Infrastructural health monitoring using corrosion sensors: past, present and future

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INFRASTRUCTURAL HEALTH MONITORING USING CORROSION SENSORS: PAST, PRESENT AND FUTURE

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SUMMARY: Infrastructural health monitoring (IHM) using corrosion sensors (or probes) is a practical approach to enhancing the safety, durability and economic operation of industrial and civil infrastructures such as underground and submerged oil and gas pipelines. A well designed IHM system is capable of acquiring in-situ and site-specific corrosion data, facilitating early detection and warning of corrosion damage, forecasting and prioritising site inspection and maintenance requirements. The need for IHM is particularly apparent when developing life extension strategies for older infrastructures. Unfortunately the application of corrosion sensors is not always successful, in particular when corrosion sensors are used for monitoring corrosion of infrastructures exposed to complex environmental conditions. This paper aims to provide a brief historical view of corrosion monitoring sensors, and discuss issues and limitations of major forms of corrosion sensors. It is shown that currently the prime challenge in corrosion monitoring is difficulties in simulating and evaluating localised corrosion mechanisms, especially when corrosion mechanisms change with time. Discussion has been extended to future development needs for enhancing the reliability and trustworthiness of corrosion monitoring sensors. Cases have been presented to illustrate potential future corrosion sensor applications with improved design and installation methods as well as with new big data based IHM information technology platforms.

Keywords: Structure health monitoring, pipeline corrosion, corrosion monitoring, corrosion probe

1. INTRODUCTION
Infrastructural health monitoring (IHM) is the application of structural health monitoring technologies to industrial and civil infrastructures such as pipelines and bridges that are vital for the provision of the nation’s essential services and the maintenance of its economic activities. Compared to all-purpose structural health monitoring that covers a wide range of structures such as aircrafts, IHM focuses on the application of sensors to perform in-situ, continuous or regular measurement and analysis of key structural and environmental parameters under infrastructural operating conditions for the purpose of warning impending abnormal states or accidents at an early stage and giving maintenance and rehabilitation advice [1]. A typical IHM system includes three major components: a sensor system for data acquisition; a data transmission, storage, mining system for feature extraction and extraction; and a health evaluation system for decision-making based on identified features in combination with identified models [2]. The first step of cultivating an IHM system for a particular infrastructure is usually the identification of major structural integrity, durability and reliability concerns, followed by the selection of sensors or probes that are able to collect data/parameters related to these concerns. Over the past decades, many specialised sensors or probes, such as fibre optic sensors, piezoelectric actuators, vibration sensors, leakage detecting sensors, pressure, flow, and seismic sensors and corrosion detection sensors/probes have been developed and utilised in many infrastructural systems for monitoring various structural and environmental parameters such as stress, displacement, acceleration, wind speed, temperature, corrosion etc. IHM was originated mainly from major bridges, probably due to high awareness of the economic and social effects of aging, deterioration and extreme events on civil infrastructures [3,4]. In the case of long-span bridges, for instance, major concerns are often wind load, temperature, traffic load, geometric configuration, strain, and global dynamic characteristics, therefore sensors selected to be installed on bridges are often anemometers, temperature, strain and accelerometer sensors [4,5]. In the case of underground and submerged oil and gas pipelines, corrosion is usually among the major structural integrity concerns because of the corrosive environmental condition and the relatively poor corrosion resistance of steel pipelines. Corrosion sensors or
Corrosion sensors are usually referred to as devices such as a fibre optic corrosion sensor that detect certain external stimuli and respond in a distinctive manner, while corrosion probes such as electrochemical corrosion probes could be described as devices that generate and detect internal changes in the probe exposed to a corrosive media. The difference between sensors and probes is often not clear, and therefore ‘sensor’ is used as a general term in this paper for describing data acquisition devices in IHM systems. An IHM system with suitable corrosion sensors, if used properly, should be able to provide in-situ and site-specific corrosion information for the early warning of structural failure and for infrastructural life prediction. However currently the fact is that successful application of corrosion monitoring sensors in complex infrastructural systems has been actually limited despite of the fact that major corrosion induced accidents are frequently reported around the world [6-9] and the fact that smart sensors have been identified as a critical national need for infrastructure transformational research in the United States [10]. This paper presents a brief review of past and current corrosion sensor techniques used for infrastructure health monitoring in order to identify weaknesses in current IHM systems and forecast future development needs. Particular focus is on difficulties, challenges and limitations in current corrosion sensor application in oil and gas pipeline systems. The main purpose is to find ways that IHM could contribute much more significantly to the management of infrastructure assets especially ‘invisible’ underground and offshore infrastructures.

