A Strategic Approach to Corrosion Monitoring and Corrosion Management

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Abstract

The introduction of modern corrosion surveillance instrumentation has opened the pathway for conventional practices to be updated. The application of a risk-based approach to the siting of corrosion sensors, the selection of modern instrumentation that is capable of detecting the onset and propagation of localized attack as well as uniform corrosion and instantaneous correlation of on-line corrosion with process chemistry data as well as with periodic inspection results, presents the opportunity for both the severity and the duration of attack to be minimized. This paper considers each of these aspects in detail and illustrates the future prospect of plant-wide corrosion and condition management.

1. Introduction

Established corrosion monitoring practice is based largely on the use of weight loss coupons, electrical resistance (ER) probes and linear polarization (LPR) methods [1, 2]. There is an implicit assumption that these are the only techniques available to evaluate metal loss due to corrosive conditions and that such instrumentation is the 'standard' monitoring equipment. Although the use of these techniques is well established, the design of off-the-shelf commercial instrumentation has been dominated by their use in the oil and gas production industry, primarily to demonstrate the effectiveness of chemical treatment products in as short a time as possible. Probe design was constrained as much by the necessity to utilize high pressure ('Cosasco-type') access fittings as by the technical requirements of the monitoring technique to be applied [3]. Furthermore, the technology is targeted primarily on the assessment of uniform corrosion and plain carbon steel.
In consequence, little, if any, thought is invested in thinking through why any specific location might be monitored and what the objective of monitoring might be in the first place. Coupon probes and monitoring sensors are scattered throughout the plant in the vague hope that they might detect damage. As the majority of probes provide only retrospective data, the focus of monitoring is primarily on providing an indication of how much damage has already been sustained, rather than in preventing it. Furthermore, it has been reported that approximately 70% of corrosion sustained by process plant is localized corrosion (pitting, crevice attack, stress corrosion cracking, corrosion fatigue, under-deposit attack, filiform corrosion, or fretting damage) [4]. Conventional corrosion instrumentation is incapable of detecting these phenomena, let alone providing a real-time indication of the onset or propagation of damage. More recently, the introduction of techniques such as electrochemical impedance spectroscopy (EIS), harmonic analysis (HA) and electrochemical noise (EN) measurements have revolutionized the field of on-line corrosion monitoring. Although EN analysis is arguably the most powerful of these, the technique has yet to make a full impact on practical real-time corrosion rate assessment, not least because the method of application and the quality of available instrumentation has been inconsistent. The difficulty in obtaining similar (let alone identical) results from different sources of instrumentation and/or from different users has served to undermine confidence in what should be viewed as the likely foundation of real-time condition management in static plant equipment.

2. Monitoring or Inspection?

There is considerable confusion about which activities constitute ‘monitoring’ and what is really ‘inspection’. On numerous occasions, plant personnel will report “we have a corrosion issue and we are monitoring it”, whereas what is really happening is some form of inspection – normally poorly planned and inadequately implemented. In the absence of a clear understanding of the objective, it is hardly surprising that the outcome is unsatisfactory. Inspection is the periodic evaluation of plant condition, normally by a skilled technician, to obtain a limited number of high-quality measurements. So, for example, if the plant is suffering from an excessively high rate of attack, the frequency of inspection might be increased to once every six months, where formerly the item was examined once a year, or even once every five years. By contrast, monitoring is a low-cost method of obtaining a large volume of moderate-quality measurements. The primary purpose of monitoring, therefore, should be to obtain a near real-time indication of the approximate rate of corrosion attack, with the objective of identifying transient operating conditions that may lead eventually to cumulative serious damage.

In the past, some plants have employed an ‘inspection only’ strategy, on the grounds that corrosion rate indications from on-line monitoring instrumentation are too approximate. In this situation, the plant initially obtains a very accurate indication of the actual condition of the plant item. However, it is then effectively operated blindly until the next inspection date, at which point a further high-quality indication is obtained to establish the new plant condition. In the event that no corrosion has occurred, it is assumed that operational conditions are satisfactory and the period between inspections can be extended. There are virtually no grounds for the basis of such a decision, however, as small changes in the service environment may cause a catastrophic change in the rate of attack being sustained by the plant. Conversely, it may be discovered that catastrophic damage has already been sustained. In this case, the only response is to increase the frequency of inspection, in the hope of detecting damage already being sustained before the mechanism has sufficient time to result in an unscheduled outage. It is evident, therefore, that although inspection provides a very reliable indication of actual plant condition, it does not offer any control whatsoever on the degree of damage being sustained by the plant.

