Structural health monitoring: a practical approach to achieving in-situ and site-specific warning of pipeline corrosion and coating failure

STRUCTURAL HEALTH MONITORING: A PRACTICAL APPROACH TO ACHIEVING IN-SITU AND SITE-SPECIFIC WARNING OF PIPELINE CORROSION AND COATING FAILURE

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SUMMARY: An approach to achieving the ambitious goal of cost effectively extending the safe operation life of energy pipelines to, for instance, 100 years is the application of structural health monitoring and life prediction tools that are able to provide long-term remnant pipeline life prediction and in-situ pipeline condition monitoring. A critical step in pipeline structural health monitoring is the enhancement of technological capabilities that are required for quantifying the effects of key factors influencing buried pipeline corrosion and environmentally assisted materials degradation, and the development of condition monitoring technologies that are able to provide in-situ monitoring and site-specific warning of pipeline damage. This paper provides an overview of our current research aimed at developing new sensors for monitoring, categorising and quantifying the level and nature of external pipeline and coating damages under the combined effects of various inter-related variables and processes such as localised corrosion, coating damage and disbondment, cathodic shielding. The concept of in-situ monitoring and site-specific warning of pipeline corrosion is illustrated by a case of monitoring localised corrosion under disbonded coatings using a new corrosion monitoring probe. A basic principle that underpins the use of sensors to monitor localised corrosion has been presented: Localised corrosion and coating failure are not an accidental occurrence, it occurs as the result of fundamental thermodynamic instability of a metal exposed to a specific environment. Therefore corrosion and coating disbondment occurring on a pipeline will also occur on a sensor made of the same material and exposed to the same pipeline condition. Although the exact location of localised corrosion or coating disbondment could be difficult to pinpoint along the length of a buried pipeline, the 'worst-case scenario' and high risk pipeline sections and sites are predictable. Sensors can be embedded at these strategic sites to collect data that contain 'predictor features' signifying the occurrence of localised corrosion, CP failure, coating disbondment and degradation. Information from these sensors will enable pipeline owners to prioritise site survey and inspection operations, and to develop maintenance strategy to manage aged pipelines, rather than replace them.

Keywords: Corrosion monitoring, Pipeline corrosion, Structural Health Monitoring, Aged pipeline

1. INTRODUCTION

Serious oil and gas pipeline incidents are often due to unanticipated failure of high risk pipeline sections where localised corrosion, cathodic protection (CP) excursions, coating disbondment and degradation could occur in an unexpected manner [1-3]. Examples of high risk pipeline sections include non-piggable pipeline sections, areas between CP units, pipeline water crossings, pipeline shoreline crossings, horizontal directional drilling (HDD) and pipelines in tunnels. These pipeline sections could present the 'worst-case scenario' conditions that are crucial to the safety and reliability of an energy pipeline. An approach to enhancing the safe operation of a pipeline is to apply structural health monitoring (SHM) and life prediction tools that are able to provide in-situ pipeline condition monitoring and long-term remnant pipeline life prediction. Currently the most common approach to pipeline life prediction is through the development and application of various asset management tools. The principle behind this approach is that the collection and modelling of historical survey and inspection data would allow for pipeline lifetime assessment based on statistical analysis of factors critical to pipeline life. Current methodologies that are often used for predicting the failure and remaining life of underground pipelines are usually probabilistic models. For instance Li et al [4] used a Monte Carlo simulation technique to calculate the remaining life of a pipeline. Lee et al [5] presented an intelligent failure prediction system for oil and gas pipeline using an Euclidean-Support Vector Machines classification approach. Senouci et al [6] developed a fuzzy-based model to predict the failure type of oil pipelines using historical data of pipeline accidents with an average percent validity of 83%. Peng et al [7] developed a fuzzy artificial neural network model, which is based on a failure tree and fuzzy number computing model, for predicting the failure rates of long-distance oil/gas pipelines and for identifying distressed pipeline segments. These asset management based pipeline life prediction tools are useful in providing an overall assessment of the aging of a pipeline; however they have a major limitation in predicting the occurrence of localised corrosion and coating failure that often occur at specific high risk pipeline locations.