2. A HISTORICAL VIEW OF CORROSION MONITORING SENSORS

The lack of visibility of corrosion and material degradation processes, especially localised forms of corrosion, occurring on ‘invisible’ infrastructures is believed to be a major contributor to corrosion induced gas pipeline explosion and oil spill accidents [6,7,10,11]. Traditionally historical inspection data are used as the main source of information for forecasting the degradation and service lives of buried pipelines. Industries such as oil and gas pipeline industry collect corrosion and materials degradation data through survey and inspection using methods such as field excavation, DCVG and in-line inspection tools (intelligent pigs, i.e. pipeline inspection gauges). These methods are expensive (e.g. pigging of a pipeline can cost $1million or more). These historical survey and inspection data are often used with asset management tools that are usually computer software developed based on probabilistic models. The hypothesis behind these models is that statistical analysis of historical survey and inspection data could allow for structural lifetime assessment and prediction. For instance Li et al. [12] used a Monte Carlo simulation technique to calculate the remaining life of a structure. Lee et al. [13] presented an intelligent failure prediction system for oil and gas structure using an Euclidean-Support Vector Machines classification approach. Senouci et al. [14] developed a fuzzy-based model to predict the failure type of oil pipelines using historical data of pipeline accidents. Peng et al. [15] 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 tools are useful in providing an overall assessment of the aging of a structure; however the success of these tools is heavily dependent upon the availability and reliability of structural condition data. Unfortunately high quality and timely data are often not available because time based routine inspections using various condition assessment tools are performed only on a periodic basis (e.g. pigging are usually done only once every 5-15 years). Another issue is that these asset management tools are often not suitable for infrastructural systems that are under localised corrosion attack and that are under the effect of dynamically changing environmental conditions.

A practical approach to acquiring in-situ and site-specific corrosion data from ‘invisible’ infrastructures is using various corrosion monitoring sensors. Over the past decades, many corrosion monitoring techniques have been developed. They can be generally divided into two distinct groups: off-line ‘retrospective’ techniques that detect cumulative corrosion damage; and on-line ‘instantaneous’ techniques that continuously measure the prevailing corrosion rates. The most widely applied retrospective corrosion monitoring/testing techniques include weight loss coupon, ultrasonic thickness measurement, radiography, electrical resistance probe, field signature method, and non-destructive inspection ‘pigs’. A summary of these techniques can be found in references [16,17].

Weight loss coupon testing is the simplest and most widely used corrosion testing and monitoring method. A metal coupon of known metallurgy, size, shape and weight is exposed to a corrosive environment and is inspected for corrosion after a period of time (e.g. every 90 days). Corroded coupons are subjected to visual and optical or microscopic examination, and measurement of weight loss due to corrosion. Corrosion products may be analysed by methods such as SEM, EDAX, XRD and infrared or Raman spectroscopy. Corrosion coupons are an excellent source of corrosion information if monitoring is continuously maintained and results are well accumulated and documented. However corrosion coupon tests have well-known limitations: they are considered to be offline, labour intensive, and not easily configured for automation and control systems. They require long exposure period to generate field test results and during this period corrosion may have already occurred to an industrial structure. They require periodic removal of test specimen from the corrosive environment which is cumbersome and may alter the progress of localised corrosion. They only detect the cumulative corrosion damage at the end of the exposure period and provide little information on specific events that may have triggered this damage. Although corrosion coupon test appears to be an easy task, there are in fact problems that often lead to unsuccessful and misleading results. For instance in the oil and gas pipeline, corrosion coupon tests were found fail to produce corrosion rate values comparable to actual pipe wall loss due to their misplacement [18].
A major challenge in corrosion coupon testing is to overcome difficulties in simulating true localised corrosion conditions and mechanisms. For instance, if a test interval of 30 days is selected for corrosion coupon tests in an oil and gas pipeline, it may lead to reporting of falsely high corrosion rates since this short exposure test may overlook changing corrosion mechanism with the formation of a protective deposit, which is vital to the ongoing corrosion behaviour of the pipeline. This short term test may also fail to detect any localised corrosion that requires an initiation period. Extension of the coupon test to 90 days may overcome some of these problems; however a 90 day test may still be far too short for microbiological build-up that often leads to localised biological corrosion in actual piping systems. Thus, a detailed understanding of the corrosion mechanism is essential for selecting appropriate coupon test parameters and durations. Another challenge in corrosion coupon test is difficulties in detecting galvanic corrosion and crevice corrosion. In an oil pipeline, for instance, corrosion coupons are typically isolated from the pipe surface; they are unable to detect galvanic corrosion effects due to the formation of a large cathodic layer of iron carbide or iron oxide on the pipe surface. As a result, a major localised corrosion mechanism responsible for a significant amount of metal loss in most piping systems is not measured. On the other hand, the corrosion coupon test is also unable to simulate or detect crevice corrosion such as underdeposit corrosion which occurs in some oil flowlines. These cases have been discussed previously in reference [17].