The alternative is to turn to monitoring. In this case, the instrumentation should operate continuously with a minimum of operator effort to provide a continuous indication of plant condition. Typically, the accuracy of corrosion monitoring predictions of damage rates initially may not be very precise. However, the continuous flow of information enables the operator to track the approximate rate of attack. This means that it is possible to take immediate action in response to a sudden increase in corrosion rate that typically is related to an unexpected excursion in the service environment. Interestingly, minor changes in the service condition can result in a dramatic change in the rate of corrosion. However, equally minor changes to take it out of the risk condition just as rapidly. Prompt response enables both the severity and the duration of attack to be reduced, thereby delivering a significant increase in the service life of the plant with minimum interference by the operator. Furthermore, it has been shown in chemical process industry applications that timely control of this nature not only reduces the rate of corrosion
attacked sustained by the plant, but also reduces the degree of product contamination that results from corrosive
degradation of the plant construction materials [5].

Perhaps the best parallel to the use of a sensitive real-time corrosion indication is to the experience of
driving a car with a real-time indication of fuel consumption. Any person who has driven such a vehicle has surely
been appalled by the drastic decrease in the indicated fuel consumption rate as soon as they press the accelerator. At
the same time, lifting the foot from the accelerator when the vehicle is slowing down immediately produces a
similarly amazing improvement in the consumption rate. Practically, the driver does not expect either indication to
be particularly accurate. However, on checking the actual fuel consumption the next time the tank is refilled, there
is no doubt that if the driver has tried to avoid harsh use of the accelerator the fuel consumption will be reasonable,
whereas if he has been clumsy with the accelerator the evidence is clearly reflected by the speed that money
disappears from his wallet.

Thus, ‘inspection’ and ‘monitoring’ are not alternatives; they are complementary techniques that should be
applied in tandem to obtain maximum effect. Monitoring provides an easy low-cost but instantaneous prediction of
the likely overall corrosion rate. It can be used to evaluate the probable effectiveness of alternative plant operating
strategies to limit or avoid corrosion damage. Inspection is an intermittent method of obtaining a very accurate but
expensive indication of the actual condition of process equipment. It does not provide any control, but it does
enable the accuracy of the predicted rate to be improved with experience. As confidence increases in the reliability
of the monitored rate, there is a solid basis for extending the intervals between inspections without increasing the
risk of unexpected failure and consequent unplanned downtime. This issue is considered later in the context of risk
based inspection (RBI).

3. Equipment and Instrumentation

Corrosion monitoring equipment and instrumentation can be divided into two broad categories:

- Conventional Instrumentation
- Advanced Instrumentation

3.1 ‘Conventional’ Instrumentation

It was reported historically that approximately 50% of expenditure on corrosion monitoring equipment was
for access fittings. Of the other 50%, half was for weight loss coupons and half for instrumentation. Of the 25%
allocated for ‘instrumentation’, two-thirds was for ER equipment and one-third for LPR equipment (and of the one-
third related to LPR equipment, at least half was not applied correctly or was being used in an inappropriate
circumstance and that could not yield any reliable data. It should be noted that these findings related primarily to the
oil and gas production and refining industries, but the volume of sales outside those sectors was sufficiently small
that for all practical purposes it could be ignored. It should be noted that these techniques apply primarily to the
monitoring of uniform corrosion. Thus, bearing in mind the findings of the DuPont survey [4], this means that a
minimum of 70% of the corrosion monitoring market currently is not addressed at all.

It should not be concluded, however, that conventional instrumentation is necessarily outdated or of no
practical value. On the contrary, corrosion coupons are an inexpensive and simple method of obtaining a visual
indication of corrosion conditions within a vessel or pipeline. It may be questionable whether this indication is more
or less valuable than a UT (ultrasonic testing) wall thickness survey, but the advantage of a corrosion coupon is that
a clean freshly-prepared surface is being exposed in the service environment on a regular basis and, provided that
the corrosion rate is not especially severe, the data so obtained serve to verify that the corrosion rate of the plant
itself is not excessive.

