford (275 CaCO$_3$ ppm). While the Cranfield water (150 CaCO$_3$ ppm) is similar to that of East Haddon water (134 CaCO$_3$ ppm) [Whittaker 2012], Steady state rates of corrosion are approximately 0.09 mm/year, which is similar to that described in this work at steady state conditions, 0.01 mm/year as in Figure 4-9 for a similar coupon with no weld. Differences of the order of about 0.002 mm/year in corrosion rate result from using different waters with hard water showing increased rates around about 50 hours at early stages. This fits well with findings.

The conductivity of the Loughborough water is almost double that of Cranfield water. It is possible that the higher conductivity, due to greater number of ions, and possibly attributed to alkali ions. However, the concentration of charge carriers within the electrolyte could dramatically reduce the corrosion rate if very low or considerably increase the corrosion rate if the concentrations are very large. The Loughborough water appears to be a little more active than Cranfield water. The shift to the left of the corrosion profile graph (Figure 4-9), shows the faster removal of the inhibitor identified previously, as the corrosion is a little more

accelerated and hence the typical corrosion peak is reached earlier. Thus, this is thought to be due to the higher conductivity or charge carriers.
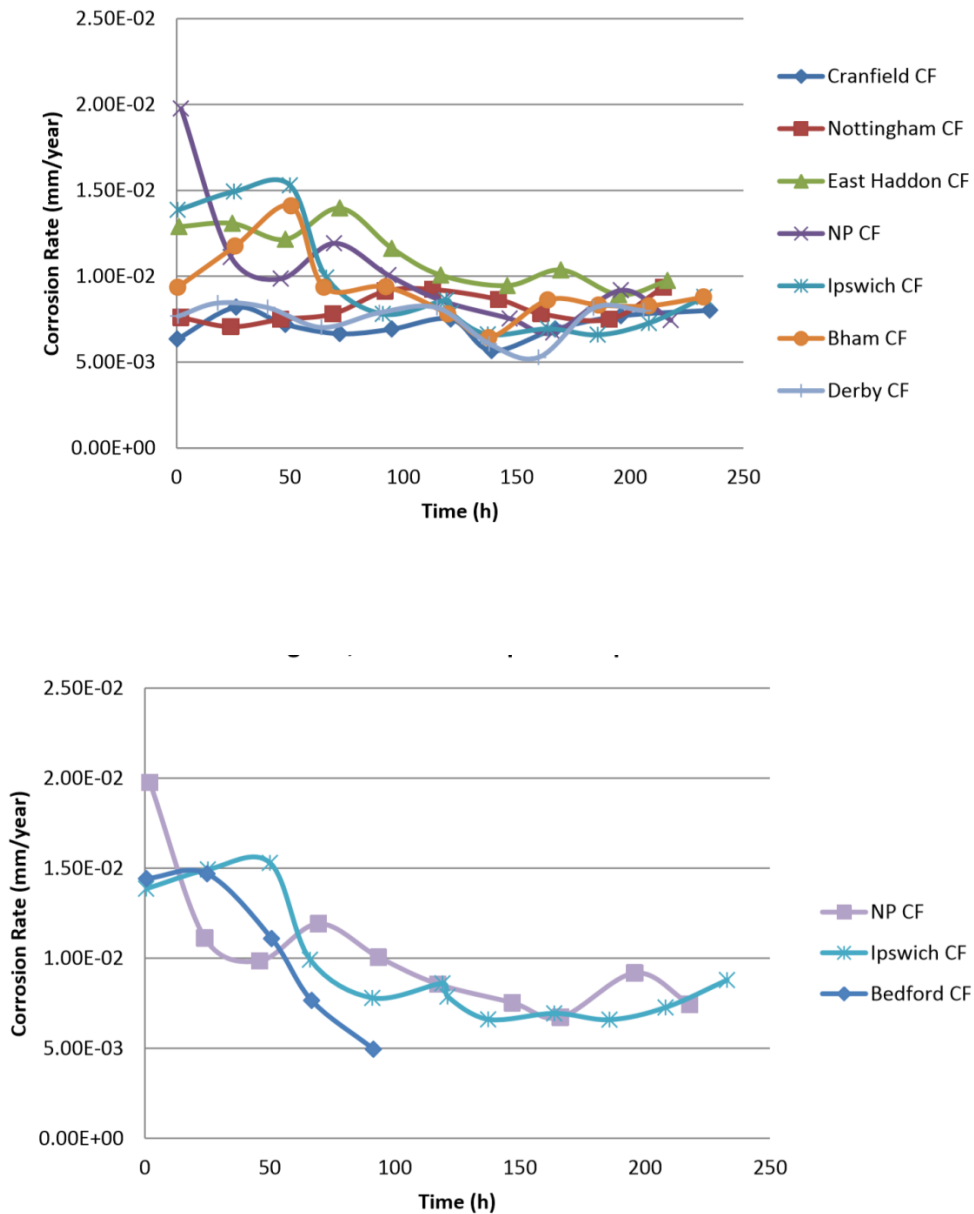
Figure 4-11 (a) Corrosion rates of cold formed carbon steel in 7 UK waters (b) Detail of Newport Pagnell and Ipswich tap waters[Whittaker 2012]

