

# An Overview of New Progresses in Understanding Pipeline Corrosion

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An approach to achieving the ambitious goal of cost effectively extending the safe operation life of energy pipeline to 100 years is the application of health monitoring and life prediction tools that are able to provide both long-term remnant pipeline life prediction and *in-situ* pipeline condition monitoring. A critical step is the enhancement of technological capabilities that are required for understanding and quantifying the effects of key factors influencing buried steel 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 and electrochemical cells 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 cracking and disbondment, cathodic shielding, transit loss of cathodic protection.

**Keywords :** *pipeline life prediction, corrosion monitoring, oil & gas pipeline, protective coatings, cathodic protection*

## 1. Introduction

Catastrophic oil and gas pipeline incidences such as localised corrosion induced pipeline explosions are reported around the world<sup>1,2</sup>. These serious pipeline breakdown incidents are often due to unanticipated failure of high risk pipeline sections where localised corrosion, cathodic protection (CP) excursions, coating disbondment and degradation occur in an unexpected manner. Although significant effort has been made over past decades to understand, predict and prevent pipeline failure, major questions remain unanswered. For instance CP excursions from safe protection potentials (e.g., -850 mV vs copper/copper sulphate reference electrode (CSE) due to various forms of stray currents are believed to affect the effectiveness of CP systems; however there is no unified consensus as to how 'big' these excursions (either in magnitude, or duration or frequency) need to be in order to warrant a major pipeline durability hazard. This uncertainty has caused difficulties in selecting CP parameters in relevant industry standards. Coating cracking, disbondment and degradation are known to cause coating damage and localised forms of corrosion such as corrosion under disbonded coatings;

however these effects have not been sufficiently quantified primarily due to the lack of technological capabilities. These issues need to be addressed if the ambitious goal of extending the safe operation life of 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 tools available to the pipeline industry, allowing informed decisions on pipeline life prediction and life extension<sup>3</sup>. 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 coating failure, ineffective CP, non-uniform mechanical strain, and 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.

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## 2. Developing Methods for Quantifying and Monitoring Pipeline Corrosion

A critical step in this research is the enhancement of technological capabilities that are required for comprehending key factors affecting buried steel pipeline corrosion and environmentally assisted materials degradation, and the development of pipeline condition monitoring technologies that are able to provide *in-situ* monitoring and warning of pipeline damage. 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 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.

It would be highly desirable if more reliable, convenient and economic techniques could be developed for monitoring buried pipeline corrosion and coating damage. 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<sup>4</sup>. 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<sup>4</sup>. Corrosion rates under CP are not directly related to polarisation resistance values typically obtained by traditional electrochemical monitoring techniques since for instance the Stern-Geary equation is intended for determining corrosion kinetics around the open circuit potential (OCP).

### 2.1 Evaluation of electrochemical methods for measuring pipeline corrosion under CP

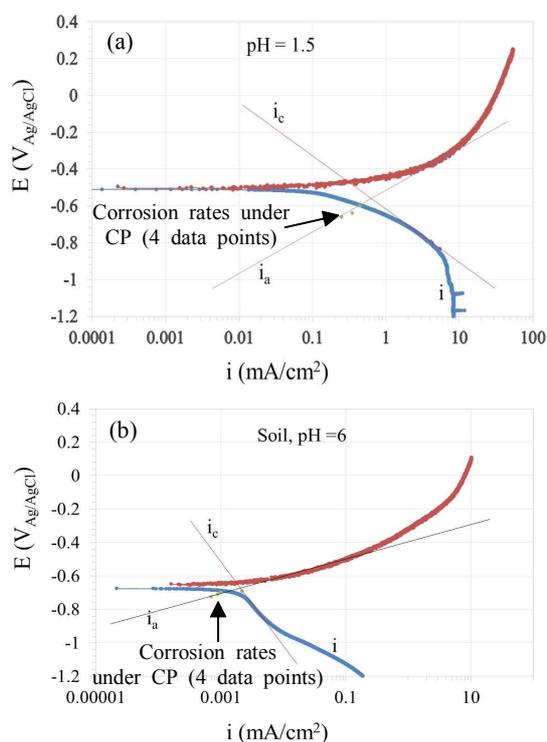
One of the first attempts to overcome challenges associated with electrochemical corrosion measurement under CP was proposed by Stern and Geary<sup>5</sup>, who proposed to estimate corrosion rates under cathodic polarisation conditions based on extrapolation of the anodic Tafel behaviour to the applied CP potential. Jones<sup>6</sup> considered that the anodic Tafel constant could be determined experimentally either directly from anodic polarisation data or indirectly from cathodic polarisation data. This approach is not preferred due to the significant corrosion damage produced to the electrode during anodic polarisation.