In locations where coupon exposures indicate that the corrosion rate is higher than desired, further
investigation is called for. It is at these points that on-line instrumentation is applied. The simplest type is ER
instrumentation. The ER technique originally was patented by Standard Oil [1], but was exploited initially by Baker
to provide a relatively rapid indication of the efficiency of its oilfield corrosion inhibitors and treatment chemicals.
The monitoring group was devolved from Standard Oil and became Rohrback Instruments, and that company is still well-recognized in the corrosion monitoring field. The main competitor to Baker at that time was Petrolite, and as the patented ER technology was licensed to Baker and Rohrback, Petrolite needed to identify alternative technology to demonstrate the effectiveness of their oil field treatment chemicals. In consequence, Petrolite licensed and developed LPR instrumentation [2]. However, whereas ER probes would operate satisfactorily in low-conductivity hydrocarbon conditions typical of oil and gas production systems, LPR instrumentation had to be used in moderate or highly-conductive environments. This was not a problem in cooling water systems or oil field installations with a high water cut, but LPR sensors did not perform well in sour systems where the sulfide deposits tend to bridge the sensor elements, or in low conductivity systems where there was insufficient moisture to provide a conductive path.

ER probes are the basic tool for oil field monitoring even today, and the technique is simple and well-understood. Nevertheless, they too have significant disadvantages. For example, in order to have sufficient sensitivity to obtain a reasonably prompt response, the sensor element must be relatively thin. Unfortunately, this means that if a short-term excursion in the rate of corrosion takes place, the service life of the ER sensor is quickly used up. In addition, any incidence of pitting attack will result in excessively high apparent corrosion rates because the sensor element is being thinned at a specific location, whereas in practice the degree of pitting may not be particularly serious. ER probes also have poor tolerance to fluctuations in operating temperature, which interferes significantly with the accuracy of the readings. For this reason it is not possible to produce a reliable temperature-controlled ER sensor and this again limits its applicability for any heat-transfer related application.

LPR instrumentation is based on an electrochemical monitoring approach. In this case, instead of monitoring the apparent change in the resistance of an exposed wire or tube, the change in resistance across an electrochemical cell is evaluated and changes in the polarization resistance value correlated with metal loss as calculated using the Stern Geary relationship [6] and Faraday’s Law. There is an implicit assumption when using the LPR technique that the “Polarization Resistance” value is directly related to the corrosion rate. In practice, this value is the sum of the solution resistance (i.e. the conductivity) of the electrolyte in the corrosion cell and the charge transfer resistance, i.e. the value of the resistance that controls the transfer of charge at the corrosion interface due to the anodic dissolution of metal to form metal ions. In moderately conductive and highly conductive environments, this assumption results in a small but constant error on the calculated corrosion rate, but the error is not problematic when comparing corrosion behavior in a suitable corrosion environment (such as in brine or treated cooling water, for example).

However, in low conductivity environments such as hydrocarbon streams containing small concentrations of moisture, or condensing environments with thin electrolyte layers, or high purity water systems, the resistance of the bulk environment introduces a large and possibly variable error component that it is impossible to compensate for using LPR instrumentation. This limitation is unfortunate, because electrochemical monitoring instrumentation has the particular advantage of proving a truly real-time response to changes in the corrosion interface.

3.2 ‘Advanced’ Instrumentation

For want of a better title, instrumentation that has been developed after the commercialization of ER and LPR technology can be grouped under the heading of ‘advanced’ instrumentation. Although it might be argued that techniques such as inductive determinations of (ER) corrosion rates, Cion (a type of specialized EN approach), and even potential mapping (FSM) might be considered to be ‘advanced’, these are perhaps best considered as proprietary attempts to claim a market advantage. By contrast, electrochemical impedance spectroscopy (EIS), harmonic analysis (HA) and electrochemical noise (EN) measurements are substantial developments of the precursor DC polarization method.

