Review

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Microbiologically influenced corrosion: a review of the studies conducted on buried pipelines

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Abstract: Buried pipelines are essential for the delivery of potable water around the world. A key cause of leaks and bursts in these pipelines, particularly those fabricated from carbon steel, is the accelerated localized corrosion due to the influence of microbes in soil. Here, studies conducted on soil corrosion of pipelines' external surface both in the field and the laboratory are reviewed with a focus on scientific approaches, particularly the techniques used to determine the action and contribution of microbiologically influenced corrosion (MIC). The review encompasses water pipeline studies, as well as oil and gas pipeline studies with similar corrosion mechanisms but significantly higher risks of failure. Significant insight into how MIC progresses in soil has been obtained. However, several limitations to the current breadth of studies are raised. Suggestions based on techniques from other fields of work are made for future research, including the need for a more systematic methodology for such studies.

Keywords: carbon steel; corrosion testing techniques; microbiological corrosion; soil corrosion.

1 Introduction

Many countries, including Australia, are heavily reliant on water pipelines to convey potable water for household and industrial consumption. These pipes form the majority of

urban water authorities' assets and are primarily buried underground in towns and cities, making access difficult and expensive (Petersen and Melchers 2012). These pipelines have long design lives and were commonly buried with little consideration of the corrosion of the external surface (Moore 2010). Failures due to leaks and bursts lead to disruption of potable water services, which has a high economic cost including loss of essential services, material repair costs and labour costs (Moore 2010). In the USA, an estimated 240,000 pipes break a year, the bulk of which is due to corrosion. It is anticipated to cost \$1 trillion to repair and replace all the necessary infrastructure over the next 25 years (Koch et al. 2016). A water main break at Tucson, Arizona in the USA led to the loss of 38 million gallons of water and cost USD 4.3 million. Further potential health repercussions exist due to the corrosion of water pipelines. An example of this comes from Flint, Michigan in the USA (Scully 2016); the mismanagement of its water pipeline infrastructure has resulted in widespread lead poisoning and also multiple cases of Legionnaires' disease in children, as a change in water supply lacked consideration of corrosion in the transmission pipelines. In Toronto, Canada, 25–30 breaks per 100 km of piping occur each year (Schuster and McBean 2008). Significant ramifications in Canada have included the flooding of an electric transformer station, roads being washed away, and ingress of contaminants into distribution pipes which are reliant on chlorine residuals to prevent infection. In Australia, 79% of the 26,700 annual pipeline breaks are attributed to corrosion with an estimated cost of AUD 123 million. 70% of this 139,000 km network in Australia, predominately critical transmissions mains, are constructed using ferrous materials, most commonly cast iron and carbon steel, and are thus highly susceptible to corrosion (Cole and Marney 2012). Importantly, studies have found that the majority of leaks and bursts are due to localized corrosion initiated at the pipe and soil interface (Cole and Marney 2012; Doyle et al. 2003). This is partially because of the heterogeneous nature of soil and the large number of microbes present in soil leading to an increased risk of microbiologically influenced corrosion (MIC). Corrosion of water pipelines has considerable economic,

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environmental and health costs that need to be reduced where possible through appropriate design, monitoring, and replacement.

MIC is a process whereby deterioration of a metal occurs directly or indirectly due to the activity of microorganisms such as bacteria (Little and Lee 2007). Fungi and archaea also exist in soil, but in research, they are either lesser known or have similar roles in the corrosion process of bacteria, and are thus grouped with bacterial categories (Usher et al. 2014a). Although microorganisms can influence corrosion to occur at higher rates than normally anticipated, they have also been shown in laboratory environments to have a protective effect as pure bacterial cultures (Usher et al. 2014a). For situations in which more corrosion occurs, MIC can lead to catastrophic failure because it is difficult to predict the corrosion rate when microorganisms are present. Multiple mechanisms have been suggested for MIC, all of which are believed to involve the presence of biofilms. Biofilms are complex localized systems within which microbes form synergistic micro-environments that allow for the survival of a variety of species (Javaherdashti 2008a). While MIC has been studied for decades in a variety of media, the mechanisms and interactions between biofilms and metals are not fully understood. This is especially true for metals exposed to soil, such as buried water mains. The soil-microbe-metal system is a complex one that is only beginning to be investigated (Fenchel 2002). Soil has a unique structure that incorporates three phases: solid, liquid and gas. This complex structure facilitates corrosion of buried infrastructure, with both chemical and physical properties of soil playing a role in determining the nature and rate of corrosion. Fundamental studies on the electrochemical behaviour of steels in soil support the determination of steps that need to be taken to ensure infrastructure such as pipelines can meet the design lives required by their application.

Many studies have been undertaken to investigate the effects of microbes and biofilms on the internal surface of potable water pipes (Allion et al. 2011; Bachmann and Edyvean 2006; Gamby et al. 2008; Mercer and Lombard 1995; Yang et al. 2012, 2014; Zhu et al. 2014). Therefore, levels of corrosion on the internal surface of water pipes and the contribution of biofilms are well understood. Because of the protective measures adopted for corrosion and the control of infectious agents, such as linings in the pipes, constant water flow and the addition of chlorine to potable water, the risk of corrosion is minimal when compared to the risk of corrosion from the external surface. Localized corrosion of the outer surface is of much greater concern, as it has led to high costs to public health and infrastructure. Cole and Marney, in their 2012 review of pipeline corrosion in soil, identified many inconsistencies

between how metal naturally corrodes in soil, how it is studied in the laboratory, and how it is modelled for life-time predictions (Cole and Marney 2012). Their review excluded MIC because of the importance and complexity of MIC, which required its own review. Following this, the various factors which contribute to MIC of carbon steel pipelines in soil were reviewed by Usher, Kaksonen, Cole and Marney in 2014 (Usher et al. 2014a). However, the different techniques, together with various laboratory and field studies used to determine the action of MIC have not been reviewed; a review of this information is necessary to gain an understanding of the different approaches that have and can be used to study this phenomenon.

This review continues the work of these two earlier studies by reviewing studies of soil corrosion of pipelines, both in the field and in the laboratory, and analysing the scientific approach of these studies to MIC. These are compared with known factors that influence MIC progression in soil to give context to the study of buried pipeline corrosion in the presence of microbes. The review encompasses water pipeline studies as well as buried oil and gas pipelines due to similarities in the mechanisms of corrosion. By widening the field of study, this enabled pertinent conclusions to be made from the findings with a larger breadth of information available, while providing conclusions applicable to both oil and gas pipelines and water pipelines. This review focusses on studies of mild steel pipelines, although several studies that use stainless steel are also included to demonstrate current techniques of studying MIC in soil. In addition, this paper reviews the techniques and conditions utilized to study the phenomenon of MIC of buried mild steel pipelines.

2 Factors to consider when examining MIC in soil

Many different factors need to be considered when designing an experiment to investigate MIC in soil. These factors include the fundamental mechanisms of iron and iron alloy corrosion as well as how the soil environment affects corrosion. Also considered are the different types and combinations of microbes associated with MIC to use in specific experiments, how nutrients added for building a more realistic system affect the metal of interest as well as the growth of bacteria, and how the different corrosion analysis techniques affect metals and bacteria. An additional factor is how methods are used to study and control the development of biofilms and corrosion impact on biofilms. These factors are discussed in detail in the following section.

2.1 Corrosion fundamentals of steel and iron

Corrosion of iron, steel and their alloys such as carbon steel is a well-understood process. Iron reacts with oxygen to form a range of oxide or hydroxide species in both hydrated and anhydrous forms. The most stable state of iron that forms in the presence of sufficient oxygen is ferrous (III) oxide (Booker and Burstein 1994). In the corrosion of iron and iron alloys, iron is oxidized at the anode to form Fe (II) (Groisman 2010). It is then further oxidized to Fe (III) in the oxide film. In low chloride solutions such as potable water, a passive iron oxide layer forms, which slows the reaction as it reduces the ability for oxygen to diffuse (Revie and Uhlig 2008). With the breakdown of this passive layer, due to factors including the action of chlorides, there is the risk of localized corrosion in the form of pitting due to localized changes in thermodynamic stability (Alvarez and Galvele 1984). This phenomenon can be because of the localized changes in pH or changes in oxygen concentration at an area of oxide breakdown, where a small area of bare metal is exposed while much of the surface remains covered by an oxide layer. Localized corrosion is of detriment to water pipelines because it is hard to predict, difficult to monitor and can rapidly lead to failure.

Iron oxides do not have strong bonds to the metal surface, resulting in sloughing of the film under atmospheric conditions and in solutions. The cathodic process of oxygen reduction in iron corrosion may occur within the rust layers (Stratmann and Müller 1994) and not just at the steel interface. For corrosion to occur, the oxide film needs to have high rates of ionic transport for ions from the electrolyte to reach the iron surface and initiate corrosion (Payer et al. 1995). This is important to understand when analysing corrosion experiments, especially if they are not being conducted under atmospheric or highly conductive conditions, such as soil.

2.2 Soil corrosion of iron and carbon steel

Soil is heterogeneous by nature and, consequently, the environment of air, water and solid particles or combinations of the three that are directly in contact with a pipe surface change along the length of the pipe. The environmental conditions along a pipeline are particularly important because the majority of failures along pipelines are the results of pitting corrosion from localized oxygen, nutrients, soil characteristics such as backfill, moisture

and microbial changes (Cole and Marney 2012; Jiang et al. 2009b; Petersen and Melchers 2016; Usher et al. 2014a). Localized corrosion is particularly prevalent in soils because of the high level of heterogeneity they exhibit. Specifically, long-term corrosion of pipelines involves a step-wise lateral growth of localized corrosion pit depth (Soltani Asadi and Melchers 2017b). This has been explored further to include the effect of water leakage after pipeline perforation due to pit growth (Melchers 2017). Soils that allow for easy drainages, such as sandy soils which have large particles and thus large pores, are less corrosive than those who tend to collect and hold water, such as clay with its tiny pores (Escalante 1989). Whether water collects in soil is also dependent on soil compression. As moisture increases in soil, connected air paths through the soil decrease, and thus oxygen diffusion decreases since diffusion through the air is magnitudes faster than through water. The liquid/gas/solid multiphase corrosion system associated with soils leads to solid soil particles that form pores, within which water or air is trapped resulting in liquid dispersion across a metal surface buried in soil (Jiang et al. 2009b). This leads to the formation of triple-phase boundary (TPB) zones, as shown in Figure 1. The geometry of these TPB zones is affected by soil type, soil compression and water content (Jiang et al. 2009a). As the length of total TPB zones on a metal surface increases, the liquid dispersion across the surface increases, and a linear increase in corrosion current density follows. Clay soils have smaller particles, more pores and thus more TPB zones, which lead to greater corrosion current densities than sandy soils. Corrosion of mild steel in soils is appreciably different from corrosion in aqueous environments because of the formation of TPB zones and microenvironments.