Electrical resistance (ER) probe is often referred to as an ‘intelligent’ weight-loss coupon test. The ER probe monitoring corrosion by measuring the electrical resistance of a thin metal test wire (sensor element) since the resistance of the wire increases as the wire becomes thinner due to corrosion dissolution. ER corrosion monitoring has been applied in industry to provide an indicator of environmental corrosivity for more than four decades. An advantage of ER probe is that it provides cumulative metal loss values without the need to remove the samples from the service environment. Another advantage of ER probes is that the technique is applicable to both conductive and non-conductive corrosion environments. A major disadvantage of the ER technique is that it is unable to detect localised corrosion since localised corrosion may neither lead to significant metal dissolution, nor noticeable change in electric resistance. It also has similar limitations as corrosion coupon tests in simulating the localised corrosion mechanisms. ER measurements generally do not respond rapidly to a change in corrosive conditions, and it was reported to take four days to respond to 1 mpy corrosion rate in the internal corrosion monitoring of subsea oil and gas production equipment [19]. Field signature method (FSM) is also considered to be a cumulative corrosion monitoring technique developed from the commonly used principle of electrical resistance determination. FSM impress a current through several electrodes (sensing pins) on the outer surface of a pipeline and the potential drops between these electrodes are measured. The sensing pins are typically separated by a distance of 2-3 times wall thickness. Changes in the geometry in the form of cracks, general corrosion, erosion corrosion, or pitting will disturb the potential field in the metal. The change in the measured potential field pattern is related to a change in pipe wall thickness, and thus the development of corrosion or cracks can be detected. The FSM technique is non-intrusive and is used to measure corrosion damage over a relatively large section of a structure. Possible limitations of the technique include its relatively slow response to corrosion. It was reported to take one year to respond to 1 mpy corrosion rate [19].

Physics based corrosion assessment methods are also retrospective in nature. Ultrasonic testing utilises high frequency sonic waves that transverse the thickness of a specimen and return to the probe to determine the thickness of the specimen. Ultrasonic probes are widely used for field inspection of cracks and corrosion damage. If sufficient numbers of test points are taken over a wide enough range, it can provide reliable corrosion inspection data. Automatic ultrasonic scanning and recording techniques combined with computer techniques are also able to produce three-dimensional maps of the corroded surface. The technique responds relatively slowly to corrosion, however, and it was reported to take four years to respond to 1 mpy corrosion rate [19]. Radiography makes use of the penetrating quality of short wave electromagnetic beams to image corrosion and to determine pit depths and the degree of thinning due to corrosion. Radiography is limited to detect narrow cracks that is oriented in directions other than parallel to the electromagnetic beams. Techniques such as eddy current are used to visualise initial cracks caused by stress corrosion or corrosion fatigue. Eddy current technique detects surface cracks, pits or other defects by measuring disturbed eddy currents on a material surface. Based on these techniques and their combination, equipment known as a ‘pig’ has been developed for internal examination of pipes and tubes. The ‘pig’ follows the flowing medium in the pipeline and records corrosion related data for analysis after it is removed from the pipe. A disadvantage of pipeline inspection using the ‘pigs’ is that they are very expensive (e.g. pigging of a pipeline can cost $1 million or more) and disruptive.