This limitation has to be addressed if the ambitious goal of extending the safe operation life of aged pipelines to 100 years is embraced by the future pipeline industry. The Energy Pipeline Cooperative Research Centre has developed a comprehensive research and development exercise directed at improving the asset management and conditional monitoring tools available to the pipeline industry, allowing informed decisions on pipeline life prediction and life extension [8]. A unified multidisciplinary research thrust has been initiated to develop pipeline protection strategies through research on pipeline degradation mechanisms, damage assessment and remnant life prediction. Our current research approaches include, (i) systematically categorising and quantifying the level and nature of damage of pipeline as a result of the combined effects of various inter-related variables and processes such as localised corrosion, coating cracking and disbondment, cathodic shielding, transit loss of CP, nonuniform mechanical strain, and other complex electrochemical and environmental conditions; and (ii) developing pipeline health monitoring and life prediction tools that work in a complementary manner to provide long-term remnant pipeline life prediction as well as in-situ site-specific pipeline condition monitoring and warning. This paper provides an overview of our current research, with particular focus on the development of new sensors for in-situ and site-specific warning, monitoring, categorising and quantifying the level and nature of external pipeline damage. A case of monitoring localised corrosion under disbonded coatings is presented to illustrate the development of a novel corrosion monitoring sensor.

2. FUNDAMENTAL CONSIDERATIONS ON PIPELINE SHM SENSORS

Currently pipeline corrosion management relies heavily on periodic time based routine inspections using pipeline condition assessment methods including the monitoring of CP conditions by the Close Interval Potential Surveys (CIPS) or IR drop coupons; the detection of coating defects by Direct Current Voltage Gradient (DCVG) surveys; the assessment of metal loss using in-line inspection tools (intelligent pigs) and historical excavations. These methods are useful for detecting stray currents, for locating big defects in the pipeline coating, and for assessing the operation of CP systems. A weakness of these inspection methods is that they are often expensive and therefore are performed only on a periodic basis (usually every 5-15 years for intelligent pigs). Another approach that should be useful for pipeline corrosion management is the use of corrosion monitoring and warning sensors. Currently the most widely adopted corrosion monitoring sensors in the pipeline industry are steel coupons and electrical resistance probes (ER probes). Steel coupons buried next to the pipe and electrically connected to it are used to assess the operation of CP systems; however conventional weight-loss measurement can be difficult for buried structures because of practical difficulties in coupon installation and excavation. ER probes, often referred to as 'intelligent' weight-loss coupons, are used to detect corrosion by monitoring the electrical resistance between the ends of an elongated coupon of constant cross-section subjected to the corrosive environment. The ER coupon can be electrically connected to the pipeline to simulate the bare metal exposed in a coating defect for detecting corrosion data under CP. A major limitation of ER probes is in the detection of localised corrosion because localised damages may not lead to any significant change in electric resistance, metal weight or ions concentration. Although corrosion monitoring has been widely applied to many industrial structures such as chemical plants, practical application of existing corrosion monitoring techniques to buried structures such as a steel pipeline has been limited.

The basic principles that underpin the use of sensors to monitor localised corrosion and coating failure are: Localised corrosion and coating failure are not an accidental occurrence, it occurs as the result of fundamental thermodynamic instability of a metal and a coating in a specific environment. It is expected that corrosion and coating failure occurring on a metal-coating-environment system would also occur on a sensor made of the same material, coated with the same coating and exposed to the same pipeline condition. Therefore SHM sensors used in industrial structures such as chemical plants should also be applicable to buried pipeline systems. Although the exact location of localised corrosion such as pitting or coating failure such as coating disbondment could be difficult to pinpoint along the length of a buried pipeline, the 'worst-case scenario' pipeline sections and high risk pipeline sites are predictable. Sensors can be embedded at these strategic sites to collect data that contain 'predictor features' signifying the occurrence of localised corrosion, CP failure, coating disbondment and degradation.