2.3 Role of bacteria types and biofilm formation in MIC

As discussed in previous reviews, many different microbes have been associated with MIC (Beech and Sunner 2004; Little and Lee 2007; Little et al. 2011; Morton and Surman 1994; Usher et al. 2014a; Videla and Herrera 2005). These microorganisms have been classified based on their perceived mechanisms of corrosion. The groups include sulphate-reducing bacteria (SRB), iron-reducing bacteria (IRB), iron-oxidizing bacteria (IOB), acid-producing bacteria (APB), and extracellular polymeric substance (EPS) producing bacteria (Usher et al. 2014a); of these, the most well-studied group is the SRB (Anandkumar et al. 2016). It

Figure 1: Schematic of triple-phase boundary zones at the pipe surface in soil during corrosion.

is important to note that bacteria and other microbes form complex localized systems known as biofilms in the natural environment, and the most severe corrosion is always associated with the presence of biofilms (Javaherdashti 2008a; Little and Lee 2007). Biofilms allow for bacteria and other microbes to survive in otherwise adverse conditions through the formation of synergistic micro-environments. Many MIC studies conducted in the laboratory report higher rates of corrosion with multiple species of bacteria present, or when using natively found biofilm complexes in comparison to using a single species (Dexter and Lin 1992; Jack et al. 1992; Little and Lee 2007). The formation of biofilms is what allows SRB to survive in aerobic environments because they can form the inner layer of a biofilm where oxygen levels are minute, as a result of the consumption of any available oxygen by aerobic bacteria on the exposed surface. An example of this is when within an aerobic macro environment, an IOB forms a tubercle and within the tubercle, an anaerobic microenvironment is established where SRB can replicate and effect corrosion (Liu et al. 2015). A similar process occurs with a CO_2 -favouring SRB that formed a biofilm to protect itself in the presence of oxygen and air (Liu and Cheng 2018a). Similar mechanisms were shown for a nitrate-reducing bacteria (NRB) in soil; however, in this case, the bacteria was also observed to be capable of consuming oxygen in an aerobic environment, which affected the oxidation process of corrosion (Wan et al. 2018). In addition, a recent study has studied the mechanisms behind different corrosion inhibition and acceleration effects of the IOB produced EPS, which depended on the age of the biofilm (Liu et al. 2017).

Numerous bacteria, yeasts and fungi have been implicated in MIC, and the many associated mechanisms are still being explored.

2.4 Biochemical mechanisms specific to MIC of mild steel pipelines

With the presence of microbes, direct or indirect MIC can occur. Higher corrosion rates than normally expected have been shown in many cases with MIC, although a protective effect against corrosion has also been shown in a study of bacteria for single cultures. Usher et al. reviewed the various factors that contribute to MIC of carbon steel pipelines in soil in 2014. The effect of MIC on corrosion is unpredictable, which means that it is difficult to anticipate the exact corrosion rates when microorganisms are present.

Several biochemical mechanisms guide MIC in soil, which has been discussed in detail (Gu et al. 2019; Wasim et al. 2018), and listed in Table 1. The characteristics of corrosion in soil involve interaction between the metal, oxygen, or the lack of oxygen, other gases and the surrounding solution. The documented mechanisms of MIC are all believed to involve the presence of biofilms. Microbes form synergistic micro-environments known as biofilms, involving EPS secreted by microorganisms, with a variety of microbial species. Biofilms, and the microorganisms within them, facilitate the biochemical mechanisms that influence the corrosion processes.

2.4.1 Effects of the biofilm layer

One common biochemical mechanism involved in corrosion is the survival of anaerobic SRB in aerobic environments. This is possible as they form the inner layer of a biofilm where oxygen levels are minute, as the bulk of the oxygen is consumed on the biofilm surface by aerobic bacteria. For example, an IOB forms a tubercle in an aerobic macro environment, within which an anaerobic microenvironment allow SRB to replicate and affect corrosion (Liu et al. 2015). In another case, CO_2 -favouring SRB formed a biofilm for protection in the presence of oxygenated air (Liu and Cheng 2018a). A similar circumstance was studied with NRB in soil, the bacterium were observed to be capable of consuming oxygen in an aerobic environment, which affected the oxidation process of corrosion (Wan et al. 2018). In addition, a recent study showed the mechanisms behind different corrosion inhibition and acceleration effects of the IOB-produced EPS depended on the age of the biofilm (Liu et al. 2017).

Table 1: A summary of the major mechanisms associated with MIC of buried mild steel.

Mechanism	Basis of corrosion	Actions of microbes
Biofilm layer	MIC-inducing microbes protected from harsh environments	<ul style="list-style-type: none">• SRB survive in anaerobic microenvironments within aerobic macroenvironments such as in a tubercle created by aerobic IOB (H. Liu et al. 2015).• Some NRB behave like aerobic and anaerobic bacteria (Wan et al. 2018).
Differential aeration	Difference in oxygen content creating anodic or cathodic regions, leading to pitting corrosion	<ul style="list-style-type: none">• Inconsistent diffusion of oxygen by biofilms (Kajiyama and Koyama 1997).• Oxygen deficiency under tubercles formed on metal surfaces (Coetser and Cloete 2005).
Acidity	Low pH increases corrosion of steel	<ul style="list-style-type: none">• Hydrogen permeation (Biezma 2001).• Release organic acid metabolites to obtain nutrients (Pillay and Lin 2013).• Carbon dioxide respiration by aerobic bacteria (Sufliata et al. 2008).• Organic carbon consumption for growth (Boopathy and Daniels 1991).
Galvanic cells	Adsorption of metals to microbe cells with large surface charge density and surface area to volume ratio	<ul style="list-style-type: none">• Precipitation of active bacteria cell wall adsorb dissolved metal ions (Beveridge et al. 1983).• Fe and Mn-depositing bacteria form metal encrusted sheaths and stalks, that can look like large encrusted masses of cells (Ghiorse 1984).
Elevated electron exchange	Significant increases in corrosion rates through direct consumption of electrons from steel	<ul style="list-style-type: none">• Nanowire facilitated electron exchange with metal (Erable et al. 2010).• Oxidation of Fe⁰ to Fe²⁺ by SRB and methanogens (Enning et al. 2012).

2.4.2 Differential aeration

Another well studied mechanism is differential aeration. The biofilm formed on the metal surface either limits oxygen diffusion in certain areas and creates an anodic region (Kajiyama and Koyama 1997; Rao et al. 2000), or form solid tubercles and deposits on the metal surface through MIC which produces oxygen deficiency under the tubercles and creates a flow of electrons to the cleaner cathodic regions, which result in pitting corrosion (Coetser and Cloete 2005; Liu et al. 2018; Pillay and Lin 2013). Pitting corrosion in itself is the most common form of extremely localized corrosion (Velázquez et al. 2009).

2.4.3 Acidity

The third major biochemical mechanism that microbes promote for localized corrosion in soil is acidity. This mechanism is based on the susceptibility of metals towards low pH environments, the creation of which is assisted by bacteria. Through hydrogen permeation in soil, the EPS and other products of the bacterial biofilm can lower the local pH, which causes an increase of iron ions released to

its surrounding environment (Biezma 2001). Also, carbonic acid is formed through the respiration of carbon dioxide by aerobic bacteria, acidifying the inner regions of biofilms (Sufliata et al. 2008). Microbes also release a wide range of organic acid metabolites to obtain essential nutrients, which can acidify the surrounding environment (Pillay and Lin 2013). Finally, as heterotrophic microorganisms that consume organic carbon for growth and increase hydrogen concentrations, accelerated corrosion can occur with SRB and methanogens using hydrogen as the electron donor for growth (Boopathy and Daniels 1991).

2.4.4 Galvanic cells

The fourth biochemical mechanism is the creation of galvanic cells through the adsorption of metals to cells. The active cell walls of bacteria precipitate and adsorb dissolved metallic ions with their large surface charge density and surface-area-to-volume ratio (Beveridge et al. 1983). A galvanic cell is then created between the metal substrate and the biofilm with the metal-rich phase formed close to the substrate (Javed et al. 2017). The formation of galvanic cells on the steel surface is caused by iron and manganese-

depositing bacteria forming metal encrusted sheaths and stalks of microbial cells (Ghiorse 1984). Because the heterogeneous bacterial cell walls can respond to different environments by change of composition, it is difficult to understand the metal bonding mechanisms involved with the formation of galvanic cells.

In a similar vein to acidic environments, some species of bacteria are able to secrete a range of volatile compounds and enzymes that accelerate corrosion (Deljunco et al. 1992). Nanowires from bacteria that facilitate the exchange of electrons with metal compounds have been discovered to promote chemical reactions as well (Erable et al. 2010). Significant increases in corrosion rates have also been observed through the direct consumption of electrons from steel, through the oxidation of Fe^0 to Fe^{2+} by SRB and methanogens (Enning et al. 2012). These studies are especially useful for understanding the exchange of energy and electrons among the microbe consortium in biofilms.

2.5 Differentiating MIC from abiological corrosion of mild steel pipelines

In mild steel pipeline corrosion, microbes primarily produce corrosive microenvironments through biofilm formation on the pipe wall. The biofilm consists of EPSs secreted by microbes and allow the survival of a variety of microbial species in this synergistic micro-environment. At the pipe surface, localised differential aeration conditions and galvanic cells are constructed in the micro-environments and can cause localised corrosion. To confirm localised corrosion by MIC, a biofilm should be visually identifiable from the pipe surface, and black or green corrosion products with pitting should form underneath the biofilm because of anaerobic corrosion (Dafter 2013). Subsequently, the biofilm will need to be tested for the presence of microbes associated with MIC using molecular microbiology (Zhu et al. 2014). The specific effects of MIC can also include bacteria manipulating local acidities at pipe surfaces. These added effects of MIC do not exist when bacteria are removed during the corrosion process. Other corrosion-inducing mechanisms specific to MIC, such as facilitating the direct exchange of electrons with steel, direct consumption of electrons from steel, and the production of volatile compounds that accelerate corrosion, also do not exist in abiological corrosion without the presence of certain microbes. The specific biochemical mechanisms that differentiate MIC from abiological corrosion have been highlighted in section 2.4.

2.6 Role of nutrients and electrolytes in MIC studies

Laboratory studies of MIC commonly involve the use of solutions and the addition of nutrients and electrolytes, to replicate the environments in which MIC is observed and facilitate the growth of microbes. Over time, the types and concentrations of compounds required to enable culturing of specific microbes in a laboratory environment have been well established (Willey et al. 2008). These compounds range from organic molecules such as peptides (Payne 1976), sugars (Rainha and Fonseca 1997) and amino acids to inorganic molecules such as sodium chloride (Chamritski et al. 2004) and iron oxides (Little et al. 1998). Conversely, the role of nutrients in corrosion is still being determined, whether microbes are present or not. It is important that when nutrients are added to a controlled environment for a corrosion experiment, this variable is considered for maximum experimental impact. Nutrients have been shown to have an inhibitory effect on corrosion on many occasions (Webster and Newman 1994). As discussed by Little and Lee, the inhibitory effect of nutrients on corrosion is dependent on the type of nutrients (Little and Lee 2014). The ratio of aggressive ions such as chlorides to inhibitory compounds present is also important. More recently, a study found that peptides, a common addition to MIC studies since it is a readily available energy source for many microbes, had an inhibitory effect on the corrosion of carbon steel when no microbes were present (Spark et al. 2016b); without this knowledge, the inhibitory effect of the nutrients could have been attributed to the action of microbes. Much debate is ongoing in the corrosion community as to whether certain bacterial species have an inhibiting effect or an accelerating effect on corrosion (Herrera and Videla 2009; Lee et al. 2006; Videla and Herrera 2009). The nutrients present in these studies are the most likely cause for the discrepancies, as a study published in 2014 showed that depending on the media used, *Escherichia coli* (*E. coli*) had either an inhibitory or an accelerating effect on the corrosion of carbon steel (Javed et al. 2014). Recent studies have shown the impact of organic carbon starvation on the accelerated corrosion induced by NRB and methanogens, providing insights into the corrosion inhibition mechanics with different nutrient levels (Jia et al. 2017; Tan et al. 2017). In addition, certain nutrient types are believed to interfere with electrochemical characterization, which can lead to discrepancies between results (Little and Lee 2007). Yeast extract, a common component of commercially available nutrient mixes, has been shown to increase the disparity between electrochemical scans performed under identical conditions (Lee and Little 2015). One study has also indicated

that several microbes are capable of regulating extracellular pH through nutrient limitation (Kryachko and Hemmingsen 2017). For the design of a successful MIC study, considerations of the nutrient types and concentrations are just as crucial as the microbes to be analysed.