Although these cumulative corrosion monitoring techniques are obviously very useful in corrosion inspection; they are able to detect corrosion only when sufficient corrosion has occurred to cause an accumulated change in the bulk material properties. For this reason the response time for these techniques is usually undesirably long. They are used only to provide off-line average corrosion data over a rather long interval of weeks, months or sometimes years. Field corrosion inspections occur relatively infrequently, usually coinciding with routine shutdown and maintenance. Peak corrosion rates are usually not detected and, most importantly, the specific time periods of peak corrosion rates are not identified. Another obvious limitation of these techniques is practical difficulties of knowing the location of corrosion damage prior to the assessment. These locations could be estimated through engineering analysis, however with the increasing complexity of industrial structures such as multi-phase oil and gas flowlines and buried pipelines, the potential damage locations are not known or are too numerous to be economically inspected using these damage detection techniques.

Corrosion rates always change with time and corrosion can accelerate rapidly and grow exponentially once initiated, and thus it is important to identify the specific time periods and environment conditions of peak corrosion rates. For this reason on-line ‘instantaneous’ techniques are important to continuously measure the prevailing corrosion rates and provide...
quantitative data for use as a process variable for integrated corrosion management systems. Instantaneous corrosion testing and monitoring techniques are usually electrochemical in nature. They include corrosion potential measurement, potentiodynamic polarisation, linear polarisation resistance (LPR), electrochemical impedance spectroscopy (EIS), electrochemical noise analysis (ENA) and many others. Electrochemical techniques rely on electrochemical corrosion theory and the measurement of electrochemical potentials and currents that are fundamentally related to the thermodynamics and kinetics of corrosion reactions. Electrochemical corrosion testing and monitoring can be fast, sensitive and versatile. Modern electrochemical instruments can measure very low corrosion rates, if properly used accurate corrosion measurements can be made in a matter of minutes in most industrial processes [20].

Corrosion potential can be easily measured by recording the potential difference between a corroding electrode and a stable reference electrode. It can be used in conjunction with Pourbaix diagrams as a basic indicator of corrosion thermodynamic status, for instance, to predict active or passive behaviour. Corrosion potential monitoring is often useful in understanding cathodic protection, anodic protection, general corrosion and stray current corrosion problems. Unfortunately the corrosion potential value on its own does not provide information on the rate of corrosion. The LPR and EIS techniques are employed to measure corrosion rates using the Stern and Geary equation and have been discussed in numerous publications. Although LPR is useful in determining corrosion kinetics, care should be taken since this technique is accurate only under several fundamental assumptions. In principle, it only applies to a uniform corrosion system with a stable corrosion potential. The corrosion process should involve only one anodic and one cathodic reaction, with both under activation control. The Tafel constants should be known, and there should be only negligible solution resistance. For this reason, application of LPR to practical corrosion systems often provides only semi-quantitative corrosion data with variable accuracy. EIS can be used as an alternative technique for determining polarisation resistance. It has some advantages in measuring corrosion under organic coatings and in studying corrosion inhibition mechanisms, for instance, it has been used to study the formation and destruction of corrosion inhibitor films and corrosion scales under simulated oil and gas production environment [21-23]. ENA can also be used to determine polarisation resistance [24-28], although the prime attraction of ENA is its possibility of early detection and warning of localised corrosion by detecting ‘noise signatures’ [29,30]. For instance, it has been used to monitor the formation and destruction of corrosion inhibitor films [28]. The noise resistance measurement has the advantage that there is no need to apply a perturbation to the test system by an externally imposed polarisation, and the instrumental system is simple. The noise signatures method was proposed to detect localised corrosion by recognising characteristic noise patterns (often referred to as noise signatures) in the time domain [29] or in the frequency domain [30]. Although some controversial issues still exist in the interpretation of electrochemical noise data, electrochemical noise has been recognised to be a rich source of information on the corrosion process and localised corrosion. For instance, the noise signatures are well recognised to be valuable indicators of localised breakdown of passive film, the incubation, initiation, propagation and repassivation processes of localised corrosion [31]. However, it should be noted that quantitative analysis of localised corrosion using ENA parameters such as pitting factor remain controversial and requires further development. Although electrochemical techniques such as LPR, EIS and ENA have been widely used in estimating the rates of general or uniform corrosion, they have major limitation in measuring localised corrosion. In fact, conventional electrochemical corrosion testing techniques have major limitations in measuring localised forms of corrosion, which is responsible for some 70-90% of all corrosion failures.