Another approach is based on the calculation of anodic corrosion kinetics without requiring anodic polarisation. This approach assumes that the anodic component is equal to the difference between experimental values and the ideal linear cathodic Tafel behaviour. Unfortunately, this assumption is only valid for systems where cathodic reaction kinetics are activation controlled<sup>5)</sup>. This represents a major limitation, since the method would, in principle, not be applicable to systems which dominant cathodic reaction rate is diffusion controlled, such as buried pipelines. Despite its limitations, this approach was widely studied. Stern and Roth<sup>7)</sup> experimentally confirmed this method by measuring steel corrosion rates under CP in acidic environments. Jones<sup>6)</sup> applied it to buried mild steel obtaining a good correlation with anodic Tafel constants estimated by the direct approach.

Following up these research efforts, we have carried out experimental evaluation of the ability of conventional electrochemical methods including potentiodynamic polarisation and impedance methods in measuring steel corrosion under CP in order to understand their applicability and limitations. To verify the possibility of using the potentiodynamic polarisation method for measuring steel corrosion under CP, as suggested by Barbalat et al.<sup>8,9)</sup>, potentiodynamic polarisation tests were conducted in 1 wt. % NaCl with pH of 1.5 and 6, and in soil saturated with 1 wt.% NaCl solution of pH 6. Anodic and cathodic polarisation tests were conducted separately. OCP was stabilized for an hour prior to polarisation measurements. Working electrode's surface area was 2.25 cm<sup>2</sup>. A scan rate of 10 mV/minute was used in all tests. The current measured in a potentiodynamic polarisation test is a net current arising from anodic and cathodic reactions, which can be expressed as:  $i = i_a + i_c$ , where,  $i$  is the net current measured in a potentiodynamic polarisation tests.  $i_a$  is anodic current and  $i_c$  is cathodic current assuming an ideal linear cathodic Tafel behaviour. As shown in Fig. 1, cathodic branch of the polarisation curve can be extrapolated to obtain cathodic current density (activation controlled) for whole range of potential. Close to the open circuit potential, deviation in cathodic current arises due to a dominant anodic reaction. Anodic current can be obtained from the equation,  $i = i_a + i_c$ , and is plotted in Fig. 1a and Fig. 1b. Anodic current density was calculated at 4 points and a best fit line was drawn which represents anodic reaction as a function of potential. Using this method at a CP of  $-850 \text{ mV}_{\text{CSE/CuSO}_4}$  corrosion rate was estimated to be  $12.9 \text{ } \mu\text{m/year}$  in saturated soil whereas corrosion rate in 1 wt. % NaCl with pH of 1.5 was estimated to be  $1045 \text{ } \mu\text{m/year}$ . This suggests that cathodic polarisation curve could be used to estimate corrosion rate of steel

under CP, however care has to be taken in measurements and in making Tafel extrapolation. A small difference in drawing best fit line or Tafel extrapolation may result in significantly different results. In cases that cathodic reaction is diffusion controlled, this method cannot be applied.

Although potentiodynamic polarisation could be used to determine corrosion rate of steel under CP, it requires the application of significant perturbations that could destroy a testing system. Aiming at imitating the success of the linear polarisation resistance method for measuring corrosion rates, some small amplitude polarisation variants of the potentiodynamic polarisation method have subsequently been proposed. For instance Gerasimenko et al.<sup>10)</sup>, proposed a method to extrapolate polarisation resistance under CP from results obtained at OCP in order to estimate corrosion rates in cathodic polarisation conditions. A limitation is that this method requires previous knowledge of the anodic Tafel constant which is hardly available for real systems. Meas et al.<sup>11)</sup>, proposed a set of equations



**Fig. 1.** Potentiodynamic polarisation curves and data fitting under two different experimental conditions: a) pH=1.5 and b) saturated sand with pH=6. ' $i_c$ ' is cathodic current extrapolated from linear Tafel extrapolation, ' $i$ ' is net current measured in potentiodynamic polarisation experiments. Line named ' $i_a$ ' is best fit line of data points obtained by subtracting ' $i_c$ ' from ' $i$ ' and represents net corrosion rate at various cathodic potentials.

to analytically calculate the corrosion rates under CP based on the corrosion rates measured at OCP, the slope of the cathodic polarisation curve at the CP potential and the area beneath the polarisation curve in the potential range in which the slope was measured. Although this seems to be a promising approach, no experimental confirmation of the technique was presented by the authors. Qamar et al.<sup>12)</sup>, further developed Meas's method and claimed to have established an analytical method that does not require knowledge of the OCP corrosion potential. However important inconsistencies appear to exist in the formulation which the method was based upon. Jankowski<sup>13)</sup> reviewed these methods and concluded that none of them is capable of fully evaluating corrosion rates in cathodic polarisation conditions.