2.7 Corrosion testing techniques

Corrosion studies are predominately designed with two aims; to understand the mechanics behind corrosion that are occurring and to determine ways to minimize the effects that lead to the occurrences of corrosion. A wide range of testing techniques can be employed to study corrosion of steel; some are more widely applicable to MIC and soil corrosion than others, therefore, limitations need to be acknowledged for each technique. Subsequently, these techniques are often used simultaneously in conjunction with techniques such as SEM, to compare with the results from sterilized samples and reveal the effect of microbes on the corrosion process (Jia et al. 2017). The techniques can be broadly categorized by whether they monitor corrosion as corrosion occurs or whether they accelerate corrosion, thus making it possible to study the effects of corrosion in a shorter period in the laboratory. Techniques that monitor corrosion as it occurs include weight loss measurement, pitting analysis, electrochemical impedance spectroscopy (EIS), electrochemical noise (EN), polarization resistance and open circuit potential (OCP). Techniques that accelerate corrosion with the application of potentials significantly greater in magnitude than OCP include cyclic voltammetry (CV), potentiodynamic scan (PDS) and potential hold (PH) measurements. These systems share a limitation in that large changes in applied potential are known to affect the growth and stability of bacteria and biofilms (Javaherdashti 2008b; Little and Lee 2007). This can cause an impact on the results obtained and needs to be taken into consideration when analysing results from these experiments. Attempts are also being made to model the effects of soil corrosion of water pipelines, although the studies have not yet extended to microbial corrosion (Petersen and Melchers 2016). Regardless of whether the techniques are old or new, research has demonstrated the importance to create realistic experimental conditions during the design of corrosion tests, and establish standards, especially for laboratory-based MIC experiments (Wade et al. 2017).

2.7.1 Weight loss

Weight loss is a commonly used technique for which samples are weighed before and after exposure to the

environment being studied (Usher et al. 2014a). From the difference in weight, corrosion rates per year can be calculated, and the relative corrosivity of different environments can be compared. Samples are often exposed from days to weeks and months. This technique is widely applied to studies conducted in natural environments, e. g., submersion of coupons in rivers (Melchers 2007), and to MIC studies in laboratories since no applied potential exist to change how bacteria respond (Usher et al. 2015). However, in certain short-term tests, detectable weight loss is not shown.

2.7.2 Pitting analysis

Pitting analysis is when the topography of the corroded metal surface is analysed for its pitting corrosion. Often pits can still be detected when weight loss is small. The maximum pit depth of a given surface at a given time is often taken when the sample is excavated, and subsequently, the rate of pitting corrosion can be assessed, alongside other information such as mechanisms of pit growth. Using SEM, the pit morphology and surface diameter can be observed after the removal of biofilms and corrosion products, whereas pit depth information is provided by profilometers such as infinite focus microscopy (IFM), confocal laser scanning microscopy (CLSM) and atomic force microscopy (AFM) (Jia et al. 2019).

2.7.3 Electrochemical impedance spectroscopy

In EIS, an AC pulse at a fixed potential is applied to a system with the impedance measured in relation to a range of AC frequencies (Amirudin and Thieny 1995). It is often used to study oxide films as they form, and to study the effectiveness of polymer coating systems. Because the voltage applied is over a very small range, it is understood not to alter bacterial cells and biofilms and thus has been widely applied to both biofilm studies and studies of MIC (Lee et al. 2006; Little et al. 2011). Although EIS is a powerful technique, care needs to be taken with selecting operating parameters and interpreting the results of EIS. Due to the complexity of this technique, expert opinion is often required.

2.7.4 Polarization resistance analysis

Polarization resistance analyses the instantaneous corrosion rate with time for a system (Mansfeld and Little 1992). Small changes in potential are applied from OCP at set intervals to measure the polarization resistance and Tafel slope values; the corrosion rate can be calculated from this data. A simplified form of this technique is linear

polarization resistance (LPR) measurements (Mansfeld and Little 1992). In LPR, the potential and current are assumed to be linear within a small range from the corrosion potential, so only two measurements on either side of the corrosion potential are necessary. LPR is widely used to determine buried pipeline corrosion rates both in the field and in laboratory studies (Dafter 2013; Moglia et al. 2004; Norin and Vinka 2003). It has also been applied to many MIC studies as it is considered a low interference technique for biofilm stability (Li et al. 2003; Mansfeld and Little 1991; Usher et al. 2014a). One of the disadvantages of this method is that issues with ohmic or IR drop can occur in high resistivity environments such as in soil. Thus, as an essential technique for corrosion analysis, various guidelines have been outlined to better interpret LPR data for steel corrosion in soil (Cull 2017).

2.7.5 Electrical noise analysis

For electrical noise (EN) analysis, fluctuations in the potential of a metal surface relative to either a fixed reference electrode or an electrode identical to itself are recorded and analysed (Mansfeld and Little 1991). These fluctuations can be used to determine corrosion rates alongside polarization resistance with the use of the Stern-Geary equation (Ohaeri et al. 2018), but they are most commonly used to assess whether localized corrosion is occurring at a site. Although this is best suited as a monitoring technique, it has been used in several MIC studies, including the study of anaerobic corrosion (Iverson and Heverly 1986) and the effects of an SRB species isolated from an oil field (Miranda et al. 2006). It is envisaged that more work needs to be done to confirm its comparative viability against other corrosion techniques with regards to its corrosion monitoring. The results are especially useful when compared with other continuous monitoring methods like LPR and EIS, that as a passive electrochemical technique it does not significantly inhibit the attachment and growth of biofilm and thus its corrosivity on the metal (Zhao et al. 2017).

2.7.6 Open circuit potential

In OCP the potential of a sample in a given environment is measured against a fixed reference electrode with no external current applied (Dexter et al. 1991). This indicates the corrosivity of a given system and can be used to determine the onset of localized corrosion. It is very widely utilized in corrosion studies, especially for those that are laboratory-based and has been used in inhibition studies (Amin et al. 2010), MIC studies (Liu et al. 2015; Obuekwe et al. 1981) and soil corrosion studies (Dafter 2014; Sun et al. 2011).

2.7.7 Cyclic voltammetry

This technique involves the cycling of potential and measurement of the resultant current (Kissinger and Heineman 1983). The potential is applied in a linear sweep in one direction and then reversed to compare the differences between a negative and a positive sweep. This allows reducible and oxidizable (redox) species to be identified. CV is widely used in electrochemical studies, which includes the study of ionic liquids (Snook et al. 2006) and the electron transfer between metal substrates and biofilms (Marsili et al. 2008). Recently, a variation called voltammetry around OCP (VAOCP), which is a non-destructive technique, has been used to monitor changes to the corrosion process and corrosion rate with time, which when complemented with EIS, can lead to new information on what controls oxygen reduction, i.e., diffusion, mixed or charge transfer control (Akkouche et al. 2016).

2.7.8 Potentiodynamic polarization scans

Potentiodynamic polarization scans (PDS) are the most commonly utilized accelerated corrosion technique. They can be conducted in one of two ways (Pourbaix 1984); in the first method, a scan is started from an applied cathodic potential then increasing gradually in small steps up to an anodic scan with the current response recorded. Alternatively, starting at OCP, a scan can be conducted in a negative direction to record the cathodic characteristics, and then a separate scan is conducted from OCP in a positive direction to record the anodic characteristics. PDS gives an overview of the corrosion reactions within a system of interest and, with the use of Tafel extrapolation, the corrosion potential and corrosion rate can be calculated from the resultant curves (Mansfeld and Little 1992). There have also been new developments in the calculation of corrosion potential and corrosion rate through a combination of Tafel extrapolation and other techniques such as the Allen-Hickling plot approach (Betts et al. 2017). The use of other techniques, however, requires additional consideration of material and environment combinations. It is commonly used to compare the effects of specific environmental conditions, the addition of inhibitors or the addition of bacteria to a system. Although widely used in MIC studies, there is a growing trend away from the technique because of the understanding that the rapid change in potential leads to the death of bacterial cells, thus not recreating the conditions experienced in nature (Usher et al. 2014a).

2.7.9 Potential hold measurements

Potential hold measurements (PH), or chronoamperometry, is a technique for which a potential is applied to a system,

and the resultant current produced is recorded with time (Refait et al. 2011). Since the current is integrated over relatively lengthy time intervals, PH gives a good signal to noise ratio compared with other techniques. PH is often used alongside CV and has been used for many applications, which include coating disbondment studies, studies of the response of bacteria to held potentials (Busalmen and de Sánchez 2005) and cathodic potential studies (Guezennec 1991).

2.8 Effect of applied potentials on steel and bacteria

Given that many electrochemical techniques used to study and control corrosion are based on potential changes, it is important to understand the effects of potentials on biofilms and bacterial species. Equipped with the knowledge of how potentials affect bacteria, better decisions can be made with regards to which techniques should be used to study and control corrosion when bacteria and other microbes are involved. An applied potential to a surface with a biofilm can either encourage the growth of the biofilm or cause it to atrophy. An applied potential has been shown to be needed for a biofilm to grow on a given surface (Erable et al. 2010). Stainless steel in seawater has been shown to more readily form a biofilm under cathodic polarization than when the steel was maintained at OCP. It has been demonstrated for certain biofilms that the more cathodic the potential applied, the more conductive the biofilm formed and thus the greater the risk of MIC (Faimali et al. 2008). Bacterial species can be isolated and identified by applying potential since certain species will migrate towards positive potentials and others toward negative potentials, based on the cell wall structure (Licina 2008). Anodic potentials have also been shown to influence bacterial activity, although the effects are less well understood. For example, the biofilm development of *Pseudomonas fluorescens* has been shown to change when exposed to cathodic versus anodic potentials (Busalmen and de Sánchez 2005). Cells were shown to rapidly elongate, double and form dispersed, mushroom-shaped biofilms when exposed to cathodic potentials. When exposed to anodic potentials, the same cell types experienced slower elongation and doubled time, also formed short cells in large numbers of flat, compact micro-colonies. The response of microbial species to different potentials needs to be considered when both studying the mechanisms of corrosion due to MIC and determining appropriate controls to prevent MIC of buried infrastructure such as water pipelines.

