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APPROACHES TO OVERCOMING ONGOING PIPELINE CORROSION MONITORING CHALLENGES

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SUMMARY: Steel pipelines are susceptible to corrosion when installed underground, especially when they are under the effect of factors such as stray currents or disbonded coatings. These factors generally increase the risk of corrosion because they could locally nullify cathodic protection (CP). Corrosion monitoring, if performed properly, can help enhance the safe and economical operation of pipelines, by providing a means of inexpensively collecting site-specific and in-situ corrosion information at any required time and frequency. The capability of corrosion monitoring to complement corrosion inspection techniques is well accepted, however, its practical application in complex industrial conditions, especially in heterogeneous systems such as underground pipelines, has been limited. Unlike conventional inspection techniques, corrosion monitoring measures corrosion happening on the pipeline surface indirectly. It measures what is occurring on the surfaces of the corrosion probes, based on the principle that corrosion occurring on a large structure such as a pipeline would also occur on a smaller probe made of the same material and exposed to the same environmental condition. Nevertheless, ensuring that the key elements of the corrosion processes affecting a large and complex structure are simulated by strategically designed and located discrete probes is currently an unsurpassed challenge. A rational strategy must be developed to ensure the reliability of the collected information using corrosion probes. In this paper, the application of corrosion monitoring in heterogeneous conditions and several factors affecting the design and location of corrosion monitoring probes for early warning of external corrosion on buried pipelines have been discussed. It is concluded that in order to ensure the reliability and accuracy of corrosion monitoring as an early warning tool, three general rules should be observed in order to ensure that the probes are capable of simulating the worst possible corrosion situation along the monitored structure, and collecting information regarding the maximum corrosion rate on their own surface.

Keywords: Pipeline, Cathodic protection, Corrosion monitoring, Stray current, Disbonded coating

1. INTRODUCTION

Steel pipelines are extensively applied as safe and economical means to transport gas, oil and other fluids to locations where they are consumed or where they are refined. In 2013, there were 34,612 Km of steel pipelines in Australia, which are an essential piece of infrastructure for the national energy industry. Due to the low corrosion resistance of pipeline steel, the external surface of an underground pipeline is protected by organic coatings and cathodic protection (CP)1-3. Insulating polymer coatings are the first line of defence against external corrosion. However, some coating defects would inevitably exist exposing the pipe’s bare metal surface directly to the environment4. When the coatings fail, CP works as a backup to prevent corrosion by polarizing the metal to a CP potential accepted as safe5. However, both protection systems could fail, especially when disbonded coatings and stray current are present, resulting in corrosion of the pipeline. Recent corrosion failures, such as the explosions in Qingdao and Kaohsiung6, have shown the importance of making efforts to ensure the structural integrity of this infrastructure assets, especially in high consequence areas. Inspection and structural health monitoring7 are practical approaches to asset corrosion management, which is particularly critical when the operational life of aged pipelines is extended beyond their initial design life.

Corrosion inspection is commonly applied for pipeline corrosion management. A large number of inspection methodologies, including potential surveys8, current attenuation9, ultrasonic testing and in-line inspection (ILI) tools10, have been used to detect and inspect defects which could threaten the integrity of pipelines. Inspection is able to detect
corrosion by measuring the accumulation of metal loss, which could be induced by corrosion reactions or physical stresses. However, they are often not sensitive enough to detect corrosion damage at its initial stage. In some extreme cases, for example, for pipelines buried deeply underground, under rocky terrain and paved roads, potential survey methods are even incapable to detect defects regardless of the size of defects. On the other hand, conventional ILI tools are not employable for all pipelines since they require launchers, receivers and a relatively obstacle free path. However, even for the cases which are suitable for ILI, the high costs involved in using these tools limit the frequency of inspection (usually between 5 and 15 years). As a consequence, inspection alone is insufficient to keep track of dynamically environmental conditions affecting the initiation and propagation of pipeline corrosion.