4.3 Dynamic Conditions: Effect of water flow
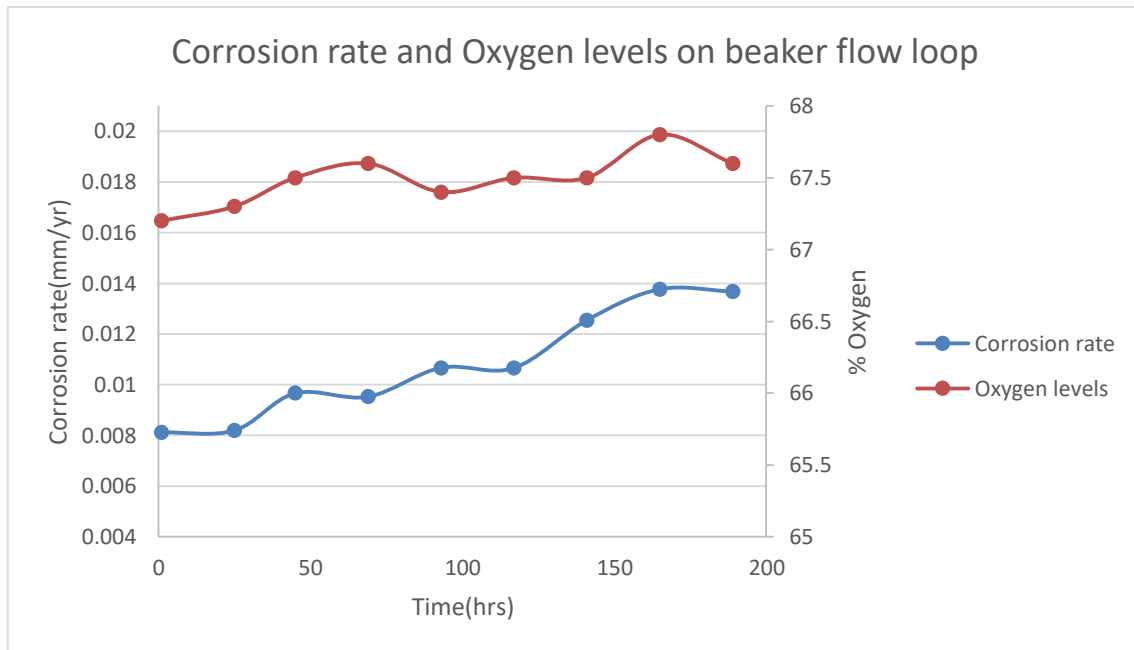
Figure 4-12 Corrosion rate and dissolved oxygen in a beaker flow loop

To explore the effect of flow rate a peristaltic pump was used in an open system at a flow rate of 17ml/s. The corrosion rate remained almost same level with no signs of coming down. The disolved oxygen levels remained high throughout the experiment at approximately 67% oxygen saturation. However there is a proportional relationship between the disolved oxygen and corrosion rate. As the dissolved oxygen increases, so the corrosion rate increases.

It is thought the corrosion remained high because of three things. Firstly, high levels of oxygen through out because of the water circulation and also having an open system that allow contact. Secondly, because of the flow rate, exposure to the surface is continuous and oxygen at the surface is replenished. Thirdly, continouous removal of the corrosion product due to the water flow. This prevented build up of corrosion product layer which insulates the surface from corroding medium. This means fresh surfaces are continuously exposed and corrosion rate remains high.

4.3.1 Effect of oxygen in dynamic conditions
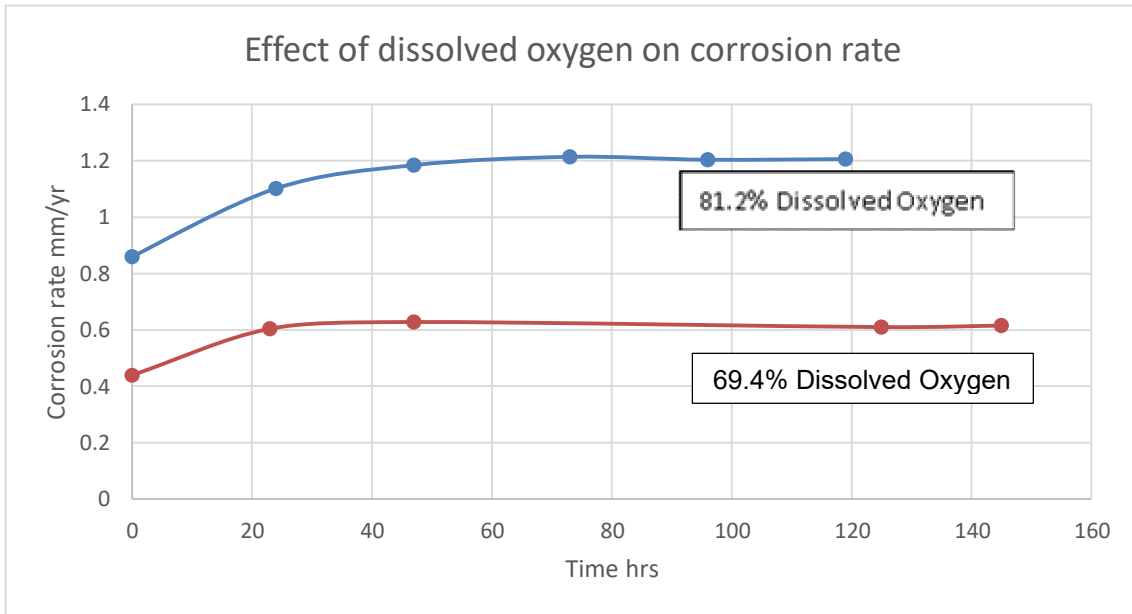
Figure 4-13 corrosion rate at 2 different dissolved oxygen levels

With much higher flow rates in the PVC system (127 ml/s, almost 10 times that of the beaker system) high corrosion rates are experienced. During the experiment with higher dissolved oxygen, there were a lot of air bubbles in the system. Air bubbles on the surface are a possible source of error when using LPR to measure corrosion. LPR measurements are calculated using the surface area in contact with the corrosive medium, so the presence of air bubbles will affect this area. Having said that, still the results obtained were still consitent with that expected, because at higher dissolved oxygen a higher corrosion rate is antcipated. By increasing the dissolved oxygen from 69.4 to 81.2% the corrosion rate doubled. This makes sense considering that in static condition adding oxygen for 5 minutes resulted in trebling the corrosion rate. It is important that when predicting service life that the level of dissolved oxygen in the system is considered.