It should be pointed out that limitations and problems associated with corrosion testing and monitoring have also been frequently reported in the literature [32-38]. For instance, Srinivasan and Kane [32,33] reported poor correlations between actual corrosion behaviour of gas wells in the Gulf Coast region and the North Sea and corrosion monitoring data obtained from various techniques including iron counts, caliper surveys, down-hole mounted coupons, radioactive sleeves, electrical corrosion probes and inspection of pulled tubing. They found that actual pitting rates were between 2 and 15 times the general corrosion rates monitored for various cases, and in some cases the differences in corrosion rates obtained using different techniques varied by an order of magnitude in value. Papavinasam et al [34,35] also reported significant concerns on some testing methodologies for evaluating corrosion inhibitors for oil and gas pipeline applications. On the other hand, Tan et al. [36-38] analysed fundamental limitations in some electrochemical methods, especially in the measurement of localised corrosion. These reports confirm difficulties and complexities in accurate corrosion measurement and monitoring using corrosion sensors.

Various designed corrosion sensors have been developed and applied in various industry applications including those reviewed by Varela et al.[39] on corrosion monitoring techniques designed for the pipeline industry. A common weakness in corrosion sensor application is that principles and issues associated with the practical application of these sensors are often not sufficiently examined and corrosion sensors are not always used successfully in the industry. In some cases corrosion sensors are used with an expectation of monitoring corrosion in a similar manner as using a thermometer to measure temperature. Inevitably these practices could lead to confusing and misleading results, and consequently successful application of corrosion monitoring in complex systems such as buried oil and gas pipelines has been limited.

3. RECENT PROGRESSES IN CORROSION MONITORING SENSORS

Extensive research has been carried out to enable the capability of corrosion monitoring sensors in monitoring localised corrosion attacks in complex environmental conditions such as in highly resistive and inhomogeneous soil media and under the effect of dynamically changing environmental conditions. This has been proven challenging because localised...
Corrosion rapidly attacks a small portion of a metallic structure as the result of fast local electrochemical dissolution. Conventional corrosion sensors such as resistance probes and LPR probes have difficulties in measuring local electrochemical dissolution. Localised corrosion remains one of the most common causes of pre-mature infrastructure failure and a major unsolved issue in corrosion science, and it is believed to be a fundamental factor contributing to the lack of predictability of infrastructure failure. A rational approach to preventing unexpected pre-mature failure of critical infrastructures is to monitor the initiation and propagation of localised corrosion using sensors.

A successful IHM system using corrosion sensors should be able to detect data related to a targeted critical corrosion mechanism in order to determine the effects of corrosion mechanisms (e.g. corrosion under sand deposits, pitting, and crevice corrosion) on corrosion kinetics and patterns. A basic principle that could underpin the use of corrosion sensors is that corrosion and materials failure are not accidental occurrences, they occur as the result of fundamental thermodynamic instability of a metal or a material in a specific environment. Therefore corrosion and materials failure occurring on a structure such as a pipeline would also occur on a sensor made of the same material and exposed to the same condition. A properly designed sensor and measurement method should be able to detect such thermodynamic instability and reaction kinetics from the sensor, and therefore facilitate the monitoring and prediction of corrosion. However this applies to localised corrosion only if the sensor surface effectively simulates a local corrosion mechanism occurring on the corroding infrastructure surface. It is important to correctly simulate a true corrosion mechanism because the corrosion severity and pattern is often determined by the corrosion mechanism, especially localised form of corrosion mechanism. For this reason, sufficient attention should be given to the understanding of localised corrosion mechanism, the possibility of corrosion mechanism change, and possible transitions from general to localised corrosion. This is a major challenge since designing or selecting sensors that are able to simulate a complicated corrosion mechanism in a particular environment-material combination is often difficult. This challenge is more acute when corrosion is affected by many inter-related variables such as non-uniform temperature and pressure, heterogeneous metallurgy, inhomogeneous soil or solution chemistry and thermo-mechanical conditions, local mechanical stress, soil and water composition, oxygen level, humidity, salinity, pH, temperature, stray currents, and biological organisms, as well as stray currents, coating defects, coating disbondment and cathodic shielding.