3 Field studies

In this section, a systematic review has been performed on the external corrosion studies of buried pipelines conducted over the years. The focus is not only on water pipes but also extending to gas and oil pipelines, which widens the understanding of how soil-microbe-steel pipeline interactions have been studied in the past. One of the most comprehensive databases on pipeline corrosion field studies comes from the U.S. National Bureau of Standards (Romanoff 1957). This report consists of a large number of underground corrosion experiments of mostly ferrous metals buried in soils that have commenced at various dates from 1910. As the report provides many raw data of corrosion in soils, several studies have since been conducted to reinterpret sections of the database. One study argues that, instead of the power functions from the original study, or the linear functions that other researchers have used, a bi-modal trend is more accurate for the modelling and prediction of most cases of long-term corrosion, specifically for terms between 15 and 17 years (Petersen and Melchers 2018). The study also argues that the chemical properties of soil (pH, salt concentration etc.) do not contribute significantly to the long-term corrosion of steel in soil. Another study adds that the soil characteristics of how pipes are buried are relevant to the long-term corrosion of steel in soil alongside moisture content, specifically the backfill soil characteristics rather than the undisturbed soil before burial (Melchers and Petersen 2018). The idea from Romanoff's work that the difference in pipeline material does not affect the corrosion rate is rejected in a separate study on pipelines in New South Wales, Australia, where improvements in material microstructure are suggested to cause different corrosion properties such as corrosion rates (Nicholas et al. 2017). Additional trends have been recognized through an examination of the techniques which are used to identify the presence of MIC in the field studies, the majority of which aimed to correlate soil properties with corrosion risks to the water pipelines to enable improved management of the systems (Table 2). In one study, the soil types found along a pipeline were pitted against standards detailing levels of soil aggressiveness (Jarvis and Hedges 1994). In others, detailed soil analysis of soil samples taken along a pipe was compared with the wall thickness of the pipe or pit depth and pit morphology, as attempts to link different soil characteristics with pipeline corrosion (Dafter 2013; Doyle et al. 2003; Melchers et al. 2019a,b; Oyewole 2011; Petersen et al. 2013; Petersen and Melchers 2014; Restrepo et al. 2009; Srikanth et al. 2005). Of the many properties of soil

examined, the key ones include soil resistivity, pH, redox potential and moisture levels. Other studies looked at the chemical analysis of soil for chlorides, sulfides and bicarbonates, but this was less common. There was a wide variety of soil analysis with some studies performing many different soil tests (Doyle et al. 2003; Restrepo et al. 2009) and others measuring only one soil property (Dafter 2013; Moglia et al. 2004); the methods used to determine the corrosivity of the system also varied. More recently, pipe corrosion studies have evolved through implementation of novel techniques such as 3D scanning for the creation of pipe surface contour maps as well as loading tests for the analysis of mechanical properties of old cast iron and steel pipelines (Li et al. 2017; Soltani Asadi and Melchers 2017a). These studies have correlated localized corrosion pit depths with a reduction in mechanical properties. With these studies, although MIC is not explicitly mentioned, they contribute to the body of knowledge of studies into corrosion in soil.

In addition to the analysis of corrosion risk from soil along the pipelines by nineteen publications included in this review, ten more discussed the potential risks from the actions of bacteria. Indeed, it was a factor first considered for corrosion of the external surface of water pipelines in 1910 (Gaines 1910). Faced with high sulfide levels in the rust samples gathered that could not be explained by the understanding of metallurgy of the time, the author hypothesized that ‘sulfur bacteria’ in the soil could be contributing to the corrosion seen in several of his pipe samples. This hypothesis was supported by the work of Wolzogen Kuhr and van der Vlugt in 1934 which examined a range of water pipes in Northern Holland (Wolzogen Kuhr and van der Vlugt 1934). They found severe graphitization of cast iron pipes in anaerobic soils, which was not replicated in aerobic soils, and this increased graphitization was attributed to the presence of SRB. Across the studies reviewed, a range of methods were used to identify the potential for MIC. Two studies identified high levels of sulfides in certain types of soils and linked this to a high risk of aggressive corrosion due to the presence of SRB (Doyle et al. 2003; Jarvis and Hedges 1994). Another study, in consideration of the risk of MIC, determined that the temperature of soil measured along the pipeline in question was lower than the optimum temperature for growth of SRB and thus the risk was negligible (Restrepo et al. 2009). One study suggested a combination of the pit morphology seen along a pipeline and the colour of the corrosion product indicated IRB as a contributing factor to the corrosion (Dafter 2013). Another study proposed that one of the main factors that influence long term corrosion is the nutrient levels and the nutrient types in soil that can

promote MIC or inhibit corrosion (Petersen and Melchers 2016). Pit morphology as an indication of MIC is controversial with many authors indicating that the pits formed by biotic corrosion can be seen in abiotic corrosion under certain conditions as well (Little and Lee 2007, 2014). Microbial culturing techniques were used by two studies to determine the presence of bacteria in corrosion products from failing pipelines, and thus the likelihood of MIC on the pipes investigated (Oyewole 2011; Srikanth et al. 2005). This technique can be of benefit and is more conclusive than the analysis of soil chemistry. However, especially where limited culturing techniques are used, bacterial species that are involved in the corrosion process might be overlooked, and other species that are not involved but are present in the environment cultured can be identified as contributing to corrosion in error (Usher et al. 2014a). This is particularly true for soil environments where it is estimated that 99% of the bacteria present cannot be cultured by traditional means. Molecular microbiology, as used by a more recent study, can eliminate the bias introduced by culturing studies (Spark et al. 2015). One example is the introduction of pyrosequencing-based assessment of bacteria for better detection and understanding of bacterial communities in soil at sites of steel corrosion (Jang et al. 2012). These ten identified studies highlight the disparity in research techniques used to study MIC, but also indicate that MIC of buried water pipes is an area requiring a greater focus.

To develop a better understanding of the approaches used in studies of soil-based MIC, the review was broadened to include field studies of gas and oil pipelines (Table 3). The environmental, economic, and health risks associated with a gas or oil pipeline failure are significantly higher than those associated with a water pipeline failure, which necessitates a need to conduct studies of the MIC-related external corrosion of these pipelines.

In 1952, the conditions along gas pipelines in New York state were reported, and the most severe corrosion occurred in clay soil with poor aeration, insufficient drainage and low resistivity (Kulman 1953). The potential for bacteria to contribute to corrosion was investigated, and their finding of the most severe corrosion occurring within clay soils was determined to be partially because of the higher incidence of SRB and MIC under those conditions. Interestingly, although this study was conducted early in the history of MIC pipeline studies, much was already known about bacteria and their roles in corrosion through studies of other systems. The techniques employed to determine the incidence of MIC and the corrosivity of the soil are common to many of the other studies found of steel pipelines thought to be exposed to MIC

Table 2: A summary of field-based studies of buried water pipelines investigating the corrosion of steel.

Authors	Year	Pipe type	Analysis techniques	MIC identification method	Microbial species examined
Gaines (Gaines 1910)	1910	Water, iron & steel	Pipe: chemical analysis, metal-lurgy.	High levels of sulphuric anhydride found in some samples, unexplainable by the metal-lurgy of the steel: considered to be due to action of bacteria.	Multiple species considered, probably 'sulphur bacteria'.
Wolzogen Kuhr and van der Vlugt (Wolzogen Kuhr and van der Vlugt 1934)	1934	Water, cast iron	Pipe: visual inspection, chemical and metallurgical analysis. Presence of iron sulfides and ferrous hydroxide.	Corrosion process of pipes compared to laboratory test results of cast iron exposed to SRB and the resultant graphitization.	SRB
Romanoff (Romanoff 1957)	1957	Water, various ferrous & nonferrous materials	Pipe: weight loss, visual inspection.	N/A	N/A
Jarvis and Hedges (Jarvis and Hedges 1994)	1994	Water, cast iron	Mapped soil types for an area based on Cast Iron Pipe Research Association's corrosivity scheme and compared to recorded breaks along pipelines.	High sulphate content and microaerobic soils labelled as highly aggressive due to SRB risk.	SRB
Doyle et al (Doyle et al. 2003)	2003	Water, cast iron	Soil: resistivity, pH, chemical analysis, soil type. Pipe: pit depth.	Sulfides levels.	SRB
Srikanth et al. (Srikanth et al. 2005)	2005	Water, mild steel	Soil: resistivity, chemical analysis, pH, microbiology. Pipe: metallurgy, microbiology.	Cultured soil and corrosion products. No microbes were cultured from corrosion products, no MIC.	SRB & APB
Moglia et al. (Moglia et al. 2004)	2005	Water, wrought iron	Pipe: wall thickness. Soil: LPR.	N/A	N/A
Schuster and McBean (Schuster and McBean 2008)	2008	Water, cast iron & ductile cast iron	Pipe: break data.	N/A	N/A
Restrepo et al. (Restrepo et al. 2009)	2009	Water, mainly cast iron, also steel, ductile iron & galvanized steel.	Soil: temp, pH, redox potential, resistivity, texture, moisture, chemical analysis. Pipe: soil-pipe potential, wall thickness, pitting, mechanical strength, metallographic analysis.	Temp measured was not in a 25–30-degree range which is optimum for SRB, so risk assessed as low.	SRB
Oyewole (Oyewole 2011)	2011	Water, n/a	Pipe: surface scrapings, pit morphology, groundwater levels, microbiology. Soil: chemical analysis, organic matter, pH, moisture content.	Cultured pipe scrapings in anaerobic and aerobic conditions.	anaerobic and aerobic
Jang et al. (Jang et al. 2012)	2012	Water, stainless steel	Pitting resistance equivalent number, corroding results, statistical calculation.	Bar-coded pyrosequencing method.	Multiple species considered
Dafter (Dafter 2013)	2013	Water, n/a	Pipe: max pit depth and pit morphology. Soil: moisture.	Pit morphology. Black and green corrosion products and high levels of organics.	IRB
Peterson et al. (Petersen et al. 2013)	2013	Water, cast iron	Soil sampling- moisture, bulk density and porosity. Pipe: pits mapped and deepest measured.	N/A	N/A

Table 2: (continued)

Authors	Year	Pipe type	Analysis techniques	MIC identification method	Microbial species examined
Peterson and Melchers (Petersen and Melchers 2014)	2014	Water, cast iron	Pipe: pit depth, age Soil: type, moisture.	N/A	N/A
Spark et al. (Spark et al. 2015)	2015	Water, cast iron	Pipe: magnetic flux leakage, microbiology. Soil: resistivity, chemical analysis, texture, pH, moisture, microbiology.	DNA extraction, PCR, Nanodrop analysis to determine the presence of bacteria and compare volumes between corrosion product and soil samples. Soil chemistry.	All soil bacteria
Petersen and Melchers (Petersen and Melchers 2016)	2016	Water, cast iron	Pipe 3D scanned data: topography, pit depths, duration of exposure, type, time of wetness modelling and analysis. Soil: characteristics, backfill status.	N/A	N/A
Soltani Asadi and Melchers (Soltani Asadi and Melchers 2017a)	2017	Water, cast iron	Pipe: digital contour map.	N/A	N/A
C. Q. Li et al. (C. Q. Li et al. 2017)	2017	Water, cast iron & steel	Pipe: 3D scanning, scanning electron microscopy, parallel plate loading.	N/A	N/A
Melchers (Melchers 2017)	2017	Water, cast iron	Topography inspection, pipe field data, pipe age.	N/A	N/A
Soltani Asadi and Melchers (Soltani Asadi and Melchers 2017b)	2017	Water, cast iron	Exhumed pipe data: composition, surface contour map, pit depth, pit area, age, accompanied soil data.	N/A	N/A

(Tables 2 and 3). Although studies along water pipelines use a range of means to determine whether MIC had or had not played a role in the corrosion of the pipelines, the gas and oil pipeline studies primarily use the culture of soil samples to determine the presence of bacterial species (Kajiyama and Koyama 1997; Kulman 1953; Li et al. 2000, 2001, 2003; Olivares et al. 2003; Pacelli 2008). More detailed studies also tested pipelines for the presence of sulfides, identifying iron sulfides through microscopy (Kajiyama and Koyama 1997; Li et al. 2000), or culturing corrosion products for bacteria (Li et al. 2000). Given that many of the bacterial species studied and attributed to MIC are found naturally in soil, further tests are required to determine whether they contribute to the increased corrosion of the pipelines, in addition to culturing soil samples. An example of a more conclusive approach was undertaken during a study in 2000 in which both soil and corrosion product samples were cultured for SRB and APB (Li et al. 2000). Comparing the results of this test, MIC did not contribute to the corrosion seen as there were no

bacteria cultured from the corrosion product. However, SRB and APB were found in the soil samples and had they only cultured these samples, the authors would likely have come to the opposite conclusion as the presence of bacteria would have led them to decide that they had influenced the rate of corrosion.