A critical step in the application of sensors for buried pipeline is the enhancement of technological capabilities that are required for overcoming specific difficulties associated with buried pipeline systems. This is not an easy task since there is an array of complex issues encountered when monitoring, modelling and predicting buried pipeline corrosion. A major difficulty is that there are too many inter-related variables such as temperature, pressure, metallurgy, soil chemistry, thermo-mechanical conditions, geometry, mechanical stress, coating defects, and CP excursions whose effects on corrosion have not yet fully quantified. Another practical difficulty is that corrosion measurement in highly resistive and inhomogeneous soil media can be very challenging due to complications in setting up and maintaining corrosion testing cells and sensors. For instance, although electrochemical methods have been widely used in many industries for corrosion measurement, their application in the monitoring of external corrosion of buried pipeline has been very limited. Conventional electrochemical polarisation based methods are difficult to be applied in highly resistive conditions because the high resistance of soil between the pipeline, i.e., working electrode, and the reference electrode, often causes a huge potential drop commonly referred to as IR drop that can cause significant corrosion rate measurement errors [9]. The large surface area of the pipeline compared to the counter electrode suggests a highly non-uniform distribution of the polarisation current that can also cause significant corrosion rate measurement errors. More importantly, it is well known that these conventional electrochemical methods can only be used for estimating general corrosion because in principle they are based on the most fundamental relationship in electrochemical kinetics, i.e Butler-Volmer equation, which only describes the kinetics of uniform corrosion mechanism and thus does not apply to localised corrosion [9,10].

The Energy Pipeline Cooperative Research Centre research teams are currently working on two complementary approaches at developing more reliable, convenient and economic techniques for monitoring buried pipeline corrosion and coating damage: (i) asset management tools based on the collection and modelling of historical survey and inspection data for pipeline lifetime assessment; and (ii) the development of pipeline SHM sensors that are able to provide in-situ monitoring and warning of pipeline damage. An advantage of the pipeline SHM tool is that it would enable site-specific and in-situ warning of unexpected pipeline failures. Information from these tools will enable pipeline owners to prioritise site survey and inspection operations, and to develop maintenance strategy to manage older pipelines, rather than replace them. This approach requires real time monitoring by placing sensors at strategic and 'worst-case scenario' high risk locations of a pipeline. Typical high risk pipeline sites would be those with high stray current activities, low soil resistivity, high underground water level, high concentration of corrosive species, and those highly corrosion rate areas identified by pigging, field DCVG survey and historical excavations. Pipeline sections of high economic and social significances may also be identified as monitoring sites. Sensors embedded at these strategic sites are used to collect data that would contain 'predictor features' signifying the occurrence of localised corrosion, CP failure, coating disbondment and degradation. Deterministic modelling of these data would provide interpretation of data acquired from in-situ pipeline SHM sensors and identify critical 'predictor features' and parameters determining the occurrence of localised corrosion, CP failure, coating disbondment and degradation. The integration and synthesis of corrosion and coating failure sensors would provide data for real-time and site specific warning of pipeline corrosion and coating failure. This concept can be illustrated by an electrochemical sensor that was designed for monitoring and assessing corrosion under disbonded coatings [11].

3. CASE STUDY: A NEW SENSOR FOR MONITORING LOCALISED PIPELINE CORROSION

In the case of underground pipeline under CP, localised corrosion attack is the most common form of corrosion damage due to a CP induced local chemical environments around a steel pipeline. For this reason particular focus should be on the development of pipeline condition monitoring tools that is able to provide in-situ monitoring and warning of localised corrosion. Localised corrosion monitoring requires the simulation of local environmental conditions on a large and complex structure such as a buried pipeline using a small probe, and the measurement of the thermodynamics and kinetics of corrosion processes occurring on the probe surface. If corrosion processes are properly simulated, the probe can provide useful information on corrosion over the larger structure. This concept has been successfully implemented in many industries such as the petrochemical industry, however, corrosion monitoring of underground pipelines remains a challenge. The highly resistive soil environment, the use of impressed current CP systems and the presence of barrier coatings make corrosion monitoring difficult. For instance CP introduces a great complication to traditional electrochemical corrosion monitoring techniques because they are only applicable around the OCP [9-11]. On the other hand, the use of barrier coatings on pipelines introduces some other complexities for corrosion monitoring. For instance a common form of pipeline damage is related to coating disbondment that generates a crevice between the disbonded coating film and the metallic pipe. This type of coating defect requires particular attention since it is found to be related to the most severe localised corrosion issues in pipelines [12-17]. The environment developed in the crevice can be significantly different to the bulk soil and the CP can be shielded to ineffective CP potential values. Little information about what occurs in the crevice can be obtained by pipeline inspection methods such as CIPS and DGVG methods. Additionally, the most used smart pigs (when applicable) have difficulties in detecting longitudinal crack associated with stress corrosion cracking produced under disbonded coatings. Moreover, existing corrosion monitoring probes such as ER probes only simulate bare metal exposures to the bulk soil with ideally no disbonded regions, consequently providing no information on the corrosion under disbonded coatings. It is known from published modelling and experimental works that the environment under disbonded coatings deviates significantly from the bulk. Due to the shielding of CP currents and isolation of the external environment, the crevice area develops a complex environment with high cation concentrations [12-15], high pH (in most cases) [12-14], negligible oxygen [13-14,16] and a gradient of potentials [13,14]. The initiation and propagation of localised corrosion under disbonded pipeline coatings are considered to be extremely challenging to monitor; at present there is no sensor technology that possesses the abilities of providing in-situ information regarding them [18]. Previously attempts to evaluate localised corrosion rates under CP include work by Sun et al. who used a coupled multi-electrode array and estimated the largest anodic current density based on statistical parameters, assuming that the local current densities measured at all electrodes follow a normal distribution [16,17]. Unfortunately, no correlation with actual metal loss values or localised corrosion pattern was presented.