Corrosion monitoring technology could be used to complement current inspection techniques. Corrosion monitoring aims to provide early warning of corrosion that could cause failure of a pipeline system, so that effective corrosion mitigation procedures could be evaluated and implemented based on the obtained parameters, such as corrosion rate, corrosion pattern and corrosion mechanism information. Corrosion monitoring is generally based on the application of specially designed probes, which are commonly made by sensing elements of the same material as the monitored infrastructure. The benefits of corrosion monitoring as an early warning system, however, are only achievable if corrosion probes are able to monitor corrosion reliably and accurately. The meaning of reliability of corrosion monitoring could be defined as that corrosion probes should be capable of simulating the possibly worst-case scenario corrosion situation along the pipeline. The meaning of accuracy of corrosion monitoring could be defined as that the information collected by the probe, including maximum corrosion rate, should reflect the corrosion processes occurring on the probe surface.

A common issue in current industry application of corrosion probes is that intuitively, in some cases, a corrosion probe is used with an expectation of monitoring corrosion in a similar manner as using a thermometer to measure temperature, which assumes a homogeneous and continuous environment. Inevitably, these practices could lead to confusing and misleading results, because localised corrosion is typically predominant in such environments. Therefore, the main challenge of corrosion monitoring comes from localised corrosion.

2. WORKING PRINCIPLE OF MONITORING PROBES

In order to effectively monitor localised corrosion, probe measurement techniques should be sensitive to measure parameters related to the controlling corrosion processes/mechanism. The premise for achieving this is to understand the working principles and limitations of different techniques for corrosion probe measurement. Over the past decades, many corrosion probes and associated measurement techniques have been reported in the historic literature for laboratory and field corrosion testing and monitoring applications. They can be generally divided into two distinct groups: non-electrochemical and electrochemical probes. Non-electrochemical probes are based on the measurement of physical parameters for corrosion assessment. They monitor various physical parameters such as strain, resistance or reluctance to reflect the structural degradation, which is induced by accumulated metal loss. However, non-electrochemical monitoring methods are not sensitive to the initial stages of corrosion, especially localised corrosion. In addition, non-electrochemical methods provide little insight on the performance of the CP system and mechanisms leading to corrosion.

Electrochemical probes, which measure electrochemical parameters for corrosion assessment, are designed based on the electrochemical nature of corrosion. The electrochemical parameters that are fundamentally related to the thermodynamics and kinetics of corrosion reactions could be utilised to indicate the intrinsic characteristics of corrosion processes. Corrosion potential is the most common electrochemical parameter monitored from buried pipelines, however, the accuracy of the value of corrosion potential is often unsatisfactory due to measurement errors introduced by the IR-drop. The polarization resistance technique is not suitable for underground infrastructures because of the high resistivity of the media and the heterogeneous nature of the soil. On the other hand, the conventional one single electrode based electrochemical corrosion probes are not capable of reflecting the localised corrosion distribution. Multi-electrode array, also known as Wire Beam Electrode (WBE), has been successfully employed in mapping the localised corrosion distribution, for example the localised corrosion of carbon steel in aqueous solution, crevice, soil, water/gas interface and even under coatings.

3. CORROSION MECHANISMS AFFECTING PROBE DESIGN

Corrosion probes should also be capable of simulating the controlling corrosion mechanisms to monitor localised corrosion in order to provide early warning. What is more, the corrosion probe should be designed to reflect the possibly worst corrosion situation under a certain corrosion mechanism in any site-specific location. Corrosion under coating disbondment and stray current corrosion are typical worst-cases of corrosion on buried pipelines. The following sections discuss the mechanisms of corrosion under disbondment and stray current corrosion and their impact on the probe’s design.