It is also interesting to note the groups of bacteria investigated; all studies focused on SRB when considering MIC as a potential risk or contributing factor to pipeline failure except for one (Pacelli 2008). Given that MIC is more advanced when multiple species are present and working together in a biofilm (Little and Lee 2007), this is of concern and suggests that the structure of these studies is limited.

4 Laboratory studies

Due to the interest in the mechanisms and rates at which soil corrosion occurs, many laboratory studies have been

Table 3: A summary of field-based studies of buried gas and oil pipelines investigating the corrosion of steel with reference to MIC.

Authors	Year	Pipe type	Analysis techniques	MIC identification method	Microbial species examined
Kulman (Kulman 1953)	1952	Gas, n/a	Soil: texture, colour, aeration, drainage, resistivity, pH, pipe to soil potential. Pipe: pit depth, visual examination, HCl test for sulfides, current flow.	Redox potential values <100 mV/SHE. Sulfides levels based on HCl test Soil samples cultured for bacteria.	SRB, SOB, APB, IB, nitrate-reducing.
Kajiyama and Koyama (Kajiyama and Koyama 1997)	1997	Gas, ductile cast iron	Soil: chemical analysis, microbiology, resistivity, spontaneous corrosion rate, corrosion potential, pipe to soil potential. Pipe: max pit depth.	Soil samples cultured for SRB, MPB, IOB & SOB. Presence of FeS. Highly anaerobic soil.	SRB, MPB, IOB, SOB
Li et al. (S. Y. Li et al. 2000)	2000	Gas, coated API 5L X 65 carbon steel	Soil: chemical analysis, microbiology. Pipe: visual examination, 2M HCl test of precipitates, SEM/EDX of corrosion product, microbiology.	HCl test to determine the presence of sulfides. Pit morphology. Soil and corrosion products cultured for SRB and APB. FeS crystal structure observed.	SRB & APB
Li et al. (S. Y. Li et al. 2001)	2001	Gas, carbon steel	Soil: resistivity, pipe to soil potential, redox potential, presence of groundwater, chemical analysis, microbiology. Pipe: max pit depth.	Soil samples cultured for SRB and APB.	SRB & APB
Li et al. (S. Y. Li et al. 2003)	2003	Gas, carbon steel	Pipe: max pit depth. Soil: chemical analysis, microbiology.	Soil samples cultured for SRB.	SRB
Olivares et al. (Olivares et al. 2003)	2003	Oil/gas, n/a	Pipe: weight loss of coupons, potential, corrosion morphology. Soil: microbiology.	Soil samples cultured for SRB.	SRB
Pacelli (Pacelli 2008)	2008	Gas, n/a	Mapped area along a pipeline with soil types identifying those at high risk for MIC. Soil: microbiology.	Cultured soil samples for anaerobic bacteria. Used gas chromatography of cellular fatty acids to ID the species once cultured.	<i>Eubacteria, clostridium & peptococcus</i>
Velázquez et al. (Velázquez et al. 2009)	2009	Oil/gas, n/a	Pipe: max pit depth, age, redox potential, coating type. Soil: pH, pipe to soil potential, resistivity, water content, bulk density, chemical analysis.	Did not consider MIC, but did look at sulphates as a corrosive factor based on the risk of SRB MIC.	SRB
Alamilla (Alamilla 2009)	2009	Gas, galvanized steel, bare steel & zinc	Soil: pH, resistivity, redox potential, chemical analysis, moisture. Pipe: CP potential, breaks, pit morphology Gumbel probability model.	Not considered explicitly. Redox potential included, <100 mV/SHE perceived to be indicative of highly anaerobic soil, also considered soil aeration.	SRB

performed in recent decades for prediction and modelling purposes (Dafter 2011; Goodman et al. 2013; Li et al. 2003; Naing Aung and Tan 2004; Sun et al. 2011). This section of the review considers laboratory-based MIC studies of mild

steel in soil to bring to light the techniques adopted to conduct these studies, and to understand the means to replicate soil conditions that surround buried infrastructure. All studies included in this section are listed in Table 4.

There are several key trends in Table 4. Firstly, tests are conducted in three different mediums: synthetic soils, solutions, or soil samples, the differences summarized in Figure 2. Secondly, corrosion tests are either based on non-accelerated corrosion techniques, such as weight loss testing, or use techniques that monitor corrosion such as LPR. Thirdly, when the effects of bacteria are investigated in these studies, either whole communities within the soil samples tested are used, or specific species are cultured and introduced to the study system. Five studies were identified that used synthetic soil with sand to which water and minerals were added (Akkouche et al. 2016; He et al. 2017; Jiang et al. 2009b; Naing Aung and Tan 2004; Sancy et al. 2010). Although these experiments did not consider MIC and four of the five also did not contain any organic matter, which is a significant component of soils (Seed 1990), each of them contributed to emphasis of the importance of soil particle size, pore structure and spacing on corrosion and aeration cells. Sandy systems can replicate many features of a soil-based system, but only those with free-flowing water, high oxygen replenishment rates and low corrosion rates. Field studies have broadly shown that clay-based water retaining soils are both more aggressive on steel and more prone to supporting microbial life (Escalante 1989; Jamieson et al. 2002; Kulman 1953). Although simulated soil composed of sand cannot replicate the more aggressively corrosive clay soil, this system is nevertheless useful for modelling and understanding the movement through soil and interactions of microbes, oxygen and electrolytes through soil.

The system most commonly utilized to study soil corrosion is solutions. A range of aqueous solutions and justification for the use of these solutions are evident across studies. One approach is to make a solution by adding distilled water to soil samples and sieving out the solid particles (Cunha Lins et al. 2012; Li et al. 2018; Wasim et al. 2017; Wu et al. 2014a,b, 2016; Xu et al. 2011). Another approach is to add minerals to distilled water to match the mineral levels measured in soil samples or a hypothetical soil/mineral ratio (Benmoussat and Traisnel 2011; Liu et al. 2010, 2019; Maocheng et al. 2016; Starosvetsky et al. 2016; Wade et al. 2017; Wan et al. 2018, 2019; Wu et al. 2010). In some cases where the focus is on groundwater as the corrosive element of the environment, solutions are designed to match the groundwater in the area of study and potential effects of the soil itself is discounted (Schütz et al. 2015; Sherar et al. 2011). The final approach is to add minerals that support the growth of the bacterial species of interest and are low in nutrients, as are most soil environments (Usher et al. 2015). Solution-based studies have demonstrated the role of different pH levels, soil nutrients and

oxygen conditions on soil corrosion as well as helped determining the corrosion products produced under different conditions. They have also been instrumental in the identification of several mechanisms of corrosion in soil.

However, as the knowledge of soil corrosion deepens, two fundamental limitations exist in solution-based studies. Firstly, it has been well established that the pore structure and heterogeneity of soil play a key role in the proliferation of corrosion of buried infrastructure (Cole and Marney 2012; Jiang et al. 2009a,b). Solutions cannot replicate the physical structure of soils. In fact, considerable differences exist between corrosion rates in soil samples and simulated soil solution, and a correlation model comparing the corrosion rates is in the process of being identified, although the effect of microbes and nutrients are not yet being considered for the correlation model (Wasim et al. 2017). Secondly, the interaction of microbes with solutions is different from how they interact in soils and with solid structures (Jamieson et al. 2002; Seed 1990; Wade et al. 2017). Bacterial cells interact with soil particles in multiple ways: they adhere to soil particles, especially clay particles that have a stronger affinity for ions because of their interactions with organic material, and they become entrapped by the pore structure because bacterial cells are at a similar size to clay particles. In solutions, bacterial cells are in planktonic form, meaning they are single cells dependent on convection of the solution for movement (Little and Lee 2007). Upon contact with a solid surface such as a metal coupon, the bacteria will settle on the surface and form a biofilm. This is very different from the behaviour of bacteria in soils, which is much more complex and reliant on the soil type, pore size and concentration of organic matter present (Seed 1990).

In addition, unlike the soil-based studies, microbes used in the solution-based studies are either cultured from soil samples or single species that are commercially available. Studies that use bacteria cultured from soil samples share the limitations of soil studies, which uses a similar method in that the species present are very dependent on the conditions used for culturing. One study had difficulties in culturing the bacterial species present in a soil sample with the same conditions that were used successfully to culture the bacterial species present in a bore water sample (Usher et al. 2015). The single species studies encounter the limitations of bacteria interaction with steel differently than how they would within a biofilm as they are found in natural environments (Usher et al. 2014a). Single species can be used to determine mechanisms of corrosion, but this needs to be considered in the context of a biofilm and synergism of different bacteria, as

Table 4: A summary of laboratory studies of soil and mild steel corrosion, focussing on MIC studies.

Authors	Year	Test system	Experimental conditions	Microbial species examined	Analysis techniques
Kajiyama and Okanura (Kajiyama and Okamura 1999)	1999	Soil, steel	Sandy and clay-based soils. PVC soil box specialized test cell. 25 °C, 90 days, sealed to prevent evaporation.	Iron bacteria and SRB in the soil samples.	Cathodic potential, soil analysis before and after testing, analysis of steel/ soil interface, weight loss.
S. Y. Li et al. (S. Y. Li et al. 2001)	2001	Soil, AISI 1018 steel	Anaerobic soil taken from the site of interest. Compared to autoclaved soil sample. Various solutions were added to the soil: Postgate medium C for SRB, fermentative acid producer medium for APB and biocide as a control. Specialized test cell.	SRB and APB in soil samples.	OCP, LPR, PDS, EIS, surface analysis: SEM and EDS. Thin-film electrical resistivity probe test and galvanic current measurement for localized corrosion.
S. Y. Li et al. (S. Y. Li et al. 2003)	2003	Soil, carbon steel	Replicating disbonded coating conditions. Anaerobic soil-148 days in the laboratory. Compared to soil samples with biocide. Specialized test cell.	SRB in soil samples.	OCP, LPR, PDS, EIS, surface analysis: SEM and EDX. Thin-film electrical resistivity probe for localized corrosion.
Olivares et al. (Olivares et al. 2003)	2003	Sediment & water, n/a	Water and sediment collected from the field in each of the two compartments of the specialized test cell. 26 °C.	SRB in the water and sediment samples.	40- or 74-day weight loss, polarization resistance, bacterial counts from coupons.
Norin and Vinka (Norin and Vinka 2003)	2003	Soil, carbon steel	Single surface exposed to undisturbed soil. Buried 2 m down at groundwater level.	N/A	Physicochemical analysis of soil samples, weight. loss, pitting characteristics.
Zhao et al. (Zhao et al. 2007)	2007	Sea mud, mild steel	Dual compartment cell containing autoclaved sea mud with and without SRB.	SRB cultured from sea mud.	60-day weight loss. Electronic probe microanalysis. TEM, EDX, EIS.
Ismail and El-Shamy (Ismail and El-Shamy 2009)	2009	Soil, mild steel	Steel coupons buried in disturbed clay silt soil and compacted.	N/A	Physicochemical analysis of soil samples, 5-day weight. loss, pitting characteristics.
Dafter (Dafter 2011)	2011	Soil, n/a	Soil samples with moisture and homogeneity controlled. Specialized test cell. Range of idealized soils compared to natural soils.	N/A	OCP, EIS, LPR short term Long term- 2 h delay then EIS/ LPR every 2 h for 45 h.
Sun et al. (Sun et al. 2011)	2011	Soil, stainless steel	Sterilized soil samples with glutaraldehyde. 23% moisture initially. Samples with 0.05, 0.2, 0.5, 1.0, 2.0 and 3.0 wt% chlorides. Specialized test cell.	SRB culture isolated from the same soils.	136-day weight loss and pit measurement test, EIS, OCP and SEM.
Norhazilan (Norhazilan et al. 2012)	2012	Soil, carbon steel	X70 carbon steel coupons cut from a pipe. Eighty-four coupons buried in soil in a bag in the ground. Soil from 5 sites.	N/A	Weight loss. ANOVA test. Measured soil moisture, plasticity and soil type.
Goodman et al. (Goodman et al. 2013)	2013	Soil, mild steel	Three samples at different heights in a cylindrical specialized test cell. Compression and moisture controlled/ monitored.	N/A	EIS, mass loss of tube overall.