In order to develop a practical tool for pipeline condition monitoring, as shown in Figure 1, a novel sensor for simulating a disbonded coating (a crevice) over a CP protected pipeline surface and for measuring localised corrosion related parameters over the CP shielded crevice [11]. Testing of the sensor has been carried out in aqueous and soil cells in order to understand the sensor's performance in buried environmental conditions. Figure 2a shows typical current density distribution maps measured after 23hs exposure of the sensor to 0.01M Na_2SO_4 saturated sandy soil at the open circuit potential (-776mV$_{CSE}$) and at a CP potential (-1050mV$_{CSE}$). The metal losses calculated from the sensor's output for each of the conditions are shown in Figure 2b. Corrosion clearly decreased when a CP potential was applied, however even at a rather negative CP potential of -1050mV$_{CSE}$, some small corrosion sites were actually detected under the disbonded area. It is believed that the accumulation of hydrogen bubbles that provided additional shielding could be responsible for this behaviour. More details on the principles of this new sensor and experimental aspects have been presented in references 10 and 11.

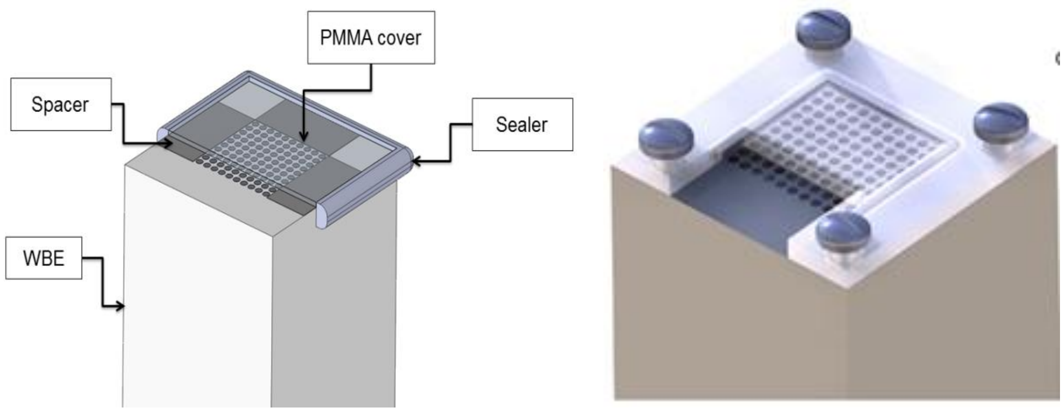

Figure 1. A novel sensor for simulating a disbonded coating over a simulated CP protected pipeline surface.

(3a)

(3b)