4.3.2 Effect of flowrate on corrosion rate
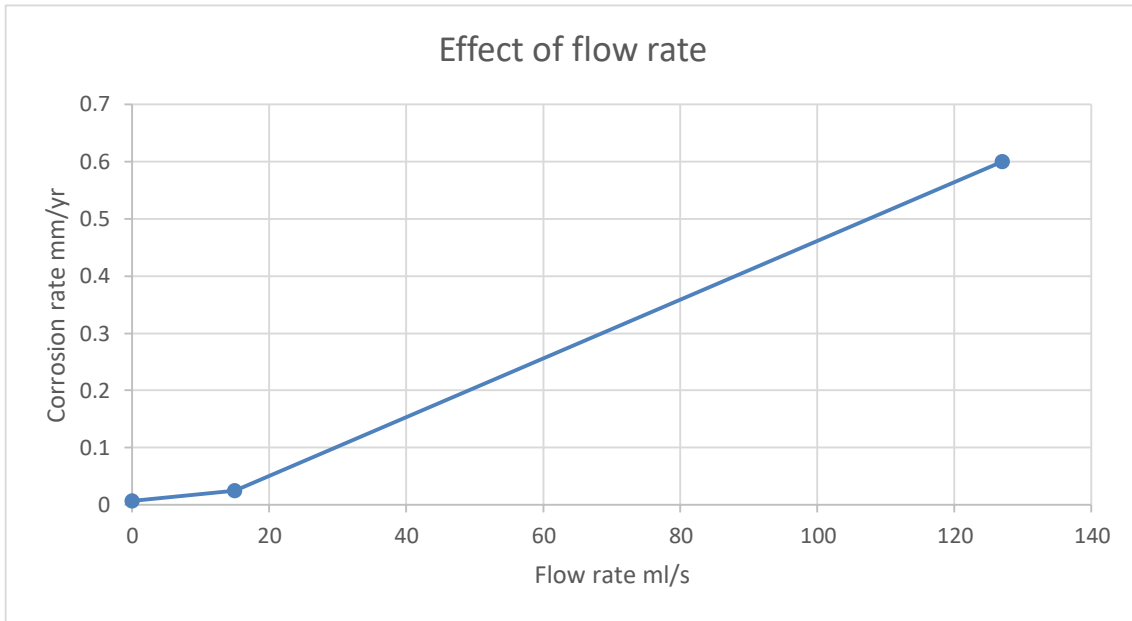
Figure 4-14 Corrosion rate at different flow rates

Figure 4-14 shows the corrosion rate with the flow rates determined above and shows there is an increase in corrosion rate with increase in flowrate from the measurements taken at 67-69% dissolved oxygen. The data on this graph was obtained from different experiments and there is a general trend. A flowing medium means the corrosion product is removed and a fresh surface is exposed. It is important therefore when predicting corrosion rate that the flow rate should be considered. With inhibitor and with a closed system with less dissolved oxygen lower rates are expected. Indeed, at a rate of 0.6 mm/year, the current 1.5 mm thick tube will be degraded by corrosion very swiftly (less than 2.5 years) without attention.

Comparing results in this study with those from previous studies

Table 4-4 shows a comparison of experimental results undertaken in this research work, with results of research reported in literature. The results under different conditions are within the range of those from reported previous research**.**

Condition	This study(mm/yr)	Previous study(mm/yr)	Reference	Comments
Stationery 68% DO	0.02	0.04	Sahal 2018	The pipes used in this study are inhibited whilst Sahal used uninhibited pipes
Stationery DO unknown	0.07-0.09	0.07-0.09	Whittaker	This is within the same range
Dynamic	1.3 @ 16l/s	1.5 @ 14l/s	Metzdorff	This is comparable

Table 4-4 Comparing current results with previous studies

Comments on service life findings from research.

It has been seen in Table 4-5, that taking all factors into consideration, some factors have a greater influence on service life.

Taking factors into consideration, the biggest influence, not assessed here but seen from literature review is the presence or not of an inhibitor. This is a priority in considerations. However, an assumption needs to be made that the inhibitor dosing is fine and topped up, so data checks are required. However, with or without inhibitor the next consideration is flow rate and dissolved oxygen.

Factors	Detail	Comments on service life model
Tube thickness, size and geometry		Material, size of tube and presence of weld can be accommodated and calculations, adjustments made
Water	0.007 mm/yr no flow,	Biggest contribution is the flow rate, and presence of dissolved oxygen.
Water flow	0.6 mm/ year flow	
Dissolved oxygen	1.2mm/yr at 81.2% dissolved oxygen	
use of inhibitors	Not assessed	This is a large contributor but is thought to be able to be accommodated in calculations
surface cleanliness	0.009mm/yr uncleaned Up to 0.03 mm/yr cleaned	In this work a surface inhibitor was present, which could be removed by cleaning. In practicality cleaning could be undertaken with flushing, however it is more likely that any flowing environment will remove the surface history within the first day or hours depending on the flow rate
Galvanic corrosion	Not assessed	Separate consideration needs to be given to this, for adjustments to be made.

Table 4-5 Summary of service life factors and finding from previous research tests

Calculation of the life of carbon steel tube in water with no flow and no inhibitor, with steady state corrosion rate determined from this work

Rate of corrosion, 0.007 mm/year and 1.5 mm wall thickness.

1.5/0.01 = 150 years at steady state (no inhibitor)

  And in dynamic condition

        1.5 mm/0.06 mm/y   = 25 years

In service both static and dynamic conditions exist, and hence it is imperative to estimate the proportion of the time in a year when each condition exist. This is

then used to calculate the contribution of each condition to the annual corrosion rate. The combined corrosion rate is then used to calculate the service life.

As an example, consider a situation where the static corrosion rate is 0.007 mm/yr and the water is stationary for 35% of the time, and a dynamic corrosion rate of 0,06 mm/yr and the water is flowing for 65% of the time,

➢ Static condition

Corrosion in a year   -   0.007 X 0.35   = 0.00245 mm

➢ Dynamic condition

Corrosion in a year -   0.06 X 0.65   =   0.039 mm

Total annual corrosion   - 0.00245 + 0.039 = 0.04145 mm

Hence the combined corrosion rate is 0.04145 mm/yr. Considering a pipe thickness of 1.5mm, the year it takes to corrode to failure is given as;

   1.5/0.04145 = 36.19 yrs

The rate of a process is determined by its rate determining step; this applies to the corrosion process. As previously mentioned, kinetic factors play the largest role in determining the rate of aqueous corrosion as polarization effects control the anodic and cathodic reactions fundamental to the process.

There are two main scenarios:

- Activation-controlled– the rate determining step is the electron transfer reaction.
- Diffusion-controlled – the rate determining step is the diffusion of reactants to/from the metal surface (mass transport controlled).