EIS was the first of these, and offered some advantage compared to DC polarization in that an alternating signal was applied to the corrosion cell, enabling the relative contributions of the solution resistance and the charge transfer resistance components to be delineated. EIS was/is particularly useful in that it can permit the contributions of various components in a corroding system to be characterized by their differing time constants, and in consequence the technique has found particular use in the research laboratory. However, it is arguable that the response of the corrosion cell is influenced directly by the application of the monitoring technique itself. For
example, the fact that the measurements are made under sequential perturbations of progressively longer amplitude means that the response of the electrochemical cell is disturbed to an increasing degree by the progressively longer and slower polarization cycles. This is an artifact of the measurement system, as a naturally-corroding system is not subjected to such external perturbations or, in many cases, to any external polarization whatsoever. In consequence, it is debatable whether corrosion rates calculated on the basis of impedance results are ‘accurate’, though the capability to measure and discount errors resulting from changes in solution conductivity and/or diffusion effects is undoubtedly useful.

Harmonic Analysis (HA) is essentially a specialized determination of the Tafel coefficients identified by Stern and Geary to be pivotal in controlling the rate of corrosion in an electrochemical system. The technique therefore is closely associated with EIS measurements though it is distinctly different and the results obtained relate more to the estimation of corrosion rate from polarization measurements than to EIM analysis as such. Again, it should not be inferred from the above comments that HA has no value as there is every justification for concluding that estimates of the Tafel coefficients obtained from HA can reflect short-term changes in the rate of corrosion indicated from LPR or EIS measurements. Thus, such determinations can improve the precision of the calculated corrosion rate. However, this still leaves open the question as to whether or not gross perturbation from the spontaneous corrosion condition will still yield ‘accurate’ corrosion rates. A better conclusion might be, for example, that the data so obtained provide more insight into the corrosion mechanism and can be used to improve the precision of corrosion rate estimates based on DC polarization or AC impedance approaches.

The advantage of the electrochemical noise (EN) monitoring approach is that no external perturbation of the electrochemical interface. Potential and current transients generated by the corrosion process itself provide the primary inputs to the measurement system [7, 8]. However, the EN technique has long been shrouded in mystery and skepticism, not least because for years it was believed impossible to monitor corrosion directly and hence it was ‘necessary’ to resort to some kind of external polarization in order to obtain a reliable estimate of corrosion activity. This assumption is ridiculous and there has been a constant progression of EN applications development, often driven by the desire to better understand complex corrosion phenomena that were not amenable to evaluation using ‘conventional corrosion instrumentation [9-12], which in due course will be exploited in plant-wide corrosion/condition management. In real terms, EN monitoring is the technical equivalent of vibration monitoring on rotating and reciprocating equipment. Who would countenance the idea of stopping a turbine or pump, putting on a vibration sensor, and then artificially shaking the machine in the hope that fluctuations in the output of the sensor could be used to determine the condition of the equipment? Yet that, in essence, is precisely what is done when using external polarization, whether DC or AC, to obtain and indication of corrosion rate. In so doing, the characteristic nuances of the electrochemical potential and current responses are eradicated in the tide of much larger external applied transients.

The key advantage of vibration monitoring technology is that analysis of the signals spontaneously generated by the passive sensor can not only characterize the degree of vibration on the machine, but the vibration ‘signatures’ can be used also to identify the source of the signature – i.e. misalignment, imbalance, broken teeth in a gearbox, loose footings on a drive. Furthermore, the rate at which such signatures develop can provide the engineer with a prediction of the time to failure, allowing scheduled outages to be arranged during which the affected component can be repaired or replaced.