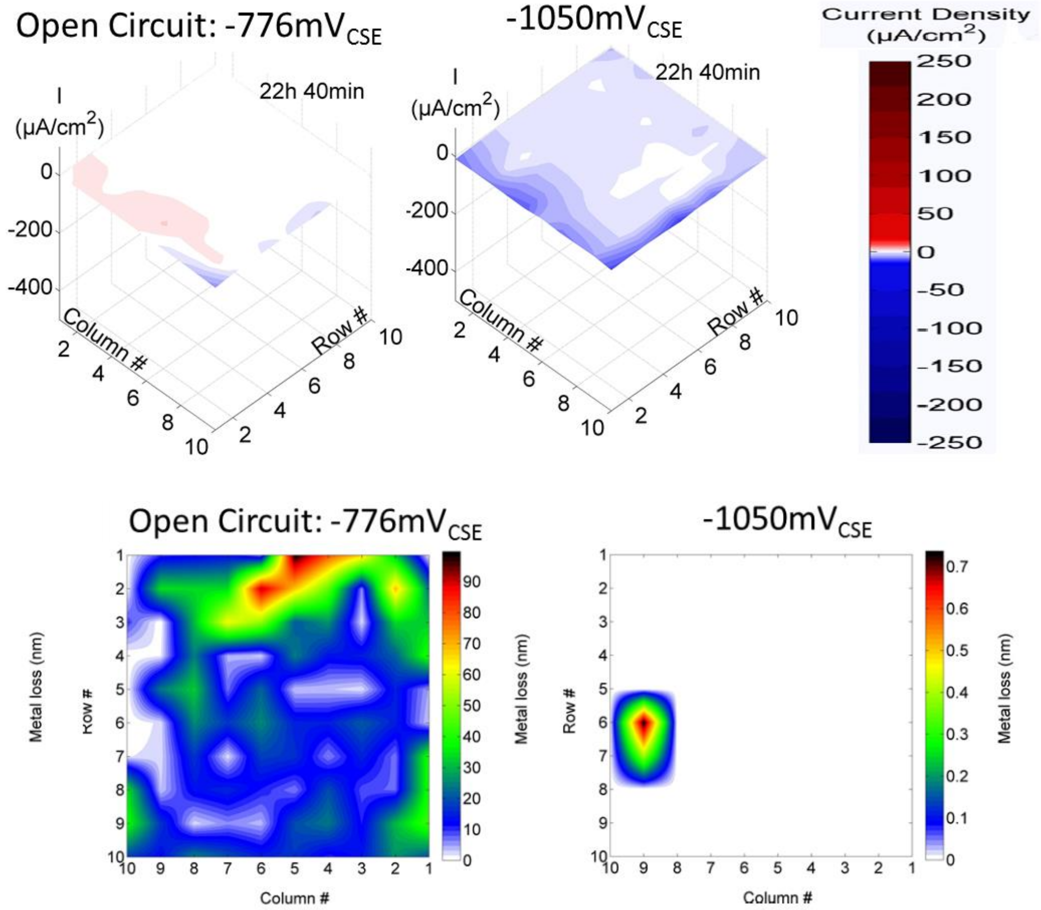

Figure 2. (a) Current density distributions over a sensor surface after 23hs exposure to 0.01M Na_2SO_4 saturated sandy soil under OCP and under CP; (b) Metal loss maps calculated from the sensor's output under OCP and under CP respectively.

Figure 3 presents the current density distribution maps obtained by the probe as shown in Figure 1 at different immersion times over a 22 hour test period. Anodic current densities are represented by positive values while cathodics are represented by negatives values. The first two rows of each current density map corresponds to the uncovered electrodes area (simulating coating defect areas), while the rest show the behaviour within the area under the crevice (simulating disbonded coating areas). In general, large cathodic current densities were found at the uncovered electrode areas. Anodic current densities were only detected under the disbonded area and the value decreased as the test progressed. The CP current profiles obtained with the probe (see Figure 3) correlate well with the results presented in other published works where significantly larger cathodic current densities were reported at the crevice opening 15,19]. However, anodic current densities were rarely reported before, they were detected occasionally as insolates data points and were often disregarded [20,21]. Particularly, Li et al. [22] reported anodic current densities at an electrode being preferentially corroded under a simulated disbonded coating, but no explanation regarding how their segmented electrode was capable of detecting anodic currents under CP was presented.

Figure 4 shows a comparison between the appearance of the electrode array surface at the end of the test period and the metal losses calculated form the probes data. A photograph of the electrode array is presented in Figure 4a where corrosion can be observed mainly on areas under the simulated disbonded coating. Figure 4b presents the metal losses calculated based on the anodic current densities detected by the probe using Faraday's law. The calculated metal losses, expressed as the thickness reduction after 23hs of exposure, shown values below 0.2μm indicating the high sensitivity of the probe. When comparing the measured (Fig. 4b) and actual (Fig. 4a) corrosion patterns, a good correlation in the general corrosion patterns for the electrodes located within the crevice is found. However, no metal loses were detected at the top three rows of electrodes. As was explained before, the high oxygen concentration at these locations prevents the probe from measuring anodic current densities at these locations. A more advanced data analysis technique capable of estimating corrosion from the cathodic current densities measured by the array at this location is being developed to overcome this limitation and will be published elsewhere.