3.1 Corrosion under disbonded coatings and probe design requirements

When a CP potential is applied on a coated pipeline, the adhesion between the coatings and pipeline could degrade from where defects (pinholes, holidays and ruptures) exist, which is known as cathodic disbondment. Coating disbondment allows the formation of a crevice between pipeline surface and the coating. Crevice corrosion is difficult to be mitigated by
CP because of the inability of CP current to reach areas under disbondment (cathodic shielding). The CP current has to flow through the holiday to the crevice bottom, and the ohmic potential drop across the solution trapped under disbondment reduces the applied CP potential to less negative values. The potential at the tip of the crevice is less negative than that of the opening, suggesting the crevice tip could not be properly protected. Many types of corrosion, such as pitting, microbiologically induced corrosion (MIC), and stress corrosion cracking (SCC) have been observed under disbonded coatings. The different types of corrosion processes occurring under disbonded coatings are usually investigated in aqueous solution. However, in soil, the actual corrosion process occurring under disbonded coatings can be different and more complex, because the trapped solution under disbondment could be absorbed by the unsaturated soil particles, leaving an air gap of zero current under CP. It has been noted that this air gap can isolate sections within the crevice from the area outside the crevice where CP is effective. Within these isolated areas, the system is at open circuit potential and a combination of cathodes and anodes is developed. After a transitory period, the cathodes tend to locate close to the air gap, where oxygen is constantly replenished and the anode tends to be stable at the crevice tip.

When disbonded coating is responsible for the ineffectiveness of CP, a corrosion monitoring probe should be designed to simulate the crevice corrosion under disbonded coatings. Varela et al. firstly developed an electrochemical probe based on WBE to reproduce corrosion under disbondment. The probe surface is covered with PMMA cover to simulate disbonded coatings. The results show that the probe is capable of evaluating the actual polarization level achieved and cathodic reaction locations both outside and inside the crevice. Moreover, coating type and crevice dimension, which could influence the corrosion under disbondment areas, contribute to probe design. The first factor is that the type of coating covering on the probe surface to simulate the disbonded coating. Corrosion under disbondment was usually investigated by simulated crevice setup, which utilised polymethyl methacrylate (PMMA) or Lucite sheet instead of real coating to simulate ‘ideally shielding coating’ impermeable to CP current and chemical species. However, thickness and aging of real coatings could influence the oxygen permeation, pH retention and CP current permeation. Therefore, the effect of real coatings on the localised corrosion behaviour under disbondment coatings should be investigated. The second factor is the dimension (e.g. gap size and crevice length) of the crevice formed on the probe surface. Larger gap size would lead to an enhanced penetration of the cathodic currents. Consequently, even the deeper region of the crevice could be polarised. However, it is found that the larger gap size would allow the dilution of the pH generated inside the crevice due to more effective ions transportation. Furthermore, the available data of crevice geometry effect is carried out in aqueous test, however, when the test is conducted in the soil, more soil would be trapped under the disbonded coating with a larger gap size, which reduces the solution volume trapped in the crevice and blocks oxygen diffusion and CP current. In addition, in the unsaturated soil, the continuity of the air gap formed in the crevice would be disrupted when the air gap is large due to sand distributing on the crevice surface. Therefore, it is a pending issue to understand the effect of gap size on the localised corrosion behaviour of the probe in the soil. These issues suggest the challenges of designing a corrosion probe for simulating and monitoring corrosion under disbonded coatings on pipelines.

3.2 Stray current corrosion and probe design requirements

Another typical worst-cases of corrosion on buried pipelines is caused by stray currents that are undesirable currents deviated from the intended path. Due to metal’s low electrical resistance properties, metallic infrastructures, such as pipelines, tend to be the alternative path of such stray currents. Depending on their sources, there are three types: direct current (DC) stray current, alternating current (AC) stray current and telluric current. In recent decades, electric transit systems have been developing rapidly and serving as the biggest and the best known source of DC stray current. Even if the running rails are isolated from ground, current could leak to the ground, depending on the rail-to-earth conductance term for each running rail. Stray current corrosion is location-dependent. At the position at which stray current enters the pipe the steel is cathodically polarised, while at the position where stray current exits from the pipe the potential is shifted anodically. At the stray current pick up point, in some cases, hydrogen embrittlement and accelerated coating damage could be induced as a result of overprotection, whereas at the discharge point insufficient protection could accelerate the corrosion of pipeline. In addition, the attack is extremely localised and can have dramatic consequence. For these reasons, the location of corrosion monitoring device is important for detecting stray current corrosion.