Another possibility is the use of electrochemical impedance spectroscopy (EIS) as a small amplitude polarisation method to measure corrosion rates under CP. Based upon suggested methods by Jankowski et al.<sup>13-15)</sup>, we have carried out experimental evaluation of the EIS method for measuring corrosion rates under various CP potentials. Prior to EIS testing, CP potential was applied for a period of an hour before EIS data was collected in a frequency range of 100 kHz to 50 mHz. Nyquist plots obtained at various potentials have been used to determine impedance values. It has been found that the impedance values increased as applied CP potential decreases from -550 mV to -900 mV; however unexpectedly further decrease in applied CP potential lead to decrease in impedance values. This is unexpected because with decreases in applied CP potential, rates of cathodic reactions are expected to increase and rates of anodic reactions are expected to decrease. This suggests that the trends in impedance change with applied CP potential did not agree to the principle of cathodic protection. Decrease in im-

pedance values below -850 mV<sub>CSECuSO4</sub> could be related to increased rate of cathodic reaction, and not related to anodic reaction that determines corrosion rate. This result suggests that impedance values could not be used to determine corrosion rates under CP.

## 2.2 Development of localised corrosion monitoring tools for pipeline under CP

Another major limitation of any of the techniques discussed above is that they are derived based on an ideal homogeneous electrode and therefore they are not suitable for situations where localised corrosion dominates. 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. The basic principles that underpin the use of corrosion sensors to monitor localised corrosion are: (i) Localised corrosion is not an accidental occurrence, it occurs as the result of fundamental electrochemical thermodynamic instability in an infrastructure such as a pipeline. Properly designed sensors such as those described in the literature<sup>4)</sup> could be able to measure such thermodynamic instability by real-time monitoring and visualising of electrochemical corrosion processes. (ii) Although the exact location of localised corrosion can be difficult to predict along the length of a buried pipeline, the locations that are sensitive to localised corrosion is predictable in corrosion engineering. Sensors can be embedded at these strategic locations in order to obtain real time data for localised corrosion monitoring and prediction. Corrosion warning information is usually from 'worst-case scenario' locations of the infrastructure. In an attempt to evaluate

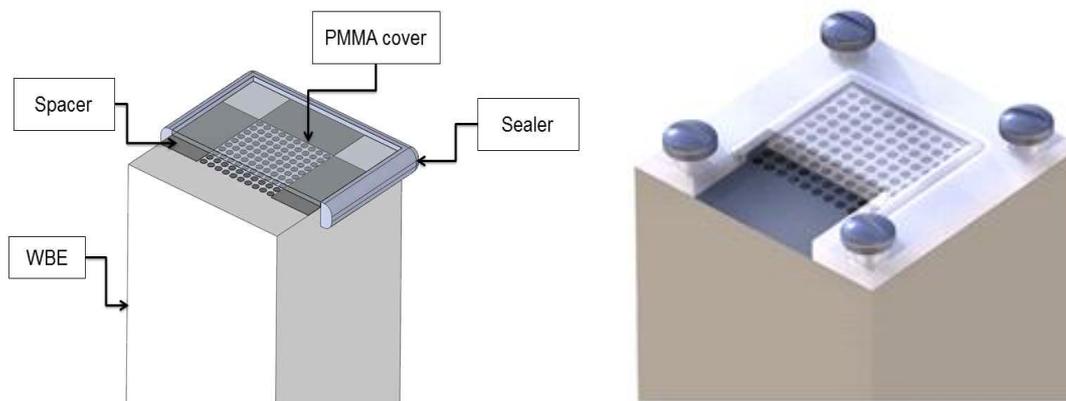
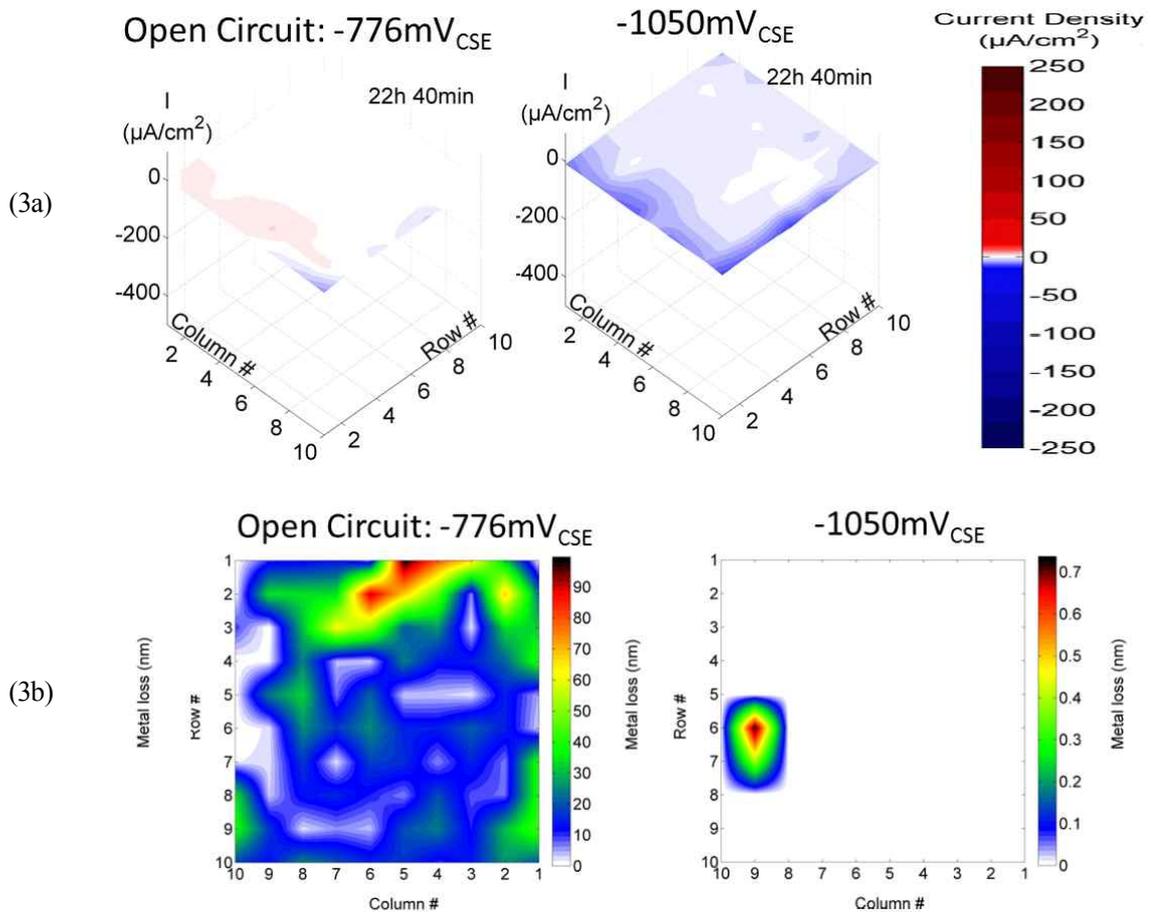