A key concept needed to understand the probe's working principle is that the current registered by each electrode of the array is net current resulting from all anodic and cathodic processes occurring at its surface. Consequently, the factors affecting this process along the crevice and uncovered areas have a marked effect on the currents registered. It has been previously reported in the literature that parameters such as complex environment with high cation concentrations [12-15], high pH (in most cases) [12-14], negligible oxygen [13-14,16] and a gradient of potentials [13,14]. At the CP potential evaluated in this work (it is the minimum protection potential accepted by pipeline industry), dissolved oxygen concentration is the main factor affecting the cathodic reactions rate. A schematic Evan's diagram showing the effect of oxygen depletion on the currents measured by the array is presented in Figure 5. The larger oxygen reduction limiting current case ($i_{Lim.1}$) represents the conditions at the uncovered electrodes, where the oxygen concentration is high. At this location, cathodic current densities ($i_{Lim.1}$) are larger than anodic current ($i_{corr.CP}$) and therefore, the net current densities measured by the array electrodes (I_{M1}) are cathodic despite some anodic reaction (i.e. corrosion reaction) may still take place ($i_{corr.CP}>0$). When considering the lower oxygen reduction limiting current case ($i_{Lim.2}$) that corresponds to the nearly depleted oxygen environment in the crevice area, the anodic current densities ($i_{corr.CP}$) could be larger than cathodic currents ($i_{Lim.2}$). Consequently, the current densities measured at this location are anodic (I_{M2}) even though both locations were considered at same CP potential in this hypothetical case. In real systems, the local CP potential within the crevice could be less negative than at its opening. In addition, pH and other solution compositional changes may also affect the anodic reaction rate. Nevertheless, none of these changes affect the rate of the diffusion controlled cathodic reaction, and consequently, in the absence of other cathodic reaction, the measurement of anodic current densities under the simulated disbonded coating should remain valid. We believe this discussion explains the electrode array's capability to detect anodic currents under CP under disbonded coatings.

Corrosion sensors such as the one shown in Figure 1 can be a component of a comprehensive pipeline SHM tool that enables the prediction of remnant pipeline life and the warning of unexpected pipeline damage. The SHM system would include sensors used in combination for measuring combined effects of coating disbondmen and for monitoring of electrochemical reactions in localized areas under a disbonded coating. For instance an electrochemical impedance spectroscopy based sensor will be used for monitoring coating disbondment. More details on this sensor has been described in reference [23]. This tool would enable site-specific and in-situ warning of pipeline failures due to localised corrosion, ineffective CP, coating disbondment and degradation by placing sensors at strategic and 'worst-case scenario' locations of a pipeline.

4. CONCLUDING REMARKS

Currently there is a lack of technological capability for pipeline engineers to monitor and detect pipeline coating deterioration and corrosion processes on a continuous basis, and to perform pro-active warning and maintenance on localised corrosion, coating disbondment and degradation, and CP excursion induced pipeline failures. Our approaches to achieving the goal of extending the safe operation life of pipelines include the development of pipeline health monitoring and life prediction tools that are able to provide both long-term remnant pipeline life prediction and in-situ monitoring and warning of pipeline damage. The principle of this pipeline condition monitoring tool is to provide real time monitoring of localised corrosion, ineffective CP, coating disbondment and degradation by placing sensors at strategic and 'worst-case scenario' locations of a pipeline, such as non-piggable pipeline and high risk pipeline sections. Information from these sensors will enable pipeline owners to prioritise site survey and inspection operations, and to develop maintenance strategy to manage older pipelines, rather than replace them. A new probe has been described to illustrate the electrochemical measurements of corrosion rates, as well as CP effectiveness, under cathodically protected disbonded coatings in highly resistive media.