Effect of Velocity

As solutions are very rarely stagnant it is important when looking into the kinetics of aqueous corrosion to consider how the velocity of the fluid will affect the corrosion rate. The corrosion rate of metals is commonly found to increase with

increasing solution velocity, however it can plateaux at high solution velocities as seen in Figure 4.15 [Kelly, 2003].
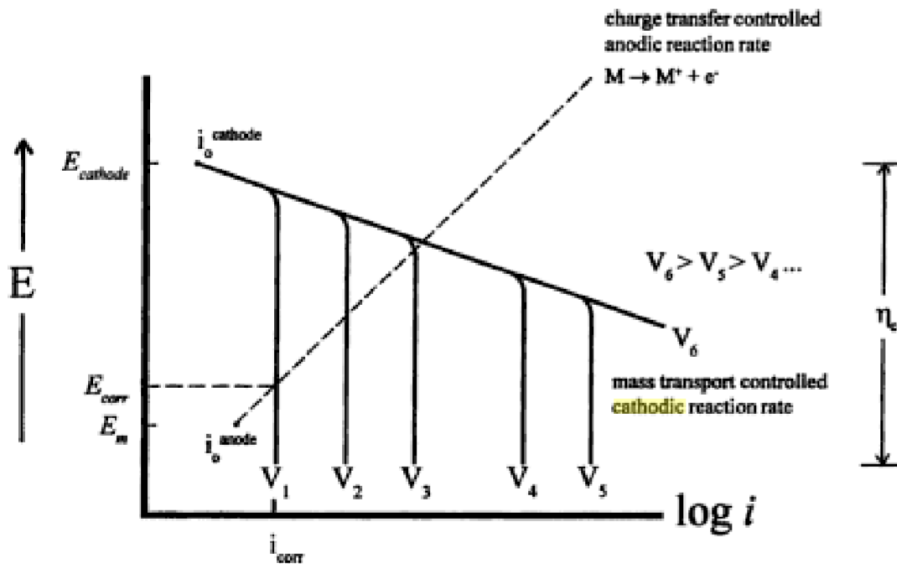
Figure 4-15 An Evan's diagram displaying the effect which solution velocity has on the corrosion rate of uncoated metals

Figure 4-15 shows a scenario in which the cathodic reaction is mass transport controlled until very high solution velocities where it becomes charge transfer controlled. During aqueous corrosion it is rare for the anodic reaction to be mass transport controlled, as metal atoms are in large supply around the anodic sites, and so Figure 4-16 represents an anodic reaction which is constantly charge transfer controlled.
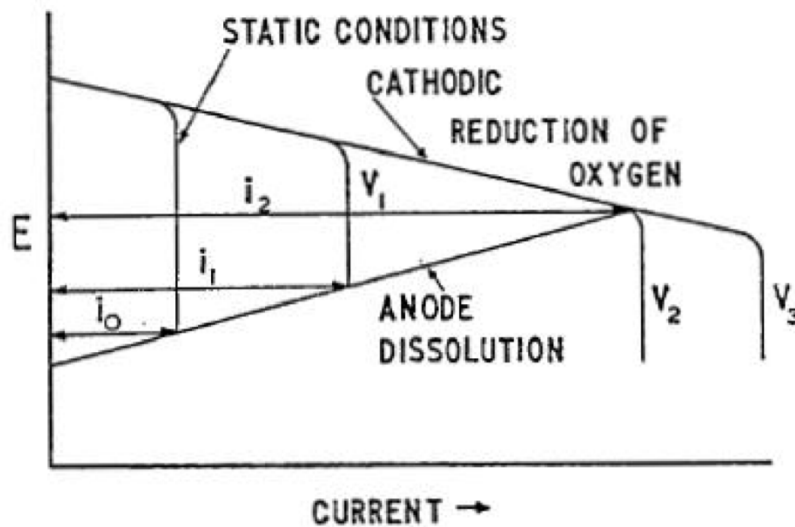
Figure 4-16 Schematic showing the difference between corrosion rates under static conditions compared to higher solution velocities[Robinson 2012]

The effect of agitating the solution, i.e. increasing the solution velocity, depolarises the reaction by supplying more oxygen to the surface of the metal. The movement of the solution carries more dissolved oxygen to the surface of the metal. If there is a greater abundance of oxygen at the metal surface, then the corrosion rate can increase. At a certain solution velocity, the amount of oxygen around the surface of the metal will be in excess, therefore the conveyance of oxygen to the metal surface is no longer the rate determining factor; the rate determining step becomes charge transfer. Figure 4-16 shows the difference between the corrosion rate under static conditions and after increased solution agitation [Robinson, 2012]. Under static conditions, the corrosion current I_o is much lower than the corrosion current, I_1, when the solution velocity is V_1.

5 CASE STUDY: Cooling water system

5.1.1 Introduction

Industrial processes can result in heat generation in the processes and/or equipment. The purpose of a cooling system is to remove the heat generated, protecting the environment and equipment. Water is the most popular medium used for heat extraction, and there are various ways of subsequently removing the heat from the water

One way of extracting the heat is the use of chiller unit. Hot water from the equipment passes through a heat exchanger where heat is transferred to water from an external circuit which contains a chiller for cooling the water. In the process the water is then recycled to cool the equipment.

As the circulating water goes through different temperature cycles, the ions or compounds in the water undergo different chemical reactions. These result in scale formation, biofilms and/or corrosion products building up inside the pipes. This reduces the energy efficiency in the heat exchanger and slows down the corrosion rate.

5.1.2 Selected Cooling System

A cooling water system at Cranfield University from one of the manufacturing buildings (Building 57) was selected to explore corrosion management for more insight. In the selected system, water is used for cooling furnaces and coating systems in the building. The system consists of 2 circuits, a primary and a secondary circuit. The secondary circuit connects furnaces. Most of the pipes in the cooling system are PVC. The pipes connecting to each furnace are copper with brass fittings and make up about 30% of the pipe material. The pumps and filter housings are made of steel.

In the secondary circuit water is pumped to the furnaces at a pressure of 4.5 – 5 bar, returning at a pressure of around 1.5 bars. The return water goes through a heat exchanger and drops in temperature from 38°C to around 25°C. A glass fibre tank is also connected to the circuit for storage.