The predictive capability is especially valuable. Mechanical maintenance is a given requirement in the operation of rotating and reciprocating equipment. The ability to anticipate a probable failure, even to the extent that its time to failure can be projected, is highly advantageous in that it allows embarrassing, inconvenient and expensive unplanned outages to be avoided altogether. It is for this reason that vibration monitoring has become the key component of so-called plant condition monitoring. Unfortunately, the main disadvantage of vibration monitoring is that it does not work well on static plant. As the majority of plant equipment is not supposed to spin or shake, this limits the applicability of ‘condition monitoring’ to only a few sections of the plant.
Electrochemical noise monitoring is the equivalent technology to vibration monitoring, but it can be applied throughout the static plant equipment – i.e. to heat exchangers, reaction vessels, and piping. When properly applied, EN also has the capacity to provide an accurate real-time indication of corrosion rate. Furthermore, EN is able to provide that real-time information in the specific low-conductivity and/or condensing environments that preclude the use of conventional LPR instrumentation. Additionally, EN can be used to identify the mechanism of attack – whether uniform, pitting, crevice, SCC, stress-assisted IGA, CF, cavitation, under-deposit attack, droplet or bubble impingement, fretting or even filiform attack. Each of these mechanisms exhibits a different and absolutely exclusive potential and current ‘fingerprint’ response generated by the fundamental electrochemical interface condition in precisely the same way that vibration monitoring is able to capture and characterize differing mechanical phenomena. Sadly, consistent shortfall in the quality of EN instrumentation and in the efficacy of its application has resulted in a persistent lack of confidence that the capability claims can be substantiated. Nevertheless, the fundamental technology is without question and there is no doubt, therefore, that in due course EN-based sensor technology will become the key to advanced plant-wide condition \textit{management}.

The term ‘management’ is emphasized here because ‘monitoring’ just adds cost. It calls for more equipment, more software, more time, more analysis, and more things to install and maintain. There is no advantage in monitoring for its own sake. Monitoring only makes sense if the results of the monitoring activity are used as a basis to \textit{change the way the plant is operated}. Whereas monitoring simply adds cost, management brings cost-benefit. Being in a position to manage the plant condition to avoid corrosion, improve product quality, reduce inspection activities, increase safety, enhance reliability and increase capacity increases the productivity and profitability of plant operations in a way that simple monitoring – counting what has been lost – can never aspire to achieve.

4. \textbf{Strategic Application}

With the above objectives in mind, how then can the breadth of corrosion instrumentation, whether conventional or advanced, be used to best advantage in the short term, while retaining the longer-term objective of plant-wide corrosion and condition management?

First of all, it is important to appreciate that ‘advanced’ instrumentation is not invariably needed. Conventional monitoring approaches may be more cost-effective and can provide perfectly satisfactory results as part of an overall corrosion management system provided that they are appropriately selected and applied. However, it is unhelpful to hope that randomly-installed corrosion monitoring equipment will provide the basis of an effective corrosion management system unless there has been a systematic appraisal of where such sensors should be installed, what type of attack the sensors are to identify, and the response that should be prompted when higher rates of attack are detected. Thus, it is useful to employ a risk-based appraisal strategy when designing the corrosion monitoring installation, tracking each stream from source to exit in precisely the same way as might be undertaken when implementing an RBI (risk based inspection) approach. In essence, this approach comprises a consideration of the plant material, service environment chemistry, operating temperature, pH, flow condition, etc., to decide when, where, and what type of corrosion might take place. In an existing plant, it may not be necessary to conduct a theoretical appraisal of such conditions; operating experience and maintenance records will provide a direct indication of where corrosion is taking place and, from the standpoint of the present strategy, any degree of corrosion greater than virtual zero is unacceptable.

The next criterion to consider is any aspect of the plant condition that might cause there to be some kind of change or excursion in the corrosion environment at that location. This might be the introduction of another process stream, a change in the operating temperature or pressure, a change in the plant construction material, a flow-related phenomenon such as turbulence, cavitation or droplet/particulate impingement. When the cause of such a change is identified, an appropriate sensor should be positioned \textit{at the location of greatest attack}. This requirement is very important. It is not useful to position a sensor designed to detect impingement attack or cavitation damaged upstream or downstream of the location at which the damage is taking place. Very localized phenomena are causing the damage condition. Similarly, it is a waste of time installing a sensor that is capable of monitoring only uniform attack if the primary cause of failure is a localized corrosion mechanism.
Having said this, some compromises are permissible. For example, if droplet impingement or erosion-corrosion (i.e. flow-assisted corrosion) is the fundamental mechanism of attack, it is possible to build a flow-cell that will generate equivalent impingement or erosion conditions in a side-stream loop that will mirror or even exaggerate the fault condition in the plant. That being the case, a suitable sensor design and choice of monitoring technique will enable an instantaneous and completely reliable indication of corrosion risk to be provided to the operator without interference in normal plant operations. Furthermore, when the service condition in the plant approaches the fault condition, remedial actions can be formulated to avoid the risk condition and their effectiveness can be verified in real time. It is true that designing such a facility is more expensive than installing a ‘standard’ off-the-shelf corrosion probe. However, if that probe is positioned in the wrong location and/or an inappropriate monitoring technique is used to interrogate it, not only is all the investment in the monitoring system wasted, but the fact that monitoring instrumentation has been installed at all can give operators a false sense of security that the risk condition is being avoided. This is a situation that should be avoided at all costs as not only is it potentially dangerous but it will also undermine confidence in the entire corrosion monitoring strategy.