Fig. 2. A novel sensor for simulating a disbonded coating over a simulated CP protected pipeline surface.

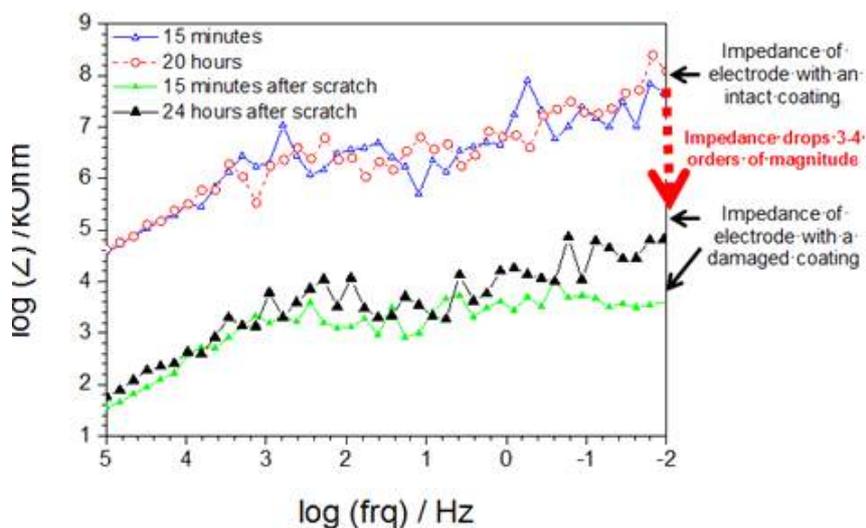


**Fig. 3.** (a) Current density distributions over a sensor surface after 23 h exposure to 0.01M  $\text{Na}_2\text{SO}_4$  saturated sandy soil under OCP and under CP; (b) Metal loss maps calculated from the sensor's output under OCP and under CP respectively.