The primary circuit removes the heat from the secondary circuit water in the heat exchangers and utilises a chiller unit for its cooling.
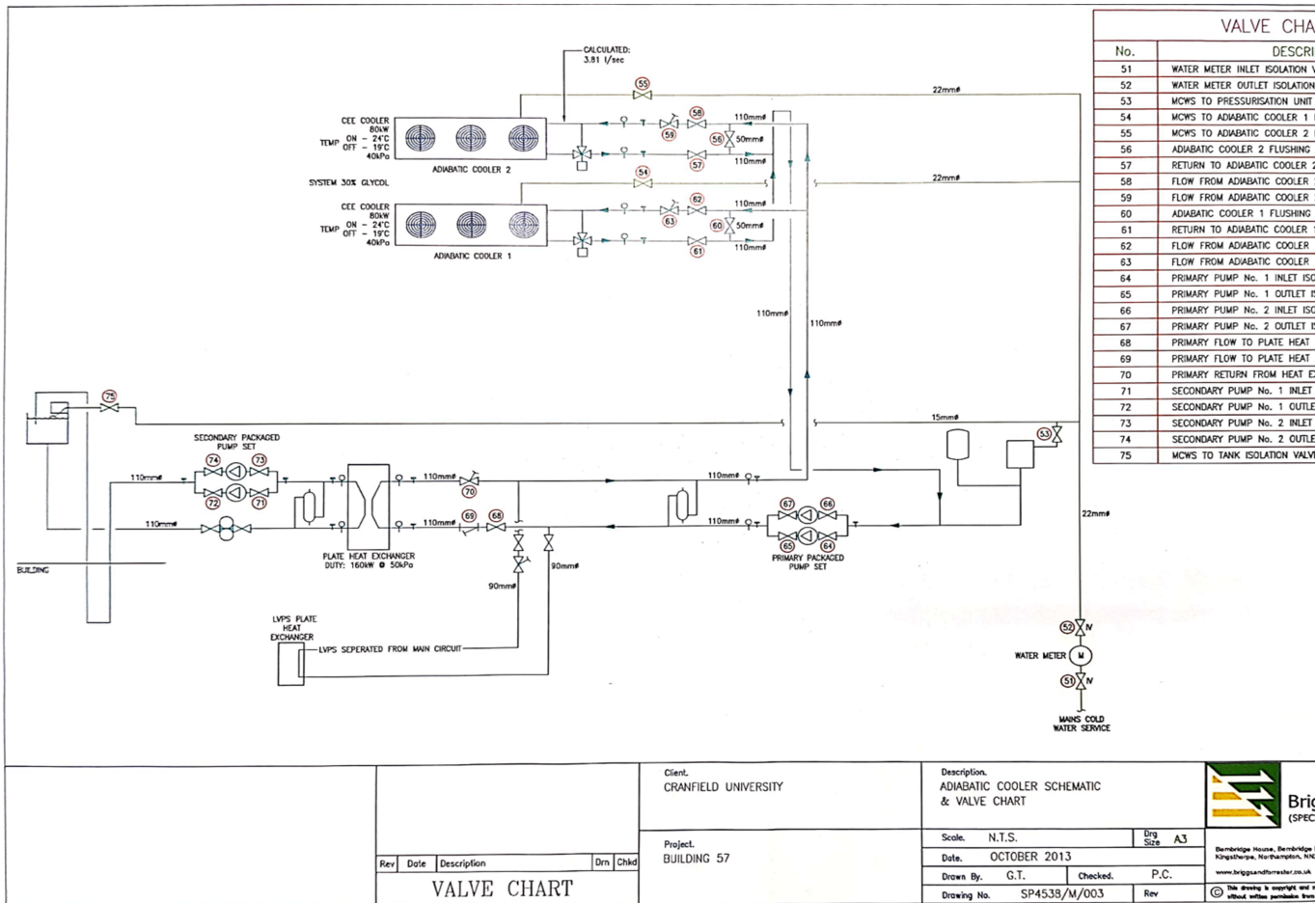
Figure 5-1 Schematic overview of the two cooling circuits

Figure 5-2 PVC storage tank

Figure 5-3 Steel filter housing

Figure 5-4 Copper pipes in the system attached to the furnaces, via multi-port system which are nickel plated brass fittings

5.1.3 History of the cooling system

It was installed in 2008 as one system, and in October 2013 the system was modified with the addition the secondary system. The system was dosed with inhibitor and glycol and their levels in water were monitored for some time.

In October 2015, the inhibitor was accidentally removed when the system water was drained and refilled. A significant increase in the particles in the filters was subsequently observed with time. Water was visibly murky and opaque with suspended solids. This resulted in more frequent cleaning of the filters. There was a breakdown early 2019, which was not corrosion related. However, corrosion was felt to be a developing issue. There had previously been a copper pipe that had needed to be replaced. Also, corrosion debris was cleared and all filters were flushed out and fresh water was used to fill the system. A decision was made to remove the filter which was previously getting blocked and required more and more frequent cleaning. Now any debris collects at the bottom of the tank and less frequent opening of the system is required.

Monthly water analysis was introduced as a way to monitor any corrosion behaviour.

5.1.4 Water analysis

Date	pH	Cond mS/cm	TH	p-Alk	m-Alk	Cr	Fe+	Cu+	Amine	Glycol %
			(ppmCaCO3)			(ppm)				
03/10/2015	7.3	354	125	0	70	25	0	0	3.2	6
02/02/2017	7.1	329	120	0	120	30	0.1	0	4	6
01/06/2017	7.2	296	120	0	100	30	0.2	0	3.8	4
No monitoring since 6/2017 to 06/2019										
Cleaning tank and monitoring resumed										
05/06/2019	7.4	325	140	0	50	40	0.5	0.2	0.1	0
09/07/2019	7.3	311	125	0	55	38	0.1	0.2	0.1	0
02/10/2019	7.2	286	115	0	55	35	0	0.1	0.1	0
07/11/2019	7.2	270	110	0	55	35	0	0.1	0.1	0

Table 5-1 Analysis from Building 57 cooling water monitoring[GEMchem 2019]

Table 5-2 below lists the possible factors affecting corrosion in the system and the likely impact of these factors.

Potential Corrosion problem	Effect	Impact on corrosion
Galvanic interaction	Stainless steel/cast Fe system. The filters are stainless steel and the housing is cast Fe	High
Dissolved Oxygen	Tank partially open cannot be closed Corroded Cu pipes leaking oxygen. Oxygen introduced during the bleeding of the system	High
Glycol	Glycol increases the conductivity of the water	Low
Polymer pipes	Conductivity increase due to polymer pipes	Low
Flowrate	Not all instruments working and hence it is low	Low

Table 5-2 Factors affecting corrosion in the system

The water analysis over the time is consistent with that expected from the brief history above. There were significant changes in the m-Alkalinity, Fe^{2+} and Cu^{2+} in the water during the time. The m-Alkalinity almost halved after the flushing of the water. This could have been coming from some dissolution and ions or due

to the additional chemicals, namely inhibitor Cetamine and an antifreeze. The amine level of 3-4 ppm is attributed to inhibitor used.

The conductivity generally decreases over the period. Bojanna Shantheyanda, [Shantheyanda, 2015] reports that electrical conductivity increases corrosion rates. He also notes that the presence of polymers increases the electrical conductivity of the system.