Ironically, confidence can be similarly undermined by installing probes where no corrosion will take place. Consistent returns that indicate that corrosion rates are zero or negligible eventually engender a feeling that the monitoring exercise is a ‘waste of time and money’, because the sensors are not sufficiently sensitive, or they are not sufficiently sensitive to the mechanism of attack, or there simply isn’t any corrosion taking place at that location. The exception to this situation is when corrosion prevention treatments or measures (i.e. control of operational conditions or chemical treatment) are necessary in order to maintain the desired/obtained low corrosion rates. In this case, there will invariably come a time when control of the treatment system will be less effective and then the corrosion response will reflect it. Ideally, in such circumstances, modern corrosion instrumentation will be applied that will provide an immediate indication in the potential corrosion risk. Not only will this engender confidence with operations personnel that the equipment is reliable but it will demonstrate the necessity and effectiveness of controllable corrosion prevention expenditure – a vital justification if uncontrolled remedial maintenance expenditures, and perhaps even plant corrosion failures, are to be avoided.

5. Interface with RBI

Risk-Based Inspection (RBI) has been demonstrated to deliver substantial improvements in process plant safety while also reducing inspection and maintenance costs. However, where intermittent excursions in process conditions can lead to substantial unexpected increases in corrosion rate, the only strategy to address the issue is to increase the frequency of inspection. This is expensive, especially if a plant outage is required, and may often be unnecessary. Unfortunately, the high potential risk may dictate that a more frequent inspection regime is mandatory. In such instances, on-line monitoring can provide a useful and cost-effective alternative to more frequent inspections. The type, location, severity and distribution of the corrosion damage should be established and then a suitable sensor designed that will detect the fault condition and can be placed at the location where the corrosion damage is most extreme.

In effect, the role of the sensor is to provide a means whereby the ‘criticality estimate’ can be updated in real time while the plant is running. All the time the sensor shows low corrosion rate, the criticality factor is low and hence the corrosion rate assumption controlling the inspection interval is valid. When the sensor detects an increase in the corrosion rate, this is indicative that the criticality factor is now high, and hence the inspection interval should be decreased. However, if measures can be taken that reduce the corrosion rate again and the decrease is confirmed by the sensor then the criticality factor is again low and therefore the originally-prescribed inspection interval should be appropriate.

Note that the inspection interval should not be extended purely on the basis of the on-line monitoring indication. The purpose of the on-line data is to verify on a continuous basis that the corrosion condition within the vessel is as expected. Inspection Codes and Standards then set the criteria that specify the inspection frequency. However, improved control afforded by on-line monitoring may well mean that future corrosion rates are lower than historical data might suggest, and on that basis the frequency of future inspections may be decreased as confidence in the accuracy of the real-time data is accumulated.
6. Future Perspective

It is not so many years ago that engine management systems were restricted to racing cars and prestige vehicles. Now they are a standard feature of even the smallest commuter cars. This is because even though the initial investment may be high, the requirement for consistent performance, consistent reliability and consistently low emissions has meant that the initial cost is immaterial as the applicability is so widespread. By comparison, in many ways chemical, refinery and petrochemicals processing equipment, power generation combustion systems, nuclear power generation and reprocessing plants and similar large production systems are still being operated on the technical equivalent of a set of points and a carburetor. If the gains in efficiency and reliability are so desirable for small vehicles, how much greater is the potential for improved management and safety for large processing systems.