localised corrosion rates under CP, Sun et al. 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<sup>16-18</sup>. 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 Fig. 2, 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<sup>19,20</sup>. Corrosion under disbonded coating due to the formation of a crevice between disbonded coating and the pipeline surface is one of the threats to a pipeline. 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. 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. Fig. 3a shows typical current density distribution maps measured after 23 h exposure of the sensor to 0.01M  $\text{Na}_2\text{SO}_4$  saturated sandy soil at the open circuit potential ( $-776\text{mV}_{\text{CSE}}$ ) and at a CP potential ( $-1050\text{mV}_{\text{CSE}}$ ). The metal losses calculated from the sensor's output for each of the conditions are shown in Fig. 3b. Corrosion clearly decreased when a CP potential was applied, however even at a rather negative CP potential of  $-1050\text{mV}_{\text{CSE}}$ , some small corrosion sites were actually detected under the disbonded area. It is believed that the accumulation of hydrogen bubbles



**Fig. 4.** EIS Bode plots collected upon epoxy coated X70 steel specimens (under CP) with and without a scratch. A flat cell, incorporating an Ag/AgCl reference electrode and a titanium mesh counter electrode was used to carry out EIS measurements. Tests were performed in 0.06 wt.% NaCl solution at an applied potential of  $-1200 \text{ mV}_{\text{Ag/AgCl}}$ .

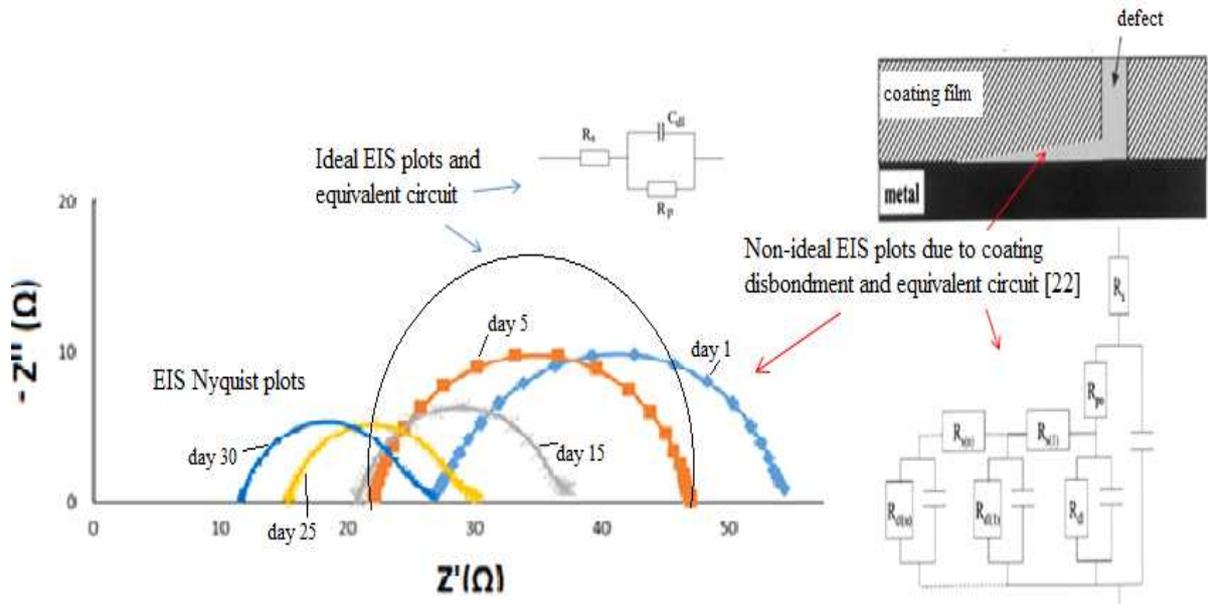
that provided additional shielding could be responsible for this behaviour. More details on this new sensor are presented in another 19<sup>th</sup> International Corrosion Congress paper<sup>[20]</sup>.

Corrosion sensors such as the one shown in Fig. 2 could be a component of a comprehensive pipeline management tool that enables the prediction of remnant pipeline life and the warning of unexpected pipeline damage. 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, such as non-piggable pipeline and high risk pipeline sections. 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.

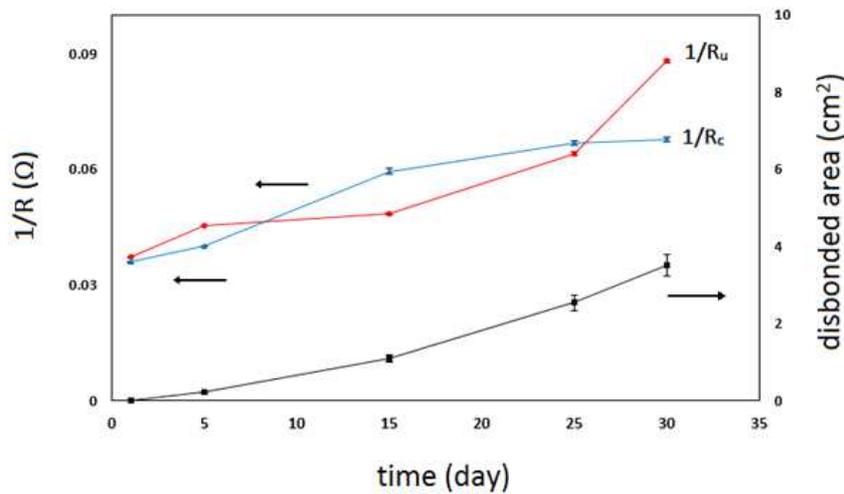
### 3. Developing Techniques for Testing and Monitoring Pipeline Coatings