After draining the system this year, the Fe^{2+} dropped from 0.5% to 0.1% even though no inhibitor is now detected in the water. Is it possible that the inhibitor might still be working if adsorbed onto the surface of the system pipes? Hao Lu [Lu 2018] suggests that some inhibitors are retained on tubes wall surfaces, can inhibit even when the surface is corrosion product and work best once in the presence of oxygen. As flushing water through the system would introduce considerable oxygen in the system there is reason to suppose there is an effective residual inhibitor on the pipe metal surfaces from previously. Having drained the system down and exposed to oxygen before refilling, this may have supported inhibition of the surfaces as Lu reports. Certainly, the concentration of Fe (II) ions does not appear to be very high which could imply there is residual inhibitor working. Of note, is that the Cu^{2+} levels in the solution have increased significantly from 0 to 0.2%.

Previously there was copper corrosion issue. Figure 5-4 shows copper corrosion outside one of the copper tubes, which has perforated. Another tube shows corrosion inside, but this is iron oxide deposit that has transferred on the copper surface presumably deposited when travelling though the water.

Figure 5-5 Corrosion on Cu tubes(a) on outer surface (b) iron oxide internally

Figure 5-4 shows that the corrosion went through the pipe, and this is another way oxygen was introduced into the system.

Galvanic corrosion from dissimilar metals is a possible concern. Indeed Espinosa Tiburcio [Espinosa 2015] showed that carbon steel-stainless steel couples can have high galvanic effect. In our case the filter housing is made of cast iron and the filters are stainless, and there is an iron-stainless steel couple in the filter housing. Additionally, it should be pointed out that the flow rate is extremely high and any leaks or opportunities when opening the system exposing the system to dissolved oxygen.

5.1.5 Corrosion measurements

Rather than assessing the corrosion via water analysis, attempts were made to assess the service life via the techniques used in the laboratory (and Chapter 4) LPR and corrosion coupon. A strip 12.9×3.8 cm was cut from a 50 mm diameter tube as used previously. Four 1.6 mm holes were drilled in each corner. It was painted at the back using vanish to stop the back and sides from corroding. Stainless steel wire was used to suspend the strip in a stainless steel bucket as Figure 5-5 and coated with varnish. The water flow rate of the pump was 21,000

ml/s. The bucket was then lowered in the filter compartment and was left for 72 hours.

Figure 5-6 B57 Coupon after corrosion before being removed from the bucket

After 72 hours, the filter compartment was opened and reference and auxiliary electrodes were suspended inside the bucket, and the working electrode terminal was connected to the coupon sample and measurements subsequently taken.

There was corrosion build up on the sample and the calculated LPR corrosion measurement was 0.117mm/yr. For high proportion of dissolved oxygen, a greater amount of corrosion would be expected. However, the dissolved oxygen levels in the system were not recorded. However, they are expected to be below 67% saturation.

5.1.6 Case Study Discussion

The corrosion rate measured in Building 57 was 0.117 mm/yr and considering that the flow rate was 21000ml/s, we would expect a much higher rate than that using the graph. The inhibitor levels now are lower than the usual levels, but in the laboratory experiments no inhibitor is added at all. This shows the importance

of simulating the exact conditions existing in the pipework system in the laboratory experiments being used to predict service life.

Currently, in Building 57, corrosion is determined by the level of Fe^{2+} in the solution. The results in Table 5-1, suggest that the corrosion rate is very low. The Fe^2 is low the readings, but there is some sensitivity to Cu^{2+} ions in the water. The inhibitor level is very low. The sources of the Fe(II) ions are the pump and the filter housing and the source of the Cu (II) ions are the pipes connecting the furnace and they are more than 5 metres apart. However perhaps there is galvanic corrosion associate with fittings and couplings. The fact that a high corrosion rate measured in the housing compartment, suggests the filter housing area is still active.

Given that there was corrosion after the inhibitor was lost, it means there has been a high build-up of corrosion product on the tube surfaces (as illustrated in Figure 5-4b, which then could shield the surface from further corrosion. The appearance of Cu (II) ions is also interesting and highlights the problem of using Fe(II) concentration in corrosion monitoring. Thus, it might be useful to use LPR probes in corrosion monitoring, providing corrosion product does not deposit on these too.

6 DISCUSSION SUMMARY

To accurately predict service life of pipework systems, the operating conditions of the system must be fully understood. These includes the:

- Water:
    - water chemistry, temperature, dissolved oxygen, pH,
    - Flow rate
    - inhibitor and concentration
- Pipework:
    - material or materials (if coupled)
    - surface condition,
    - presence of a weld

The expected percentage of time the water is stationary and moving must be determined. This is important because any laboratory work must under the same condition as the pipe system under investigation otherwise any predictions will be inaccurate.

For stationary conditions, the setup is the same as in Chapter 3 and the conditions are created to simulate the ones in pipework systems. However, it is so much more relevant to gather data on corrosion rates at a flow. Thus, data is required for any metal in the system, a closed loop constructed and filled with water to determined corrosion at the required flow rate. The surface area ratios of parent metal to other metal pipe of the other metal pipes in the pipework system can be assessed. The LPR electrodes can be installed in the pipework like in section 3.6.2 and or coupons. Water analyses are also very helpful particularly the level of dissolved oxygen. The proportion of the time the water is flowing is more useful to calculate to corrosion in a year.

In order to predict service life, the conditions under which the pipework system is exposed need to be fully understood. Laboratory tests and the case study showed the effect of different environments on the corrosion rate. The contribution of each condition to annual corrosion must be estimated and this is then used to

determine the service life of the pipework system. Estimates of the time at dynamic conditions is critical, because the corrosion rate of flowing water is very different to that of stationary water. The percentage of other metals or alloys in the system and their contribution towards annual corrosion must be considered. The effect of dissolved oxygen and how it be can be introduced in the system must be considered also. The presence of inhibitor and how it contributes to annual corrosion is also to be studied for the respective pipework system. The contribution of the weld, if present, must be investigated.

When all the contribution of different conditions towards annual corrosion is estimated, the annual corrosion can be predicted. This is then used to determine service life, taking into consideration the minimum working thickness of the pipe.

For dynamic conditions it seems the most sensible way is to use different flow rates and plot these on a graph of corrosion rate with flow and extrapolate the corrosion rate at the pipework system flowrate. The contribution of the dynamic conditions is calculated using the percentage of the dynamic condition to the total time. The corrosion taking place in a year is calculated by assessing the worst case contribution and average or most likely behaviour. Thus, service life can be predicted.