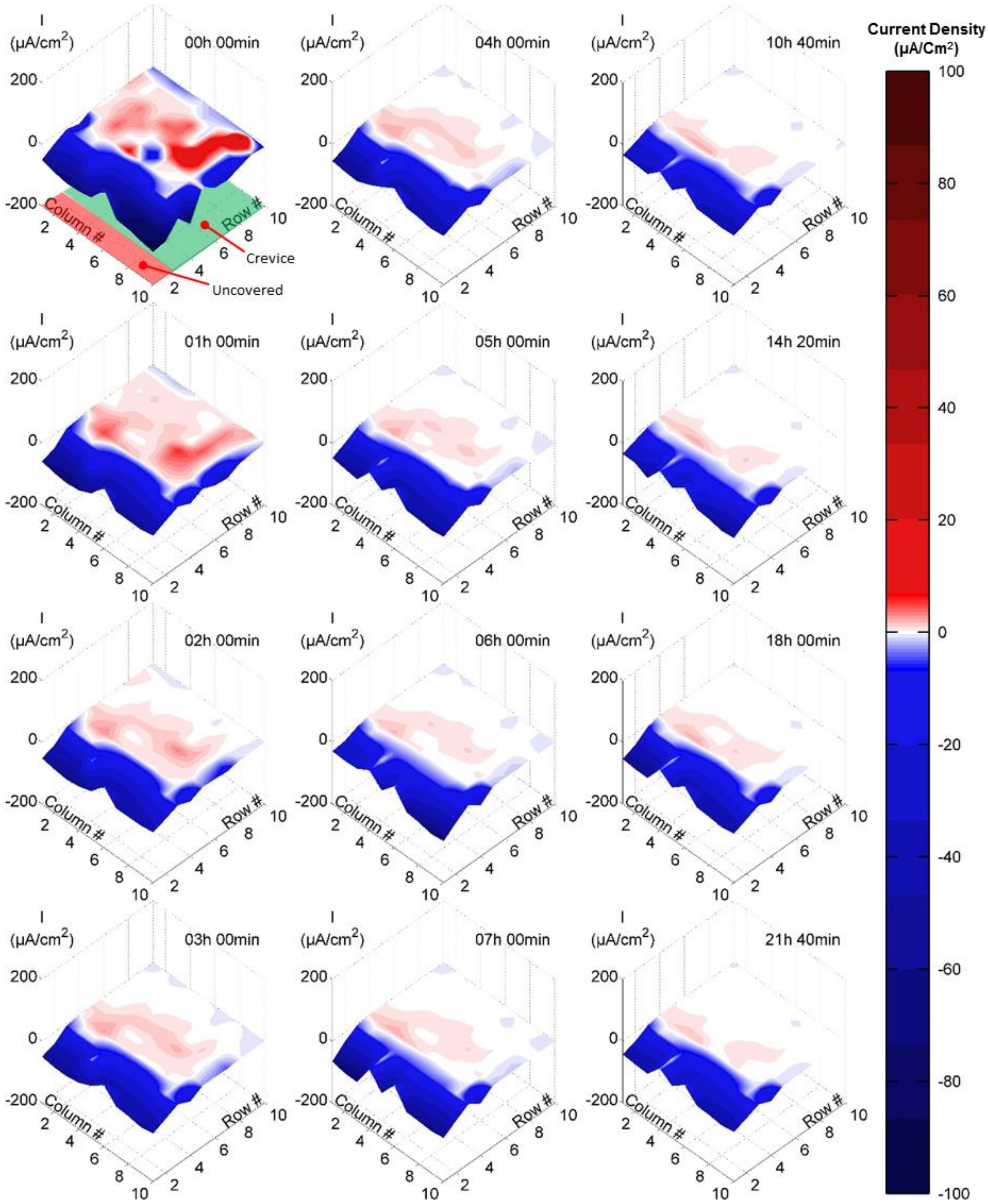

Figure 3. Current density distribution maps at several immersion times in 0.001M Na_2SO_4 at -760mV$_{Ag/AgCl}$.