The first and most vital 'line of defence' against pipeline corrosion and degradation is probably the protective coating. Pipeline coating failure has been identified as the area where the most energy pipeline issues have been found<sup>[21]</sup>. Currently the failure of field joint coatings (FJCs) is responsible for the majority of corrosion issues in some pipelines although the FJCs may represent only 5% of the coated area in a pipeline system. The impact of inappropriate selection of coatings may culminate in cracking of coatings under mechanical strain in hydrostatic test-

ing and pipe bending, as well as coating disbondment under excessively negative cathodic protection voltage. Traditionally the DCVG is a survey method for detecting defects in the pipeline coating. It is based on the measurement of the potential difference between two reference electrodes placed at a constant distance. It can be performed simultaneously with the CIPS (hybrid surveys). At the coating holiday locations, due to the lack of a coating acting as a barrier the protective current density increases leading to uneven distribution of current and IR drops. The DCVG method detects these IR drop gradients. While this method is a very effective tool to locate coating defects, no general relationship between the potentials measured and the defect size could be made. The IR drop measured at each area is affected by many other factors in addition to the defect. Other important limitation of these surveys is that they cannot distinguish disbonded coatings from intact coatings. This is due to the fact that in the case of disbonded coatings, the protective current is shielded by the coating film. Developing sensors for monitoring coating degradation, disbondment and local damages is therefore desirable. One of our recent developments is shown in Fig. 2. Another development is coating assessment based on EIS measurements under CP in a standard three-electrode flat cell (PAR). As shown in Fig. 4, the presence of a scratch in epoxy coating caused a significant decrease in impedance value (a drop of 2-4 orders of magnitudes). These results indicate that EIS can be carried out under cathodic protection in highly resistive media and that EIS data could be used to detect coating



**Fig. 5.** A complex equivalent circuit proposed to fit the ‘non-ideal’ EIS plots measured from electrode with a disbonded coating<sup>22</sup>, and a typical set of EIS data obtained after different periods of cathodic disbondment testing using a flat cell, incorporating an Ag/AgCl reference electrode and a titanium mesh counter electrode.



**Fig. 6.** Correlation between charge transfer and uncompensated resistances and disbonded area against time for coated steel during 30 days exposure under  $-1.4 V_{Ag/AgCl}$  CP potential.

damage under simulated energy pipeline cathodic protection conditions.

Another closely related area of application of the EIS method is for simulating and measuring the cathodic disbondment of thick pipeline coating (usually over 500  $\mu m$  in thickness). EIS tests were carried out under applied CP potential conditions. In a typical experiment a sinusoidal potential wave at applied CP potentials ( $-760 mV_{Ag/AgCl}$  or  $-1200 mV_{Ag/AgCl}$ ) with an amplitude of 10 mV was applied to a coated specimen with an artificial defect. Impedance response was measured over frequen-

cies between  $10^5$  Hz to  $10^{-2}$  Hz, recording 10 points per decade of frequency. The most critical step of using EIS is the extraction of useful information from EIS diagrams. An equivalent circuit such as the one shown in Fig. 5 is needed to fit the non-ideal EIS plots measured from our experiments in order to extracting useful information related to coating disbondment. By carrying out EIS analysis using the complex equivalent circuit, various parameters including solution resistance ( $R_s$ ), coating capacitance ( $C_c$ ), double layer capacitance ( $C_{dl}$ ), polarisation resistance ( $R_p$ ), pore resistance ( $R_{po}$ ), could be determined. These