Although many organizations have adopted the term ‘management’ to describe their corrosion control measures, in reality most are still at the ‘monitoring’ stage, with no real understanding of the targets or available benefits from the implementation of a comprehensive corrosion and condition management strategy. The word itself does not matter, it is the understanding of what the word means that is crucial, though a lack of appreciation of the underlying intent can mean that the entire opportunity is squandered. The primary objective of this paper, therefore, was to attempt to track the development of corrosion instrumentation technology in order to be able to demonstrate clearly the future target and the means to achieve it. There is still work to do but the technology to achieve the goal now largely is available. Miniaturization is probably the next development step but there is plenty of advantage in the current generation of equipment for implementation to be progressed immediately.

7. Conclusions

There is an increasing acceptance that corrosion monitoring is an important tool for the measurement and control of corrosion damage in process plant operations. However, many industries employ a scatter-gun approach to on-line monitoring, installing corrosion probes of one sort or another randomly around the plant in the hope that they may detect attack and provide an indication of how rapidly damage has progressed. The speed of response of conventional instrumentation is too slow to give control and therefore the established approach to corrosion engineering has been largely based on off-line materials selection and reactive actions on damage reports or failure incidents.

The introduction of modern corrosion surveillance instrumentation has opened the pathway for conventional practices to be updated. The application of a risk-based approach to the siting of corrosion sensors, the selection of modern instrumentation that is capable of detecting the onset and propagation of localized attack as well as uniform corrosion and instantaneous correlation of on-line corrosion with process chemistry data as well as with periodic inspection results, presents the opportunity for both the severity and the duration of attack to be minimized, thereby opening the way for real-time management of corrosion conditions within the plant. Future developments of modern on-line electrochemical monitoring technologies offer the opportunity for real-time control, with its associated benefits of improved safety, reduced operating and maintenance costs, extended service life, lower contamination levels and higher product quality.

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References

1. “Conductometric corrosion measurement system”, Andrew Dravnieks Arthur J. Freedman, Standard Oil Company, US Patent No. US3094865 A, 1959.
2. “Method and apparatus for determining corrosion rate”, James M. Kilpatrick, Petrolite Corporation, US Patent No. US3406101 A, 1963.
3. “Adapter for handling fluid under high pressure”, Jay P. E. Gould, Grant Corporation, US Patent No. US2752228 A, 1956.
4. Bovankovich, J. C. "On-Line Corrosion Monitoring", Materials Protection and Performance, pp 20-23, June 1973.
5. Ohtsu, T., and Miyazawa, M., “Materials Selection and Corrosion Management in a Process Containing Halides”, CORROSION 2012, Paper No. 0001352, Houston, TX: NACE international, 2012.
6. “Electrochemical Polarization I: A Theoretical Analysis of the Shape of Polarization Curves”, Stern, M., and Geary, A. L., J. Electrochem. Soc., Vol. 104, No. 1, pp. 56-63, 1957.
7. Hladky, K., USA Patent 455709, European Patent 084 404 A3, Canadian Patent 418938.
8. Eden, D. A., Dawson, J.L., John, D.G., USA Patent 5139627, European Patent 0302073.
9. "Corrosion Surveillance Applications for Nuclear Power Plant Systems" Roarty, D. H, Bogard, W. T, Cox, W. M., Moore, D. C. A, and Quirk, G. P., Paper 192, NACE Corrosion 93 New Orleans, March 1993.
10. "A Review of EPRI Projects Since 1984 that used Electrochemical Noise Instrumentation", Syrett, B. C., and Cox, W. M., ASTM Symposium on Electrochemical Noise Measurement for Corrosion Applications, Montreal, Canada, May 1994. (Published in ASTM Special Technical Publication 1277: Electrochemical Noise Measurement for Corrosion Applications, J. R. Kearns, J. R. Scully, P. R. Roberge, D. L. Reichert, and J. L. Dawson (eds.). Amer. Society for Testing and Materials, West Conshohocken, PA, pp. 173-185 (1996).
11. “Risk Mitigation in Modern Plant Health Management”; Cox, W. M., Miyazawa, M., Foong, M., and Aller, J. A. Plenary Paper presented at the NACE India ‘CORCON 2000’ Conference, Mumbai, November 2000.
12. Cox, W. M., de Jong, M., Swensen, D., “Real Time Monitoring of Corrosion and Fouling in Power Generation Boilers and Waste to Energy Plants”, Corrosion 2012, Salt Lake City, NACE, March 2012.