Over the past decade there are various research and development effort for developing corrosion sensors to monitor localised corrosion due to the interaction of local environment and materials. As examples, several electrochemical sensor have been developed based on an electrochemically integrated multi-electrode array known as the wire beam electrode (WBE) [16,17,36-38]. The WBE was initially developed to detect and monitor local defects in organic coating films [39]. Its application has later been extended into the study of localised corrosion including crevice corrosion [40], water-line corrosion [36] and localised carbon dioxide corrosion in an oil flowline [41,42]. Two important characteristic of the WBE method that are particularly valuable for the investigation of pipeline corrosion are, (i) WBE is applicable to high resistance underground or multi-phase pipeline environment, which has been demonstrated in a previous study [42,43]; (ii) WBE can map corrosion processes on an instantaneous and continuous basis [44]. In order to achieve the highest possible sensitivity of detecting early signs of localised corrosion, the WBE can be used in conjunction with electrochemical noise analysis since ENA has the advantage of providing early warning of localised corrosion initiation. The combined WBE-ENA technique is capable not only of measuring the corrosivity of the environment and the rates of corrosion, but also detecting the occurrence of localised corrosion well before localised corrosion becomes visible [37]. The WBE has also been used in various corrosion research [45-49]. Here we describe several localised corrosion sensor designs to illustrate current status of corrosion monitoring sensor development. The capability of the electrode array based corrosion probes in detecting the initiation and propagation of localised corrosion and coating failure is illustrated in these cases.

**Case study: Designing a sensor for monitoring underdeposit corrosion (UDC)**
The challenge of simulating and measuring complex localised corrosion mechanism is achievable. This can be illustrated by a practical case of developing a corrosion sensor for monitoring evaluating the performance of underdeposit carbon dioxide corrosion inhibitors under simulated oil flowline conditions [50]. Corrosion inhibitors are used to prevent internal oil pipeline failure due to pitting and mesa corrosion under solid deposits such as sand and biofilms. A problem is that the efficiency of corrosion inhibitors is often unquantified in the field because it is considered to be nearly impossible to assess by normal corrosion testing techniques [51]. Underdeposit carbon dioxide corrosion is believed to be controlled by factors including galvanic effects between a large cathode (structure surface) and a small anode (surface under deposits), failure of inhibitors to penetrate the deposits and the retention of aggressive species in the deposits. A corrosion sensor should effectively simulate these controlling factors and measure their effects on corrosion rates and patterns. Tan *et al* [50] designed a corrosion monitoring sensor based on the WBE, where the WBE working surface was partially covered with a rubber ‘O’ shaped ring filled with sand to simulate a localised underdeposit corrosion environment. This partially covered WBE becomes a new sensor that effectively measured and monitored very different corrosion behaviour in a CO₂ saturated brine environment with and without the presence of corrosion inhibitor imidazoline. This case clearly illustrates the successful detection of complex underdeposit corrosion and the effects of inhibitors.

**Case study: Designing a sensor for monitoring dynamic corrosion under anodic stray currents**
An electrochemically integrated multi-electrode array based sensor has also been designed to facilitate the in-situ monitoring and visualisation of electrochemical processes occurring on buried steel surfaces under cathodic protection (CP) and anodic transient conditions [52]. The WBE method has been applied for the first time as a new sensor for detecting...
localised corrosion initiation under various dynamic anodic transient influences. More details on the sensor design and data analysis methods can be found elsewhere [52]. This corrosion sensor worked under CP has enabled significant progress to systematically categorise and quantify the level and nature of damage of pipeline as a result of CP excursions. A common phenomenon that was observed from these sensors is that shortly after an anodic transient was applied to a CP protected steel surface, anodic current and corrosion activity dropped dramatically from an initial anodic current peak value. This has been explained by the passivity of steel under CP induced high pH condition. Another phenomenon observed by inspecting the occurrence of local anodic currents in WBE maps was that localised corrosion initiation occurred after a critical duration. This critical duration could be explained by the breakdown of passivity under the effects of anodic transient induced pH and surface chemistry changes. This work suggests that the WBE sensor can be used as an effective tool for studying localised corrosion initiation under the effect of complex factors, as well as for the in-situ monitoring of stray current corrosion of buried steel structures [52].