Table 4: (continued)

Authors	Year	Test system	Experimental conditions	Microbial species examined	Analysis techniques
Sani et al. (Sani et al. 2016)	2016	Soil, carbon steel API 5L X65	Two soil samples, three moisture contents: 15, 20, 25 wt %. Soil dried and autoclaved. Sterile deionized water.	SRB – <i>Desulfovibrio desulfuricans</i> isolated from the same site.	Soil chemical analysis, XRD, particle size distribution, soil pH, soil resistivity, weight loss, optical microscopy.
Melchers and Petersen (Melchers and Petersen 2017)	2017	Soil, cast iron	Soil samples from location dried and broken down, water added for 9 moisture content and compaction levels, stored in containers for 3 months.	N/A	Loading tests, mass loss.
H. Liu and Cheng (H. Liu and F. Y. Cheng 2017)	2017	Soil, carbon steel API 5L X52	Soil samples dried and sterilized, mixed with diluted Na ₂ SO ₄ solution (pH 7.1) and 10 wt% SRB containing culturing medium. Purged with N ₂ /CO ₂ gas.	SRB seeds isolated from soil.	Weight loss, SEM, 3D topography characterization, live and dead cell counting, OCP, EIS, PDS.
H. Liu and Cheng (H. Liu and F. Y. Cheng 2018b)	2018	Soil, carbon steel API 5L X52	Sterilised soil samples mixed with simulated original soil solution buffered to pH 7.2. Mixture with 10% modified barr medium and SRB. Purged with N ₂ and compared with no bacteria.	Purchased SRB – <i>Desulfovibrio desulfuricans</i> .	21-day Weight loss, SEM, CLSM, OCP, EIS, PDS.
Mineta et al. (Mineta et al. 2018)	2018	Soil, carbon steel	Sieved red soil and carbon steel placed in specialised two-electrode cell system that is temperature-controlled and with constant water supply.	N/A	Specialized test cell for EIS.
X. Li and Sun (X. Li and Sun 2018)	2018	Soil, carbon steel Q235	Sterilised soil mixed with distilled water to create different moisture contents, also mixed with carbamide. Inoculated SRB culture added whilst bubbling N ₂ .	Purchased SRB – <i>Desulfovibrio desulfuricans</i> .	Redox potential measurement, weight loss, OCP, PDS, EIS, SEM.
Quej-Ake and Contreras (Quej-Ake and Contreras 2018)	2018	Soil, carbon steel API 5L X52	Three samples from different locations, dried, sieved and mixed with deionized water. X52 pipeline steel buried inside.	N/A	Soil chemical and physical analysis, OCP, PDS, EIS, CV, SEM.
Hendi et al. (Hendi et al. 2018)	2018	Soil, carbon steel API 5L X70	Black soil mixed with water to create moisten soil for electrochemical studies and weight loss measurements.	N/A	15-day Weight loss, SEM, XRD, OCP, PDS, EIS.
Yu et al. (Yu et al. 2018)	2018	Soil, carbon steel Q235	Sieved and autoclaved red soil mixed with deionised water and either bacteria inoculated nutrient agar or nutrient agar itself (API-RP38 nutrient).	Cultured SRB.	MPN cell counting, OCP, PDS, EIS, SEM, CLSM.

Table 4: (continued)

Authors	Year	Test system	Experimental conditions	Microbial species examined	Analysis techniques
H. Liu et al. (H. Liu et al. 2019)	2019	Soil, carbon steel API 5L X52	Regina clay soil sampled in Canada, ground, sieved and sterilised, then mixed with original soil solution to make wet soil for both weight loss and electro-chemical experiments. Wet soil used for several millimetres in specialised electrochemical test cell. Aeration techniques were used. X52 pipeline steel samples used.	N/A	10-day weight loss, SEM, 3D stereoscopic microscope, OCP, EIS, PDS.
Azoor et al. (Azoor et al. 2019)	2019	Soil, cast iron	As a general characterisation of soil, silt sourced from Canada and purchased clay & sand are used. Specialised test cell with NaCl solution mixed with clay, sand or silt; HYPROP tensiometer used to generate moisture retention curves.	N/A	OCP, PDS, LPR, soil moisture retention & oxygen diffusion measurement.
Wasim et al. (Wasim et al. 2019)	2019	Soil, cast iron	Cast iron samples buried in soil environments of different combinations of acidity and water saturation, for 6–18 months. Clay soil used from a landfill site in Melbourne, Australia.	N/A	6, 12, 18 month weight loss test, XRF, XRD, EBSD.
Naing Aung and Tan (Naing Aung and Tan 2004)	2004	Sand, mild steel	Sand at 20 °C. Added deionized water, 3.5% NaCl solution or 3% K ₂ Cr ₂ O ₇ inhibitor solution.	N/A	Wire beam electrode of 100 identical wires to map galvanic corrosion.
Sancy et al. (Sancy et al. 2010)	2010	Sand, cast iron	Samples cut from the side of a cast iron pipe that was already corroded. Mineral water saturated sand.	N/A	EIS, metallography, SEM.
Jiang et al. (Jiang et al. 2009b)	2009	Sand, A3 carbon steel	0.1 M NaCl solution with 99.1% quartz sand.	N/A	PDS, EIS, droplet size calculations.
Akkouche et al. (Akkouche et al. 2016)	2016	Artificial soil, S235JR carbon steel	83% fine sand, 14.5% kaolinite and 2.5% peat. Wetted with 0.01 M NaCl solution. pH 5.8 ± 0.1. Specialized test cell.	N/A	O ₂ concentration, water content, EIS, voltammetry around OCP, Raman spectroscopy, residual thickness.
He et al. (He et al. 2017)	2017	Sand, carbon steel API 5L X70	Compacted 99.2% quartz sand with 1.5 wt% NaCl and 18% deionized water in specialized three-electrode system.	N/A	OCP, PDS, SEM.
T. M. Liu et al. (T. M. Liu et al. 2010)	2010	Solution, carbon steel Q235	0.01 M NaCl solution used as matrix soil solution.	N/A	PDS, EIS.
Y. H. Wu et al. (Y. H. Wu et al. 2010)	2010	Solution, carbon steel Q235	Simulated soil solution (NaCl, CaCl ₂ , Na ₂ SO ₄ , MgSO ₄ , NaHCO ₃ , KNO ₃). 4 pH values: 3, 4, 5, 7 to compare effect of PH.	N/A	Weight loss, PDS, 30 min OCP, EIS.

Table 4: (continued)

Authors	Year	Test system	Experimental conditions	Microbial species examined	Analysis techniques
Benmoussat and Traisnel (Benmoussat and Traisnel 2011)	2011	Solution, carbon steel API 5L X60	Simulated soil solution based on measured components from most aggressive soil samples along GZI pipeline. CO ₂ bubbled to decrease pH to 6.7.	N/A	PDS (cathodic from OCP, then stabilized OCP, then anodic) OCP, EIS.
Sherar et al. (Sherar et al. 2011)	2011	Solution, carbon steel API 5L X65	1×, 5×, 1/5× postgate medium (NaCl, MgCl ₂ ·6H ₂ O, KH ₂ PO ₄ , NH ₄ Cl, Na ₂ SO ₄ , MgSO ₄ ·7H ₂ O, sodium lactate, yeast extract, and sodium citrate). Neutral pH. Also, a 1× without lactate, yeast & citrate. Aiming to mimic the groundwater, not the soil itself. Degassed to be anaerobic.	Bacterial consortium cultured from an oil well, dominantly SRB.	Weight loss, SEM of surface to investigate biofilm formation and corrosion morphology.
Xu et al. (Xu et al. 2011)	2011	Solution, carbon steel Q235	Soil solution extracted from soil sample with water added at 5:1 ratio. Autoclaved.	SRB culture isolated from the same soils.	EIS, OCP, SEM and EDS of fixed samples.
Lins, Ferreira and Saliba (Lins et al. 2012)	2012	Solution, carbon steel API 5L X52	Aqueous extract of soil and synthetic solution (NaHCO ₃ , KCl, CaCl ₂ ·2H ₂ O, MgSO ₄ ·7H ₂ O).	N/A	EIS, PDS with Tafel, OCP, chemical analysis of soil. SEM.
T. Wu et al. (T. Wu et al. 2014a,b)	2014	Solution, carbon steel API 5L X80	Specialized mechanical testing and electrochemical cell unit N ₂ bubbled to maintain anaerobic conditions, pH 7–7.2. Soil solution made from soil samples with a 1:1 soil to water ratio.	SRB – <i>Desulfovibrio desulfuricans</i> .	EIS, XPS, SEM & EDX.
Schütz et al. (Schütz et al. 2015)	2015	Solution, A37 low-carbon steel	Two solutions- a minimal media to match the groundwater at the study site and a simplified version with sulphate concentration to match the groundwater. pH 7. 30 °C under anaerobic atmosphere with and without bacteria.	<i>Shewanella oneidensis</i> strain MR-1.	Weight loss measurement and corrosion product analysis. 1- & 5-month experiments.
Usher et al. (Usher et al. 2015)	2015	Solution, 1010 carbon steel, iron granules & 316L stainless steel	Anaerobic, HH medium ((NH ₄) ₂ SO ₄ , MgCl ₂ ·6H ₂ O, KH ₂ PO ₄ , CaCl ₂ ·2H ₂ O and trace elements). pH = 7.	Soil sample cultured in solutions: mostly SRB.	DNA extracted, pyrosequencing to determine species. Weight loss, SEM, gas analysis, ion-exchange chromatography, Raman spectroscopy, X-ray diffraction, pH, redox potential.
Starosvetsky et al. (Starosvetsky et al. 2016)	2016	Solution, mild steel	Rust grown on coupons and placed in ammonium ferric citrate solution (sodium lactate, HEPES, ferric ammonium citrate brown yeast extract) pH = 7.1.	<i>Shewanella oneidensis</i> , <i>Geobacter sulfurreducens</i> .	Weight loss, analysis of Fe products present, bacterial molecular id, Fe ²⁺ /Fe ³⁺ ratio measurements.