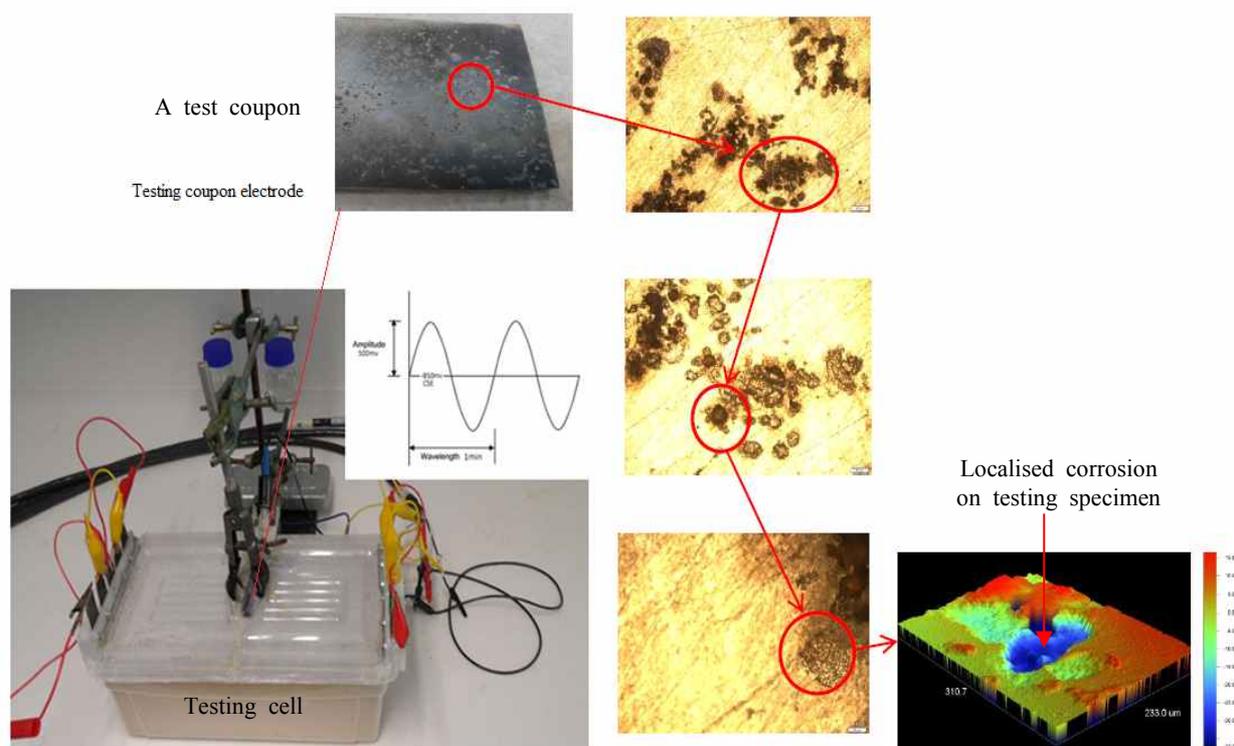
electrochemical parameters could be correlated to coating disbondment that can be determined based on observation of electrode surface. A typical correlation between electrochemical measurement and coating disbondment observation is shown in Fig. 6. Correlation shown in Fig. 6 suggests that EIS analysis could provide *in-situ* information on the processes of cathodic disbondment occurring at the interface of coating and steel pipeline. A further progress in this research is the combined use of the EIS and the array electrode that could provide more detailed spatial and temporal information regarding coating disbondment processes. Therefore EIS has the potential of monitoring coating disbondment in the field. Results from this latest development will be reported elsewhere.

#### 4. Developing Methodologies for Quantifying the Effects of CP Excursions

Excursions from the standard CP potential (e.g.  $-850 \text{ mV}_{\text{CSE}}$ ) due to stray current, traction and telluric influences are observed and measured rather frequently on pipelines. These external interference signals are considered to be stochastic in their nature (i.e. the magnitude, duration, timing are all random). It has been shown that CP excursions can be over a huge potential range, for instance  $+5 \text{ V}_{\text{CSE}}$  to  $-18 \text{ V}_{\text{CSE}}$ <sup>23)</sup>. Such excursions shift CP potential significantly away from the standard 'safe' CP potential of  $-850 \text{ mV}_{\text{CSE}}$ . It is known that such CP potential excursions can affect CP efficiency; however currently there is no consensus on how 'big' they, either in magnitude, length or frequency, need to be to warrant a major pipeline durability hazard. This uncertainty has caused difficulties in selecting CP parameters in industry standards. Although significant effort has been made to systematically categorise and quantify the level and nature of damage of pipeline as a result of CP excursions, there are still major difficulties in drawing decisive conclusions because of the complexity of the electrochemical corrosion processes occurring at the complicated soil/buried steel interface. A major difficulty in stray current corrosion research is the lack of reliable and reproducible experimental methodologies that are able to systematically categorise and quantify the level and nature of damage as a result of various modes of CP excursions<sup>24)</sup>. Given the large number of variables, it is an important task to develop and adopt suitable research methodologies and strategies.