7 CONCLUSIONS

1.   Data from a range of measurement methods and systems in small scale laboratory tests and flow loops to represent pipework systems were generated and contributing factors identified.

2. The data generated was used to demonstrate correlation and the main factors influencing corrosion measurement across length scales in static and dynamic environments and details are given below:

3. In an uninhibited system, increased flow rate and dissolved oxygen have the greatest influence on mild steel welded pipes in tap water by increasing corrosion rates and reducing service life.

4. In static conditions in tap water with mild steel welded pipe, the corrosion rate stabilises after about 10 days whilst in dynamic conditions steady state can occur within hours.

5. In tap water the dissolved oxygen (DO) determines the corrosion rate, not the accumulation of corrosion product on the surface. Corrosion rate increases with increasing DO.

6. The weld increases the rate of corrosion significantly (in static conditions), hence it is important to consider the proportion of the weld area to the total surface area when predicting the service life of pipework. In this work 31 and 50mm pipes and also sections of the pipe were used as samples and the corrosion rate differ in still water upto 10 days. After the 10 days, the results are similar.

7. Surface condition is important when measuring corrosion, the presence of grease, oils and/or inhibitor affects the results surface condition and cleaning the surfaces makes a significant difference in the corrosion rate.

8. The flowrate directly affects the corrosion rate, the higher the flowrate the higher the corrosion rate. Therefore it has to be considered when predicting pipework corrosion.

7. A combination of both water analyses and electrochemical monitoring of coupons and direct measurements of pipes is a valuable way to access

corrosion rates and service life. Support with water quality monitoring of ions, specifically Fe, or Cu aids support.

8. If using metal (or coupons) as reference electrodes for monitoring corrosion rates (such as with linear polarisation resistance measurements), careful attention to the degradation of the probe itself from corosion is required; such as regular cleaning to remove corrosion products or awarenss of using the same probe in an inhibited system.

9. Recommendations for qualitative and quantitative approaches to improve and predict service life accurately from lab corrosion rates. A service life model (in Chapter 4.3.2) shows that basic service life using laboratory test results can be linked and for large scale conditions. It is anticipated that both qualitative and quantitative approaches can be used to predict service life

Good Practice Recommendations

- Regularly maintained LPR probes and/or coupons should be used to monitor corrosion rate, together with water analysis to predict the corrosion rate of pipework systems at any given time in future.

- If coupons are used, their handling need to be careful to avoid introducing bacteria into the system

- Where LPR probes are used they should be cleaned of corrosion product and recalibrated regularly, for example during shut down or maintenance otherwise the accuracy of the probe will be compromised

- Air/oxygen leaks of in pipework systems will increase the corrosion rate and reduce service life.

- The presence of other metals affect the potential of the system and hence needs to be monitored as corrosion rates of the metal and galvanic interactions from a combination of metals will have an influence.

8 RECOMMENDATIONS FOR FUTURE WORK

The effect of different metals in the pipework system needs to be investigated. Experiments need to be carried out with varying length of other metal pipes (eg copper (Cu) in conjunction with steel), to see how corrosion varies with length. This can be done in the laboratory using a flow loop with a steel pipe and various length of Cu pipe. Alternatively, it can be carried out in with varying the furnaces in circuit and monitoring corrosion changes.

9 REFERENCES

Abayarathna 1998; Abayarathna D. Ali R *Overview of Hydrogen Permeation Measurement and Monitoring Techniques*. NACE International 1998

Aqua; http://aqua-holding.com/en and private communication

Amtec: *www.amteccorrosion.co.uk/heatingcooling.html* (last visited 11.02.2020)

Anaee 2016: *Tribocorrosion,* University of Technology, Iraq 2016

Anquetin 2010; *Anquetin C, Cranfield MSc Thesis* 2010

Atlas 2010; *Atlas Steel Technical Note No.7" Galvanic Corrosion".*2010

Autodesk: *www.autodesk.com/solution* (last visited 10.02.20)

Agrawal 2001, Agrawal A.K in *Encyclopaedia of Materials: Science and Technology*, 2001

Bardal 2004: Bardal E *Different Forms of Corrosion Classified on the Basis of Appearance.* 2004 Corrosion and Protection *pp 89-191* Part of the Engineering Materials and Processes book series (EMP) ISBN 1852337583

BS EN 10255:2004, *Non-alloy steel tubes suitable for welding and threading. Technical delivery conditions*, BSI, 2004.

BS EN 10217-1:2002, *Welded steel tubes for pressure purposes. Technical delivery conditions. Non-alloy steel tubes with specified room temperature properties,* BSI, 2002

Building.co.uk: CPD6 2019; *Design considerations for portable water pipework*

Burstein 1995: *Surface Roughness and the Metastable Pitting of Stainless Steel in Chloride Solutions* CORROSION ; Journal of science and engineering.1995. https://doi.org/10.5006/1.3293603

Butler 1978 ;Butler G and Ison H (1978) *Corrosion and its Prevention in waters*.

Published by R. E. Krieger Publishing Company SBN 10: 0882755153 / ISBN 13: 9780882755151

Carson 1951: *Effects of Velocity on Corrosion by water Industrial & Engineering Chemistry* **1952** *44* (8), 1745-1752 DOI: 10.1021/ie50512a019

Corrosion Doctors: *corrosion-doctors.org/Inspection* (last visited 10.02.2020)

Corrosionpedia: *www.corrosionpedia.com/definition/469/erosion-corrosion*(last visited 09.02.2020)

Espinosa 2015: Angel Espinosa, Cranfield MSc Thesis 2015

Francis 2002. *Bimetallic Corrosion .NPL*

Fredj 2012: *Corrosion Of Carbon Steel In Waters Of Varying Purity And Velocity* – NACE International conference 2012

GEMchem 2019; GEMchem Ltd, Bristol. Water analyses undertaken.