Table 4: (continued)

Authors	Year	Test system	Experimental conditions	Microbial species examined	Analysis techniques
Maocheng et al. (Maocheng et al. 2016)	2016	Solution, carbon steel API 5L X80	Specialized test cell- crevice cell to simulate coating dis-bondment. NS4 solution (KCl, NaHCO ₃ , CaCl ₂ ·H ₂ O and MgSO ₄ ·7H ₂ O). Solution saturated with 5% CO ₂ /N ₂ .	N/A	EIS, SEM, OCP, pH.
T. Wu et al. (T. Wu et al. 2016)	2016	Solution, carbon steel API 5L X80	Specialized mechanical testing and electrochemical cell unit N ₂ bubbled to maintain anaerobic conditions. Soil solution made from soil samples with a 1:1 soil to water ratio and autoclaved.	SRB – <i>Desulfovibrio desulfuricans</i> .	OCP, anodic polarization, tensile testing.
Wade et al. (Wade et al. 2017)	2017	Solution, 1010 carbon steel	Immersion tests separately in nutrient broth and M9 medium, sterile abiotic test as control medium, 12-h short term tests, 14–28-day long term tests. Regular medium replenishment.	<i>Escherichia coli</i> .	SEM, EDS, 3D surface profiling, mass loss, statistical distribution.
T. Liu and Y. F. Cheng (T. Liu and Y. F. Cheng 2017)	2017	Solution, carbon steel API 5L X70	Extracted soil solution (NaHCO ₃ , NaNO ₃ , NaCl, Na ₂ SO ₄ , CaSO ₄ , K ₂ SO ₄ , MgSO ₄) purged with N ₂ /CO ₂ gas. Seven days under cathodic polarization.	SRB – <i>Desulfovibrio desulfuricans</i> .	MPN, SEM, EDS, AFM.
Wasim et al. (Wasim et al. 2017)	2017	Solution & Soil, cast iron	Specialized set up for both simulated soil solution (NaHCO ₃ , MgSO ₄ ·7H ₂ O, CaCl ₂ ·2H ₂ O, KCl, NaNO ₃) and actual clay soil from the field; 3 test pH setups.	N/A	Moisture, pH, temperature, mass loss, XRD.
Wang et al. (Wang et al. 2017)	2017	Solution, carbon steel API 5L X80	SRB culture inoculated in sterilized simulated solution (MgSO ₄ ·7H ₂ O, CaCl ₂ , NaHCO ₃ , KNO ₃ , Na ₂ SO ₄) in a three-electrode cell, pH at 7.49.	SRB – <i>Desulfovibrio</i> genus.	Gram staining, SEM, EDS, EIS.
H. Liu and Cheng (H. Liu and Cheng 2018a)	2018	Solution, carbon steel API 5L X52	Specialized set up for simulated soil solution (NaHCO ₃ , NaNO ₃ , NaCl, Na ₂ SO ₄ , CaSO ₄ , K ₂ SO ₄ , MgSO ₄), purged with N ₂ gas. pH of 7.2.	SRB – <i>Desulfovibrio desulfuricans</i> .	MPN, SEM, EDS, AFM, stereoscopic microscope, XPS, live/dead straining analysis.
Wan et al. (Wan et al. 2018)	2018	Solution, carbon steel API 5L X80	A diluted solution from mixing near-neutral pH and high organic matter content soil (1:1), then mixed with activated SRB strain.	NRB – <i>Bacillus cereus</i> .	OCP, LPR, EIS, SEM, EDX.
X. Li et al. (X. Li et al. 2018)	2018	Solution, carbon steel API 5L X80	Simulated soil solution prepared based on soil on site, then mixed with SRB culture medium, operated in a standard electrochemical cell.	SRB – <i>Brevibacterium halotolerans</i> – culture isolated from the same soils.	SEM, EDX, XRD, XPS, OCP, EIS, PDS.

Table 4: (continued)

Authors	Year	Test system	Experimental conditions	Microbial species examined	Analysis techniques
Mjwana et al. (Mjwana et al. 2018)	2018	Solution, S235JR carbon steel	Carbon steel submerged in an electrochemical cell with prepared soil simulated solution as the electrolyte.	N/A	VAOCP (voltammetry around OCP), OCP, EIS, XRD, LPR, mathematical modelling of the polarization curves
Karthick et al. (Karthick et al. 2018)	2018	Solution, mild steel & galvanized iron	Two types of clay soil locally available sieved and autoclaved. For weight loss, steel packed in 100% saturated soil. Extract medium used for electrochemical studies.	SRB culture isolated and counted from the same soils.	XRD, XPS, total viable. bacteria count, OCP, EIS, PDS, weight loss (laboratory and field), SEM, visual examination.
T. Wu et al. (T. Wu et al. 2018)	2018	Solution, carbon steel API 5L X80	Filtered and autoclaved soil solution transferred into a specialised cell, then bacteria is inoculated and mixed with the soil solution. Static stresses are applied to X80 steel before performing in-situ electrochemical studies and ex-situ surface analysis.	NRB – <i>Bacillus cereus</i> .	LPR, OCP, EIS, immersion tests, SEM, EXS, XPS, SSRT analysis.
Wan et al. (Wan et al. 2019)	2019	Solution, carbon steel API 5L X80	Activated NRB mixed in leaching simulated solution from soil obtained from a soil depth of 1.2 m and culture medium. Mixture submerged in specialised electrochemical corrosion cell.	NRB – <i>Bacillus cereus</i> .	SSRT, LPR, AC corrosion, EIS, OCP, PDS, SEM, EDX, live/dead staining, XPS.
Sanni et al. (Sanni et al. 2019)	2019	Solution, carbon steel API 5L X52	Groundwater collected and mixed with nutrient broth to incubate bacteria. Different inhibitors mixed with the mixture for weight loss analysis.	<i>Aciithiobacillus thiooxidans</i> .	Weight loss, Tafel polarization, SEM, FTIR.
Meroufel et al. (Meroufel et al. 2019)	2019	Solution, ductile cast iron	Soil solution prepared from soil sample and distilled water with volume ratio 1:5.	SRB – <i>Desulfovibrio desulfuricans</i> isolated from soil.	OCP, EIS, most probable number (MPN), XPS, EDS, SEM.
Shahryari et al. (Shahryari et al. 2019)	2019	Solution, carbon steel API 5L X70	SRB from soil sample inoculated in near-neutral soil simulating medium under oxygen-free nitrogen headspace. Standard three-electrode set up.	SRB <i>Citrobacter</i> sp. strain.	PCR, FESEM, EDS, OCP, EIS.
T. Wu et al. (T. Wu et al. 2019)	2019	Solution, carbon steel API 5L X80	NS4 near-neutral soil simulating medium inoculated with SRB in API RP-38 medium. Specialised crevice cell combined with a multi-sample loading frame used.	SRB	EIS, PDS, SEM.

within a biofilm, interactions among microbial species alter how they obtain energy and nutrients. Even with these limitations, owing to the replicable results, soil solution is still the most popular test medium for laboratory-based

electrochemical corrosion tests, especially for studies on the effects of MIC (Karthick et al. 2018; Liu and Cheng 2018a; Mjwana et al. 2018; Sanni et al. 2019; Wu et al. 2018). An example of this is an investigation of the influence of

Figure 2: Approaches to the application of test mediums in laboratory MIC tests of buried pipelines.

cathodic protection (CP) potential on biofilms, which suggested that even though CP potentials more negative than the recommended potential can control uniform corrosion, pitting corrosion can still occur under the CP facilitated bacteria attachment and growth on the steel surface (Liu and Cheng 2017).

The last system used are soil samples, conducted with buried coupons in the ground, with soil samples in recreated conditions outdoors (Norhazilan et al. 2012) or by taking soil samples into the laboratory and use specialized test cells developed by individual research groups (Dafter 2011; Goodman et al. 2013; Hendi et al. 2018; Li et al. 2003; Li and Sun 2018; Mineta 2018; Olivares et al. 2003; Quej-Ake and Contreras 2018; Sun et al. 2011; Yu 2018; Zhao et al. 2007). Each of these types of tests has its limitations, especially when MIC is considered. The study which investigated soil corrosion by the burial of samples directly in the ground were limited to conducting weight loss and surface analysis as they were unable to connect reference electrodes to the coupons (Norin and Vinka 2003). Further, they did not consider MIC. For tests with soil samples moved either into a laboratory or to another site, it is difficult to recreate the soil conditions in its original location. Compression of the soil (thus the pore sizes) will change as will the moisture levels, which may influence the corrosivity. However, this is a matter of further investigation, as a short-term corrosion study highlighted the significance of moisture levels for corrosion in clay soil and also concluded that differences in soil compaction did not significantly influence mass loss from corrosion (Melchers and Petersen 2017). These laboratory studies are particularly important as both factors have been highlighted in the field studies reviewed as impacting on corrosion levels (Tables 2 and 3).

What is also interesting is that all studies which used soil samples from the environment in a laboratory set up used specialized test cells devised by the research groups. Each test cell had different components, different sizes, and was designed to increase or reduce different factors. In one case, the experiment was designed to enable a direct comparison between the corrosion of steel samples exposed to biotic and abiotic samples (Zhao et al. 2007). In two separate studies, test cells were designed to control the homogeneity and moisture levels in the soil for the duration of the test (Dafter 2011; Goodman et al. 2013). Both found difficulties even with the specially designed systems. Given moisture levels have been found to alter the rate of corrosion of pipelines independent to the soil type (Murray and Moran 1989) and the presence of microbes (Sani et al. 2016), the ability to control the moisture is crucial for accurate interpretations of laboratory studies. In particular, Azoor, Deo, Biribilis and Kodikara has discussed the mechanisms of soil moisture on corrosion in detail, with regards to different soil types (Azoor et al. 2019). Other studies also mentioned the importance of the control of evaporation to maintain moisture levels, although the moisture levels were not monitored to ensure the effectiveness of their methods (Kajiyama and Okamura 1999; Sun et al. 2011).

Bacteria were introduced in one of two ways in these experiments. Either cultures of bacteria were nurtured from the populations in the soil samples and then reintroduced to soil samples once they had been sterilized (Liu and Frank Cheng 2017; Sani et al. 2016; Sun et al. 2011; Zhao et al. 2007) or soil samples were assumed to contain bacteria and compared with sterilized soil samples (Kajiyama and Okamura 1999; Li et al. 2001, 2003; Olivares et al. 2003). In the first instance, bacterial species present in the sample are dependent on the culturing

techniques used, which has the advantage of being able to identify what groups of bacteria will be present. The soil sample properties can be readily controlled and monitored, although the sterilization process will alter the original properties as it removes the native microbe populations and changes compaction of the soil. With the second method, a broader understanding of MIC based on environmental conditions and soil types can be obtained. However, it can be difficult to identify a potential corrosion mechanism from the results based on the microbe community, since it is currently a problem to recognize the specific bacteria and active species present. Also noteworthy is that it is difficult to replicate results and gather sufficient data for statistically significant results to determine corrosion mechanisms because every soil sample is unique, and thus, so is the degree and type of corrosion associated (Jack et al. 1992). This is particularly the case with accelerated corrosion testing techniques such as CV and potentiodynamic polarization scanning, which is one of the reasons why so few of the laboratory studies used these techniques. Also, as movement of microbes and oxygen are difficult in soil which results in greater electrochemical resistivity exhibited in soil, in some instances MIC studies using soil samples have allowed for a longer settling time for test cells to before conducting tests (Liu and Cheng 2018b; Liu and Frank Cheng 2017). For all the difficulties, soil samples are still useful to create a better understanding of the effects of microbes on soil corrosion in general and the nature of MIC in the inherently complex soil environment.

5 Limitations of current studies

Across the field studies and laboratory studies reviewed, several aspects become apparent:

- Limited microbiologically influenced corrosion research

Of the 56 laboratory studies included in this review, only 32 were MIC studies; the relatively limited number of MIC studies suggests that this is a developing area that would benefit from further research.

- Important contributing factors

Moisture, aeration levels, and soil types are some of the critical factors controlling the corrosion rate of mild steel, and the impact on how well bacteria can flourish and contribute to corrosion.

- Replication with soil samples

Every soil sample is unique in the degree and associated type of corrosion, thus are difficult to replicate and require complicated techniques to ensure consistent

compaction and moisture levels, resulting in difficulties in replicating results and then gather sufficient data for statistically significant results to determine pertinent corrosion mechanisms.

- Replication with simulated soils

Simulated soils using sand cannot replicate clay-based systems which are the soils with the highest corrosion risk for buried infrastructure, making them impractical as a system for the study of buried pipeline MIC in soils.

- Replication with soil solutions

Solutions can mimic the chemical composition of soils and are the most accessible system to study microbes, but the physical composition of soil is essential for both the propagation of corrosion and the interaction of bacteria within their environment.