Our strategy to systematically categorise and quantify the level and nature of damage as a result of various modes of CP excursions is to conduct several different types of

complementary tests and computational modelling. Major effort has been made to develop an aqueous cell that could improve experimental control and address issues associated with experiment reproducibility. This is an important step towards overcoming ambiguities in CP excursions test results; however initial trial using an aqueous corrosion cell was not successful, because of the mixing up of  $\text{OH}^-$  and  $\text{H}^+$  ions from anodic and cathodic reactions, and failure of simulating true high pH conditions over CP protected surfaces. In order to better simulate the pH environment on steel surface, a novel electrochemical cell has been designed by utilising an electrolyte that mimics the high resistivity of soil and an ion selective membrane that separates the electrolytes in the anodic and cathodic zones. The membrane avoids pH changes due to the mixing of solutions from the anodic and cathodic zones, while maintaining conductivity to ions in the electrochemical cell. The improved experimental method exhibited expected CP behaviour with high pH value recorded in the cathodic zones and lower pH recorded in the anodic zones. This experimental setup was further enhanced by improving uniform current distribution using multiple CP anodes. Electrolytes of  $1000 \text{ ohm-cm}$  resistivity have been selected as 'baseline' moderate corrosive media which are appropriate for completing accelerated corrosion tests in a relatively short period of time. The predesigned 'baseline' CP excursion signals are  $\pm 250 \text{ mV}$  sine wave superimposed on the standard CP potential of  $-850 \text{ V}_{\text{CSE}}$  with 1 cycle per minute. It has been shown that this new corrosion cell is able to simulate the conductivity, pH and CP excursion conditions over a bare pipeline surface. It also enables *in-situ* observation of accelerated corrosion processes and patterns, and the correlation of corrosion behaviour with different forms of potential excursions over various experimental periods. Steel corrosion as a result of several selected forms of CP excursions has been categorised and quantified using this aqueous corrosion cell under simulated energy pipeline environmental and cathodic protection conditions. Corrosion pattern and rates were found to change significantly with varying CP excursions signal amplitudes ( $\pm 250 \text{ mV}$  and  $\pm 500 \text{ mV}$ ), CP potential levels ( $-850 \text{ mV}_{\text{CSE}}$  and  $-900 \text{ mV}_{\text{CSE}}$ ) and pH conditions. Faraday law calculation and surface profile analysis has been adopted as methods for corrosion analysis. It is clear that localised corrosion rates are much higher than general corrosion rates. Corrosion rate results from surface profilometry analysis and from Faraday's law calculation are similar in most cases if only general corrosion rates on general surface area are considered. Details on this new aqueous testing cell have been presented elsewhere<sup>25)</sup>. Although the aqueous corrosion cell test is very useful



**Fig. 7.** A new sand box electrochemical cell designed and applied to categorise and quantify the level and nature of damage as a result of various modes of CP excursions. A coupon after 15 days test in the soil sand box electrochemical cell.

in fundamental research of stray current corrosion, eventually it does not fully simulate soil and field conditions, especially the pH and oxygen and ions diffusion conditions. Therefore experiments have been further extended from an aqueous corrosion cell to a sand corrosion cell and huge sand boxes. Various forms of soil and clay cells have been designed in order to achieve upscale of the lab testing of pipes subjected to CP excursions in buried environmental conditions. A typical sandy soil cell experimental setup is shown in Fig. 7. The medium in the soil test was 1000 ohm.cm sandy soil. The resistivity was adjusted by a 0.5 mol/L NaCl solution. The whole cell was sealed to preventing evaporation during the experiment period. The testing cell parameters are the same as the aqueous cell, except that no membrane was needed in this sandy soil cell. In a typical test, a pre-designed interference signal of  $\pm 500$  mV on CP  $-850$  mV<sub>CSE</sub> was applied to a steel specimen, after a constant CP of  $-850$  mV<sub>CSE</sub> was applied to it for 24 hours. After 15 days test in the sandy soil cell, as shown in Fig. 7, localised corrosion occurred on the coupon surface. Our test results suggest that pH condition over a simulated pipeline surface is critical in corrosion behaviour. Under high pH conditions, the steel coupon surfaces were passive. Although

this passive film can reduce general metal dissolution, it can lead to localised corrosion when a large interference signal, e.g.  $\pm 500$  mV, was imposed on the steel surface. This result also suggests that the aqueous corrosion cell could only mimic several features of the sandy soil cell. Therefore our current tests are carried out in both aqueous and soil cells to take advantage of both testing cells.

## 5. Summary

Currently there is a lack of technological capability for pipeline engineers to monitor and capture 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, (i) to systematically categorise and quantify the level and nature of damage of pipeline as a result of the combined effects of coating failure, ineffective cathodic protection (CP), nonuniform mechanical strain, and complex electrochemical and environmental conditions; and (ii) to develop 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. A pipeline condition monitoring tool is therefore developed for *in-situ* monitoring and warning of unexpected pipeline damage. The principle of this pipeline condition monitoring tool is that 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, 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.

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