Grimmer 2017; Grimmer G, *Cranfield MSc thesis 2017*

Gupta 1994: *The effect of dissolved oxygen on corrosion behaviour of mild steel.* University Institute of Engineering and Technology, Kanpur

Hackerman 1952; Hackerman. N. (1952) Effect *of Temperature on Corrosion of Metals by water.* https://doi.org/10.1021/acs.energyfuels.5b01045. *ACS Publications*

Jireh: *www.jireh.com/automated-corrosion-scanning/*(last visited 10.02.2020)

Lambert 2002. *Corrosion mechanisms- An introduction to aqueous corrosion, Hampshire: Corrosion Prevention Association* 2002

Lorek 2018; *What is BIM(Building Information Modelling)* Constructible 2018

Lu 2018: Lu., H *Cranfield MSc Thesis 2018*

Mairs 2018. *www.dezeen.com/2018/04/18/new-london-architecture-nla-survey-tall-buildings-report-survey-uk* (last visited 12.02.2020)

Mertdzorff 2015*; Cranfield MSc Thesis 2015*

Metal Supermarkets 2014 *www.metalsupermarkets.com/difference-between-pipe-and-tube/*(last visited 09.02.2020)

Myrdal 2010. Myrdal, R. *Corrosion Inhibitors – State of the art, Blindern: SINTEF Building and Infrastructure.* Publisher COIN Project report (SINTEF Byggforsk)2010. ISBN 9788253611686

Nanan 2019; Nanan K, *Understanding pitting corrosion to prevent catastrophic failures.* Corrosionpedia. March 2019

Nathan 1973; *Corrosion Inhibitors, National Association of Corrosion Engineering*, Houston, Texas, USA. https://doi.org/10.1002/maco.19740251032

Rabald 1968: Rabald E et al *Corrosion Guide. 2nd Ed., Elsevier Publishing, p. 882 (1968)* Publisher Elsevier Science; eBook ISBN**:** 9780444600059

Rithdang 2014, *Under-deposit corrosion rate evaluation in cooling water system by weight loss, profilemetric and electrical resistance methods*, Applied Mechanics and Materials Volume 548-549:242-246. April 2014

Robege 1999. Robege, P.R *Handbook of Corrosion Engineering, New York: McGraw-Hill* ISBN 0-07-076516-2 (alk. paper)

Robinson 2015. *Principles of Corrosion* Cranfield University 2015

Rothwell 1986. Rothwell, A.N *The preferential corrosion of weldments', UMIST University, Thesis No 773 (unpublished*)

Roy 2012; Roy A. Parisher, Robert A. Rhea, in *Pipe Drafting and Design (Third Edition), 2012*   Gulf Professional Publishing, eBook ISBN**:** 9780123847010 Paperback ISBN**:** 9780123847003

 Sahal 2018; Sahal Cranfield MSc Thesis

Sarin 2004. Sarin et al *Iron Corrosion Scale Growth, Iron Release and Coloured Water Formation* DOI: 10.1061/(ASCE)0733-9372(2004)130:4(364)

Sheir, 1963. Vol. 1: *Basic Concepts, High Temperature Corrosion*

Suez: Handbook of Industrial Water Treatment, Suez Water Technologies and Solution https://www.suezwatertechnologies.com/(last visted 10.02.2020)

Vargel 2004: *Corrosion of Aluminium, 2004* Published by Elsevier Science ISBN-10 0080444954, ISBN-13: 978-008044956. 2004

Whittaker 2012: Whittaker *Cranfield MSc thesis 2012*

Winston 2008: Winston, Revie, R. and Uhlig, H.H. (2008), *Corrosion and Corrosion control an introduction to corrosion science and Engineering. 4th edition ISBN*: 978-0-471-73279-2

Yang 2010; Yang L, Chiang K.T, in *Understanding and Mitigating Ageing in Nuclear Power Plants, 2010* published by Woodhead Publishing.ISBN 978-184569-511-8

Zhu X 2019: Zhu X et al *Comprehensive energy saving evaluation of circulating cooling water system based on combination weighting method* 2019 Applied thermal engineering. DOI: *10.1016/j.applthermaleng.2019.113735*

10 APPENDIX

A1. Linear Polarization Resistance Measurement Procedure
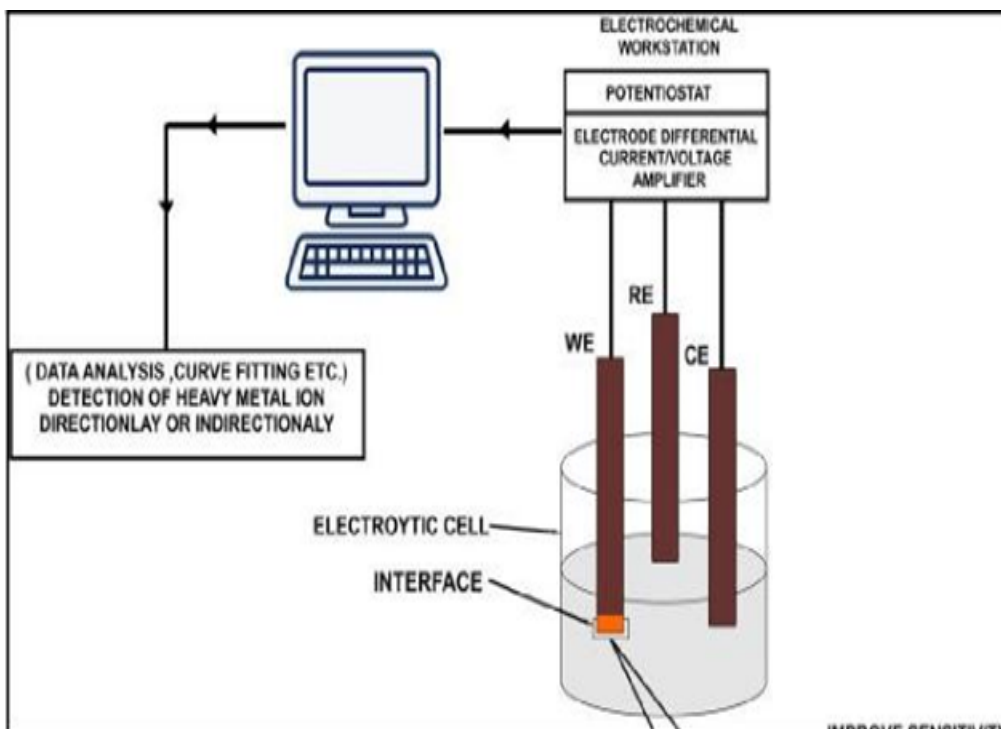
Measurements were carried out using GiLAC machine. The reference and calomel electrode were connected to respective terminals on the machine and the sample being measured was used as the working electrode. Care was taken to make sure the electrodes were not touching.

The area in contact with the corrosive medium is calculated in mm2 and input into the machine. The LPR number was read from the machine, and from this the corrosion rate was calculated.

A2 Example of online flow loop [Aqua Holding]