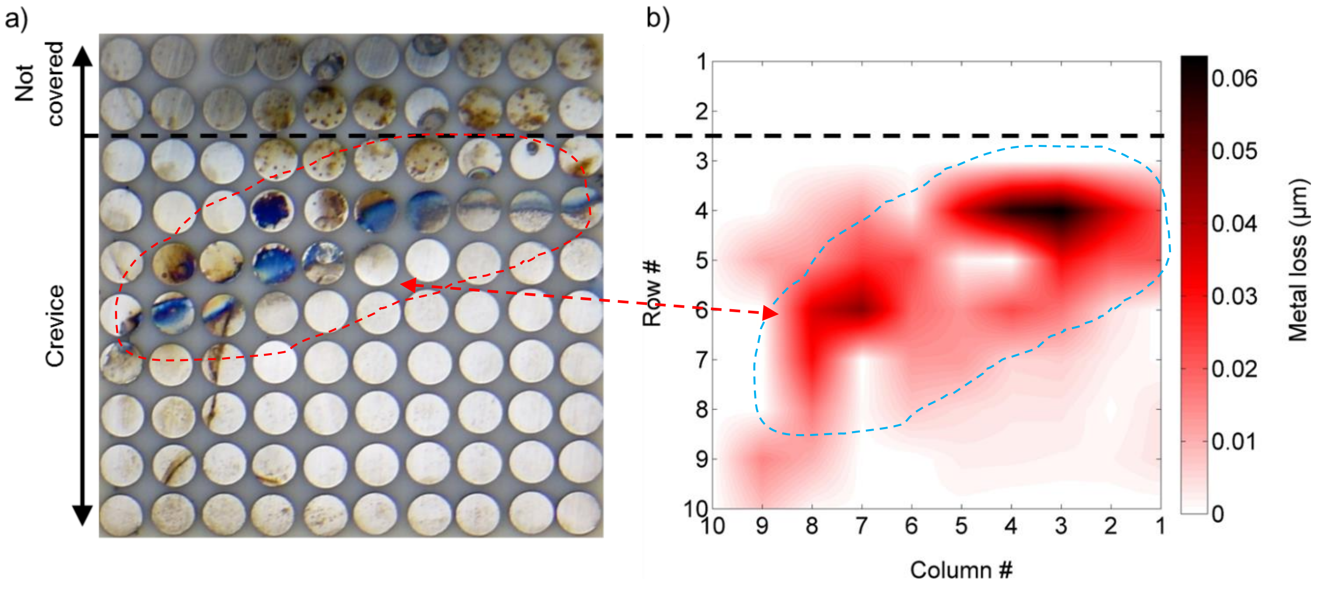

Figure 4. Comparison between actual (a) and measured (b) corrosion patterns.

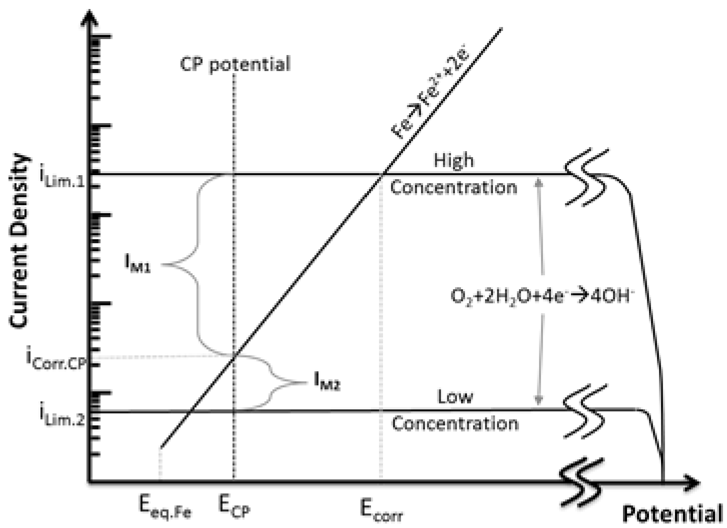

Figure 5. Schematic Evan's diagram of the probe's working principle.

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Facundo Varela, also known as Bob, is a PhD Student in the Institute for Frontier Materials at Deakin University, working on an Energy Pipeline CRC sponsored project. He completed his materials engineering studies with honours in the Instituto de Tecnología Jorge A. Sábato in 2009. As bachelor final year project, he joined Professor Maria Forsyth's Group at Monash University where he worked on the Inhibition of Stress Corrosion Cracking in aluminium 7075. His PhD project attempts to develop new corrosion monitoring technologies to measure corrosion rates under disbonded coatings in underground structures.

Professor Maria Forsyth completed her PhD in January 1990 at Monash University and moved to Northwestern University to take up a Fulbright Fellowship in the area of solid electrolytes for lithium batteries. On her return to Melbourne she worked at DSTO for a year before joining the Department of Materials Engineering as a Lecturer in 1993. In 2001 she was awarded an ARC Professorial Fellowship and is currently the Chair in Electromaterials and Corrosion Sciences at Deakin University, within the Institute for Technology Research and Innovation (ITRI). She is co-author of over 280 refereed journal papers, has delivered over twenty invited talks in the last 5 years and has over 7000 citations at present