- Identifying specific bacteria

It is difficult to determine what bacteria are present and the active species cannot be isolated, thus the results can only show that higher levels of corrosion are occurring without the ability to identify a potential mechanism.

- Lack of emphasis on microbes other than sulphate-reducing bacteria (SRB) in soil

A general emphasis across all soil studies on SRB exist, with most only examining the effects of this single group of bacteria. Risks associated with the presence of SRB have led to the focus on the presence of sulfides in soil as well as consideration of soil aeration. Given it is well established that mixed-species biofilms are the most aggressive, that SRB is more corrosive in conjunction with other bacteria types and that many different groups of bacteria are known to contribute to corrosion, it is important to have more studies on microbial species other than SRB, and more studies on mixed-species biofilms.

6 Prevention and treatment of MIC

The most significant factor that distinguishes MIC from abiological corrosion of buried pipelines is the biofilm formed on the pipe surface, as highlighted in previous sections and Table 1. Prevention of MIC of buried pipes through impeding biofilm growth can be achieved by altering the pipe surface as well as the surrounding environment. To do so, both the metal substrate and the soil environment need to be unfavourable for biofilm attachment and growth.

In terms of the surrounding environment, oxygen levels in the soil environment directly impact MIC on ductile cast iron pipelines (Meroufel et al. 2019). As a result, one way to prevent MIC on a buried ductile cast iron pipe is to bury the pipe in more compact soil. This not only

prevents efficient aeration, but also minimises the formation of air pockets in regions of differential aeration that can contribute to ideal conditions for corrosion (Shreir et al. 1993). To achieve this, during burial of water pipes for service, backfill soil need to be well packed and carefully chosen, preferably with high clay content, to reduce soil permeability and inhibit oxygen as well as moisture diffusion (Melchers and Petersen 2018). The chemical composition of the soil environment can also be controlled to prevent MIC. Two studies have identified high levels of sulfides in soils and linked this to a high risk of aggressive corrosion due to the presence of SRB. Therefore, by avoiding burial locations with high sulfide levels in soil, biofilm growth due to SRB can be inhibited (Doyle et al. 2003; Jarvis and Hedges 1994).

For the metal substrate, long-term biofilm development favours rough surfaces; conversely, biofilms slough more easily from flat surfaces (Alnnasouri et al. 2011). Therefore, bacteria colonisation and biofilm growth can be reduced on a more polished pipe surface. This is the result of the reduction in contact area with the surface, unfavourable energetic situations created and repulsive surface-bacteria interaction forces (Feng et al. 2015). Mechanical properties of pipes are also known to affect biofilm attachment and subsequent biofilm growth. Welded regions are known to be susceptible to various forms of corrosion, including MIC (Shabani et al. 2018), as the change in steel microstructure due to welding can promote corrosion. Unpolished welding has been reported to be more susceptible to biofilm attachment when compared to polished welding (Liduino et al. 2018). In addition, it has been reported that high internal residual stresses commonly associated with welding are known to promote adsorption biofilm rupture and hence anodic dissolution at the pipe surface. This combined with the effect of limiting machining and welding of pipelines to reduce external tensile stress, would improve corrosion resistance of the pipe to MIC (Li et al. 2018). In summary, reduced corrosion susceptibility of biofilm and subsequently MIC of buried pipelines can be achieved by a smoother pipe surface, minimizing regions of high internal stresses through treatment such as annealing and post weld heat treatment (PWHT), as well as limited and polished welding to pipelines.

Beyond limiting biofilm growth, there are other potential solutions to the treatment of MIC on buried pipelines. Cathodic protection is sometimes used to protect pipelines buried underground from corrosion. However, previous studies conducted on SRB have shown that the cathodic protection system may provide favourable conditions for microbes to grow, leading to pitting corrosion underneath the biofilm, even with inhibited uniform corrosion (Kajiyama and Okamura 1999; Liu and Cheng

2017; Olivares et al. 2003). In a study conducted by Li, carbamide which is widely used as a fertilizer was suggested to not only reduce the soil redox potential but also inhibit SRB growth in soil, making it a potential inhibitor for MIC of buried carbon steel pipes (Li and Sun 2018). However, the effect of carbamide on specifically biofilm growth is yet to be explored.

7 Recent developments

A replicable system that can mimic the physical and chemical components of soil as well as allow for various factors such as particle size, moisture levels and oxygen concentration to be readily controlled, would be of great benefit to overcome the limitations. Agar, a by-product of seaweed widely used in microbiology, has been added to rock fragments in a previous study that investigated the MIC of nuclear waste storage containers (Castro et al. 2004), and has also been used for surface MIC studies (Iverson 1966). The combination of the physical properties of a gel and the non-reactive support it provides for bacteria suggest it could make a good basis for the study of soil MIC. Recently, research has commenced of the development of an analogue for soil for corrosion studies with the use of agar. Development was shifted to semi-solid agar when the higher concentrations of agar were established to have restricted electrolyte flow, leading to a lack of consistency between results; the shift to semi-solid agar led to consistent results representative of clay-based soils (Spark et al. 2016a,b). The properties of semi-solid agar lend themselves to the development of a porous and readily controllable analogue of soil for fundamental corrosion studies especially for those involving MIC in soil. Bacteria have since been added to the system and the capabilities of the system further tested (Spark et al. 2016c). This research suggests much potential in the development of agar-based systems for the study of corrosion in soil, however much is still to be understood, including the possibility of many other ways to replicate the physical characteristics of soil for fundamental MIC studies.

In addition, gels have previously been investigated to replicate sewage sludge, wherein corrosion is partially controlled by its physical structure, using silica and polyacrylamide gels to mimic the sludge structure (Gu et al. 2013; Lu et al. 2012). However, the use of silica and polyacrylamide gels would not be applicable to MIC studies since the gels would not support the growth of bacteria and could be broken down by bacterial species. Other than replicating the physical components of soil for the fundamental study of MIC, current attempts are being made to correlate corrosion in soil and corrosion in

simulated soil solution (Wasim et al. 2017). Developments in modelling of pipeline soil corrosion systems include the development of bi-modal trends for the long-term external corrosion of water pipelines that can become more significant for MIC studies once extended to bacteria studies (Betts et al. 2017), and the mathematical modelling for corrosion rates prediction of the triple-phase boundary zone (He et al. 2017). Down the line, mathematical correlation models would allow results from the more assessable laboratory studies to represent steel corrosion in soil better, especially when microbes are considered.

Molecular microbiology is a relatively new field that, over the last decade, has begun to be employed in the study of corrosion. This technique enables whole populations of bacteria to be identified, limiting the biases associated with culturing techniques. It also enables more than one type of bacteria to be easily investigated. With the advent of newer, faster and cheaper DNA and RNA sequencing technologies (Caporaso et al. 2012), it is now possible for bacteria and other microorganisms to be identified based on their molecular structure in a relatively short period. This technique has been used to identify microorganisms in rust tubercles in a marine environment (Usher et al. 2014b) and from this has enabled associations drawn between the bacteria species present and the potential mechanisms of corrosion. Many further applications of molecular microbiology are possible within the field of MIC, including the study of corrosion products on the internal surface of potable water pipes (Zhu et al. 2014). Metagenomic techniques that are more efficient and less time consuming have also been employed in or suspected to benefit MIC studies (Eckert and Skovhus 2018). Furthermore, what is called Next Generation Sequencing will allow for the identification of MIC-inducing microbes that have not been cultured or studied before. Because one environmental sample may contain more than 10,000 microbial species, these massive data sets will require skilled analysts and vast computational power to be processed. The development of these novel, sophisticated techniques have been described in detail (Machuca Suarez 2018). But so far, these applications have not been utilized widely in the study of corrosion on the external surface of buried potable water pipes. So far, there has been four studies exploring the possibilities of applying molecular microbiology to corrosion products found on the outer surface of water pipes (Jang et al. 2012; Shahryari et al. 2019; Spark et al. 2015; Usher et al. 2015). Here, molecular microbiology has much potential in field studies of the external corrosion of pipelines.

New techniques are also being applied beyond the scope of MIC in soil. Atomic force microscopy and 3D scanning techniques have been used to analyse and compute the topography of corroded surfaces of water pipelines, for the purpose of better understanding the fundamentals of steel in soil corrosion (Liu and Frank Cheng 2017; Petersen and Melchers 2018). A MIC probe based on electrical resistance (ER) probes is currently being developed, where biofilm can be grown on the metal plate of the ER probe under laboratory conditions, then inserted in soils close to underground pipelines susceptible to external MIC. This method enables the study of external MIC of buried pipelines under realistic field conditions by instantaneous measurement of the corrosion rates and online monitoring of corrosion mitigation measures (Manama 2016). With a large amount of research being conducted on mild steel corrosion in soil, studies have also identified the most significant experimental parameters for soil corrosion, to lead the way for more realistic testing procedures during the design of corrosion experiments; parameters include test media composition, immersion temperature, immersion time and medium replenishment (Wade et al. 2017). Other studies include the investigation of the mechanical properties of corroded pipelines through loading tests for the determination of the degradative effects of corrosion on pipeline properties (Li et al. 2017; Soltani Asadi and Melchers 2017a). Developments of general corrosion studies of mild steel in soil can be incorporated with MIC studies conducted in soil and together will benefit the development of the understanding of pipeline MIC in soil.

8 Conclusions

Since the first indication that bacteria could be influencing corrosion of pipes in soil in 1910, many laboratory and field studies have been undertaken into this phenomenon covering water pipes and oil and gas pipes. In the field, the emphasis to date has been on soil analysis, metallurgy, and culturing of bacteria, though this has started to be supplemented with molecular microbiology techniques. In the laboratory, three main systems have been used: solutions that replicate the nutrient composition of soils, sand-based artificial soils that replicate the porous nature of soils and soil samples from sites of interest. These systems have provided us with much insight into how soil corrosion progresses, both with and without the presence of microbes.

The review has identified the need for a more systematic approach for the study of buried mild steel water

pipeline corrosion, especially when MIC is suspected, and numerous field studies and laboratory studies have supported this. The studies include the adoption of a test system that is more representative of the soil environment under laboratory conditions, whilst maintaining control over critical variables. A clearer understanding of the mechanisms and interactions of soil-based MIC can be achieved when experimental design allows for the chemical and physical properties of soils to be replicated and precisely controlled as corrosion in soil and movement of bacteria is dependent upon these properties. Among others, one method has been recently developed, utilizing semi-solid agar to replicate both the physical and chemical properties of soil in a controlled and reproducible manner for accelerated corrosion and electrochemical testing. Going forward, greater consideration should also be given to the bacterial species studied in the laboratory and tested for field studies. Although it is well known that the most aggressive MIC occurs when biofilms formed by communities of microbes are present, this is not reflected in laboratory tests and field investigations. Molecular testing techniques will increase the possibility of more thorough identification; however, it must be used wisely. Communities taken from soil samples along a pipeline cannot in isolation identify causative microbes, they must be compared with samples taken from the corrosion product itself.

With further development of a more standardized approach to the study of MIC of buried water pipelines, major improvements can be made in the modelling and monitoring of localized corrosion, thus reducing the occurrence of leaks and bursts of buried pipelines. This would have significant positive impacts on asset management of water infrastructure, reducing the economic and health risks of water pipelines.

Abbreviations

CV	cyclic voltammetry
EIS	electrochemical impedance spectroscopy
EN	electrochemical noise
EPS	extracellular polymeric substance
IOB	iron oxidizing bacteria
IRB	iron reducing bacteria
LPR	linear polarization resistance
MIC	microbiologically influenced corrosion
OCP	open circuit potential
PDS	potentiodynamic polarisation scans
PH	potential hold
SRB	sulphate reducing bacteria
TPB	triple phase boundary

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