**Case study: Designing a sensor for monitoring coating cathodic disbondment under overprotection**

Cathodic disbondment is a major form of electrochemically induced coating failure that frequently takes place at the metal/coating interface on cathodically protected steel infrastructure such as pipelines. Extensive research over the past decades has developed good understanding of the phenomenon, however currently there is no technique that can be used to perform in-situ monitoring of its occurrence in the field. Traditional methods of evaluating cathodic disbondment of pipeline coatings are based on ex-situ visual inspection of excavated pipes. The electrode array has been designed as a probe for monitoring and evaluating the cathodic disbondment of defective coatings [53]. It is illustrated that local electrochemical impedance measurements using an electrode array sensor have significantly improved sensitivity for monitoring the propagation of cathodic disbondment of defective coatings compared with the conventional overall electrochemical impedance and local current measurements approaches. This new approach also provides the opportunity of eliminating the effects of the low impedance coating defect regions on the visibility of higher impedance regions deep in the disbond coating, facilitating the probing of electrode processes and mechanisms in selected regions of heterogeneous electrode surfaces.

**Case study: Designing a sensor for monitoring of localised corrosion processes under disbonded coatings**

A new sensor [54-56] has also been designed to monitor the distribution of corrosion under disbonded coatings by measuring electrochemical currents over an electrode array surface partially covered by a crevice that simulates a disbonded coating. The sensor has been evaluated using immersion tests at open circuit potential (OCP) and under CP conditions. Under both OCP and CP conditions, anodic as well as cathodic current densities were detected within the crevice. Corrosion patterns were estimated based on the current density distributions from two different methods [56]. The acceptable level of correlation with the corrosion damage observed at the array surface at the end of the tests suggests that the sensor surface has the potential to monitor localised corrosion under disbonded coatings. Using sensors to simulate and detect early stages of corrosion or to measure corrosion susceptibility under disbonded coatings could provide a valuable and inexpensive means of obtaining in situ monitoring information on the health of a structure.

4. **FUTURE OUTLOOK TO CORROSION MONITORING SENSORS**

In order to make corrosion sensors more useful for IHM systems, several major weakness have to be overcome. The improper design and use of corrosion sensors that fail to simulate various corrosion mechanisms and possible changes in corrosion mechanisms with the extension of corrosion processes is a major reason that false corrosion rates and patterns are reported from corrosion monitoring. The incorrect installation and application of corrosion sensors/probes is another source of corrosion monitoring error. Another challenge is to develop or select suitable measurement and data analysis techniques that are able to detect and analyse data from corrosion sensors that contain ‘predictor features’ signifying the occurrence of corrosion and materials failure.

**Future development to enhance the reliability of corrosion sensors**

It is a highly challenging task to design reliable corrosion sensors, especially localised corrosion sensors, which are able to effectively simulate corrosion behaviour in actual service environments and reliably evaluate the effects of various factors on corrosion processes, rates and mechanisms. It is well appreciated that corrosion sensors needs to simulate the actual service exposure environment; however relatively less considerations have been given to the effects of environmental parameters on corrosion patterns and mechanisms. It is not uncommon to receive misleading test results due to inappropriate selection of testing parameters and measuring techniques. This challenge is more acute when corrosion is affected by many inter-related variables such as non-uniform temperature and pressure, heterogeneous metallurgy, inhomogeneous soil or solution chemistry and thermo-mechanical conditions, local mechanical stress, coating defects, and cathodic cathodic potential and excursions. These effects may have not yet fully quantified and need to be better understood and used in corrosion sensor design and application. In order to fully realise the advantage of corrosion sensors for providing site-specific and in-situ warning of unexpected structure failures, corrosion sensors may need to be placed at strategic and ‘worst-case scenario’ high risk locations of a structure. For a buried pipeline, for instance, typical high risk structure sites could 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 survey and historical excavations. Sensors embedded at these strategic sites can be used to collect real-time and site specific data that would contain critical ‘predictor features’ and parameters needed for modelling and predicting localised corrosion, coating disbondment and degradation.
Future development to enhance the data analysis and IF platform for IHM systems

Another development trend is a big data based IT platform for corrosion data management and analysis. Corrosion sensors should be a part of the data sources to help overcome weaknesses in asset management models. Although sensors can provide useful in-situ data from selected locations of an asset, there is a need to integrate data from limited monitoring sites into the whole database by suitable models in order to provide fuller coverage of a huge structure (e.g. a 1000km underground pipeline). An information platform would enable the integration of various data inputs and allow industry to cost effectively gather information on the in-service integrity of assets/infrastructure, gain high levels of confidence in the condition of the asset, timely maintenance, safety and continuous availability/operation of the asset. A web-based information platform that can link up multiple industries and multi-disciplinary areas of research would be extremely useful for infrastructure health monitoring, failure prediction and life extension. However such a web based information platform is complex to develop because it requires expertise from several disciplines.