In terms of corrosion caused by stray current, corrosion failure prefers to occur at uncoated surfaces, therefore a corrosion probe for simulating and monitoring stray current corrosion can be an uncoated metal surface. Huo et al. has applied WBE probe to monitor the evolution of dynamic anodic transient effect on the corrosion occurring on the buried pipeline surface. It has been shown that WBE probe is able to measure local anodic currents and visualise current distributions over the probe surface under the effects of CP and dynamic anodic transients. However, the optimum probe dimension needs to be clearly understood. Historically, efforts have been made to evaluate the effect of specimen size on pitting corrosion exposed to aggressive species. Aziz et al. found that the pitting probability of 2S aluminium specimen in tap water increased with the increase of exposed area, until remaining constant as the value of specimen area reaching 60cm². In addition, the authors pointed out that the pitting probability became zero at some small value of the exposed area. Burstein et al. found that the decrease of 316 stainless steel specimen size increased the pitting potential measured in acidic chloride solutions using potentiodynamic technique. Likewise, the results of Li presented that the average pitting potential decreased significantly with increasing specimen size. In addition, the pitting probability was quantitatively correlated with specimen surface area proportionally. Therefore, the maximum pitting depth, which is associated with pitting damage estimation, is a function of exposed specimen area. However, localised corrosion induced by stray current would be different. Stray current is generally dynamic (fluctuation with time). When stray current is absent, different size defects
have different current under CP, leading to different concentration of hydroxyl generated on the defect surface. When metal surface is under attack of discharged stray current, different size of defects would experience different initial states. Especially, smaller defect tends to have more positive polarization potential. Thus, it requires more understanding how will the defect dimension influence the localised corrosion distribution induced by stray current.

Assuming that there is an ‘ideal probe’, which could simulate the controlling corrosion mechanism of pipeline defects and provide precise measurements of parameters regarding the controlling corrosion processes/mechanisms, the selection of the most adequate location for its installation is still not trivial. Therefore, the second challenge of corrosion monitoring results from probe installation.

4. FACTORS INFLUENCING PROBE INSTALLATION

In terms of practical applications, we should consider not only the reliability and accuracy of corrosion monitoring system but also its economic cost. If the quantity of monitoring points is above the optimum number, the costs of monitoring would exceed any savings generated, then the application of probes would be counterproductive. The installation of corrosion probes would be critical to obtain as much corrosion related information as possible from the optimized number of probes. Therefore, the corrosion probes should be installed at the ‘worst-case scenario’ locations among a certain length of pipeline, representing the possibly maximum corrosion rates in such a segment. The following sections present how to identify the possibly worst scenario concerning corrosion under disbonded coatings and corrosion induced by stray current.

4.1 Environmental factors influencing probe installation

Soil is typically a multiphase corrosion system, discontinuous and heterogeneous, consisting of gas phase, liquid water phase and organic solid phase, which changes the pH retention, oxygen concentration, electrolyte available could contribute to localised corrosion and affect corrosion monitoring. The effect of soil moisture on corrosion under disbondment has been evaluated by Varela et al. An air gap will form in the crevice when the soil is unsaturated or when the soil undergoing wet/dry cycle. However, more soil factors need to be investigated to understand the effect of different environmental factors, such as, soil particle and carbon dioxide, on the corrosion behaviour under disbondment.

4.2 Corrosion mechanism affecting probe installation

The probe installation for stray current corrosion monitoring should be based on the analysis and understanding of corrosion mechanisms. Two simple and specific cases are discussed below to show where to install probes for stray current corrosion monitoring. In the first example, the stray current is caused by the impressed current from a CP system when the pipeline crosses a foreign protected pipeline (Fig. 1a). If the probe is installed at location A and B, where the stray currents are picked up, more negative current could be possibly recorded. However, if the probe is installed at the intersection between two pipelines (i.e. location C), where the stray currents are discharged, the probe is capable of catching up the maximum corrosion rate. Therefore, location C in this case with possibly maximum corrosion rate is more reliable for probe installation.