Other future development needs to enhance the IHM system

For wide application of corrosion sensors based IHM system, there are needs of future developments in terms of instrumentation, data acquisition, communication systems and data mining and presentation procedures for diagnosis of infrastructural ‘health’. These have been discussed in reference [1-5] including,

1. The GPS has provided new possibilities for direct measurement of infrastructure and should be used in IHM.
2. An exhaustive cost–benefit and reliability analysis will be required to show assist infrastructure operators/owners that benefits outweigh costs and that the IHM system is reliable.
3. A better understanding of the design, implementation and early operation of the instrumentation system, as well as the quality of the instruments and their survival rate, the expected performance and critical locations in the infrastructure are needed to plan for fewer but more reliable sensors.
4. More research on optimal placement of sensors, and careful planning using scenarios of detectable degradation or damage, together with examination of similar operational SHM systems, will lead to more efficient sensor deployment.
5. Data collection, storage and communications: Wireless or land links are a necessity for remote unmanned installations; dialup modems or permanently connected leased lines may be used. Robust low-cost wireless systems play an increasing communications role but due to present limited data capacity, data compression or pre-processing will be necessary unless data are slowly sampled static signals. Successful SHM procedures should incorporate the means to compensate for or filter out the environmental and noise effects or at least establish confidence levels for anomaly detection against noise [5].
6. Data mining and information presentation: One of the most significant issues with SHM is converting data to information, an issue addressed in detail elsewhere in this set of papers. Not to be overlooked is the charting or presentation of information to operators who are very unlikely to be familiar with the sophisticated underlying numerical procedures [5].

5. CONCLUDING REMARKS

A major problem in today’s management of infrastructure assets especially ‘invisible’ underground and offshore infrastructures is the lack of information regarding corrosion and materials degradation and their effects on the safety, reliability and durability of these assets. The lack of information regarding the interaction of local environment and materials hinders our ability to provide sufficient warning and maintenance of ‘hidden’ assets. A practical approach to overcoming weaknesses in conventional corrosion and materials degradation data and asset management models is structural health monitoring using corrosion probes/sensors. Corrosion sensors, if designed, installed and used properly, are practical tools to cost effectively acquiring in-situ and site-specific corrosion data that are critical for predicting the occurrence of localised corrosion and materials failure occurring at specific high risk structure locations of infrastructures. Although there are weaknesses in existing corrosion sensors and their application practices, corrosion monitoring is a cost effective, practical and useful method for enhancing the safety, reliability and durability of civil and industry infrastructures. The principles, issues, advantages and disadvantages of corrosion sensor technologies for corrosion testing and monitoring has been briefly reviewed, with particular focus on their application in the oil and gas pipeline environmental conditions. It is found that a major challenge in corrosion monitoring is difficulties in simulating localised corrosion mechanisms. Cases have been presented to illustrate that conventional electrochemical methods have limitation in measuring localised corrosion, and that the electrochemically integrated multi-electrode arrays are considered to be able to monitor localised corrosion. Several cases have been described to illustrate the importance and difficulties of simulating and monitoring localised corrosion.

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7. AUTHOR DETAILS

Dr Mike Yongjun Tan is a Professor in Applied Electrochemistry and Corrosion Technologies at Deakin University in Australia. Dr Tan’s principal teaching and research interests are in corrosion science and engineering and their applications for enhancing the reliability and durability of civil and industrial infrastructures. His work over the past two decades spanned the range from fundamental study on issues such as electrochemical heterogeneity and passivity, and applied research on issues such as corrosion testing and monitoring, localised corrosion prediction, corrosion inhibition and anti-corrosion coatings, to industry engagement and contracted research on issues such as pitting corrosion of external and internal oil pipeline, and corrosion of desalination pipeline weldments. He is also a Research Program Leader of the Energy Pipelines Cooperative Research Centre Australia. The goal of this Coatings and Corrosion research program is to cost effectively extend the life of pipeline infrastructure by mitigating corrosion and environmentally assisted degradation of pipelines. He is the author of some 170 publications and approximately 100 industry reports todate, and a research book entitled ‘Heterogeneous Electrode Processes and Localized Corrosion’ (2013 John Wiley & Sons). He is also the Asia Pacific Editor for the Corrosion Engineering, Science and Technology (Formerly known as British Corrosion Journal, since 1965).