In the other example, the stray current is caused by the DC transit system when the pipeline is parallel or cross the tracks (Fig. 1b). Likewise, the location near the DC substation, where stray current is discharged, tending to form the worst corrosion, is the best location for installing the probe to monitor the stray current corrosion reliably. In addition, at the stray current pick up point, in some cases, accelerated coating damage could be induced as a result of overprotection, therefore, the pickup points could be the possible installation locations for monitoring corrosion under disbondment. Currently, as mentioned before, except potential measurement, the results of ER probe and galvanic probe are not capable of indicating the occurring of pick-up and discharge. However, the potential measurement is subjected to the effect of IR drop. In addition, these different probes could not reflect the localised corrosion nature of stray current at the discharge point and could not provide the actual polarization at the pick-up point which is associated with cathodic disbondment. Although WBE probe has demonstrated potential capability for monitoring localised corrosion induced by simulated anodic transients, more experiments are required to understand the effect of monitoring location on stray current corrosion monitoring.

Furthermore, how to identify the installation location for dynamic and more complex stray current corrosion is still unclear. For example, if the discharge point is dynamically changing in locating, such as in the case of a tram with regenerative braking, there is no single location where the probe should be installed. Therefore, further research exploring the possibility to track the location of the discharge point using several probes should be carried out.
4.3 Probe installation orientation issues

Interestingly, different orientation of the bare metal defects, for example upwards and downwards, could produce different water dispense patterns because of gravity, which could also bring about different corrosion patterns of defects. Therefore, it is necessary to study the effect of orientation on corrosion behaviour under the interference of stray current.

In terms of corrosion under disbondment, the possible defects on the pipeline surface could have different orientations, such as facing downwards, upwards, sideways or lying flat. The effect of probe orientation has also been investigated in saturated sandy soil at hydrogen evolution potential. If they are overprotected (such as $-1250\,\text{mV}_{\text{SCHE}}$), the accumulated gas would occupy different positions of the crevice, for example, if the opening crevice faces downwards the hydrogen bubbles would accumulate at the whole area of the crevice, while if the opening crevice faces sideways the hydrogen bubbles would accumulate at the side of the crevice. The accumulation of hydrogen would shield CP current, which generates low current density area under disbonded coatings. More corrosion is expected at these low current areas. Therefore, in above same environment of the saturated sandy soil at hydrogen evolution potential, the corrosion probes should be installed with faces downwards to simulate the worst corrosion situation. However, in unsaturated soil, different volume of solution pattern by virtue of gravity and absorption by soil particles would be generated on pipeline crevice surface under disbonded coatings. Therefore, it is necessary to study the effect of orientation on corrosion under disbondment.

5. FINAL REMARKS

In order to use corrosion monitoring probes as an effective early warning tool, corrosion probes should be representative of the worst possible corrosion situation along the monitored pipeline section. In order to achieve this purpose, three important aspects should be considered: probe design, measurement technique and installation. Based on the preceding literature review and analysis of industry case studies, three rules are proposed:

1. **Probe design/selection:** Corrosion probes should simulate the controlling corrosion mechanism affecting the structure and recreate the worst possible condition for that specific corrosion mechanism.

2. **Probe measurement:** The electrochemical technique on which the probe operates should be sensitive to measure parameters related to the controlling corrosion processes/mechanism.

3. **Probe installation:** Corrosion probes should be strategically installed at worst-case scenario locations.

_If corrosion probes are designed and applied according to these ‘rules’, the results of the probes would be reliable and accurate enough to provide early warning of corrosion in buried pipelines._

Although this hypothesis might seem straightforward, the implementation of these basic concepts to a heterogeneous and dynamic system such as an energy pipeline is deceptively challenging to fulfil these requirements because of the insufficient understanding of the pipeline corrosion process. As discussed on the preceding discussions, in addition to the complex effect of environmental factors on corrosion, the effect of the probe’s geometrical dimensions, orientation and location are not well understood, denying the possibility of accurate and reliable corrosion monitoring.

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Overcoming Environmental Challenges Using Innovative Approach Of Dynamic Underbalance Perforating. Corrosion monitoring – ongoing monitoring of corrosion rates and oilfield process stream corrosivity and the measures adopted to control the corrosion process. It allows assessing changes in corrosivity with time and determining control measures' effectiveness. Monitoring of corrosion inhibitor deployment process. It includes control of the treatment's technology and inhibitor's quality control. Assessment of actual technical condition of pipeline by means of inspection techniques for provision of mechanical integrity assurance. CJSC "CORMACO" possesses all required pr