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ABSTRACT

Inspection of pipelines susceptible to internal corrosion is a key ingredient in maintaining their reliable throughput. While conventional inspection techniques consisting of inline inspection, radiography and ultrasound remain the mainstay of most integrity programs, challenging circumstances in some cases make manual inspection impractical or cost prohibitive. In these cases, Electrical Field Mapping (EFM) has provided a practical solution to safe operation without expensive and potentially dangerous dig programs. Historically, this approach required manual site visits for data collection and significant analysis overhead requiring highly trained personnel.

In this paper, we discuss a new approach to EFM data acquisition where wall thickness data is acquired, transmitted, analyzed and displayed automatically and remotely with virtually no human overhead and minimal operating costs. An overview of a PinPoint monitoring setup covering 180 degrees of a NPS 8 pipe is described. This advanced EFM system allows operators to observe, essentially in real time, highly precise wall thickness data covering the lower half of the pipe. In the case study presented we describe the method whereby recent corrosion measurements from a NPS 8 carbon steel sweet shallow natural gas pipeline are delivered to the operator using a conventional web browser.

Keywords: Corrosion Monitoring, Remote Data Acquisition, Corrosion Inhibitors

INTRODUCTION

Introduction to Corrosion Monitoring Techniques

Corrosion monitoring today is performed using a variety of techniques¹, each with its own strengths and weaknesses. For pipeline applications, inline inspection (ILI) has become popular as it allows one to cover entire pipeline segments in a single run. ILI, however, is costly to perform on a frequent basis and overall accuracy between runs makes precise corrosion monitoring particularly challenging. For routine, accessible inspection applications, numerous non-destructive examination (NDE) methods have been developed to locate and / or screen for wall loss using ultrasound, x-ray, and magnetic particle techniques. These methods, however, are ideally suited for inspection rather than monitoring, as they allow operators to move a single sensor device between many locations. Other methods, however, have been designed for monitoring wall loss at fixed locations over longer time scales. Many of these techniques in turn offer the advantage of yielding more precise corrosion rates due to the fixed nature of the sensing apparatus.

Historically, internal corrosion has been monitored using weight loss coupons. This method has been the standard method of corrosion monitoring in pipelines due to its simplicity and low replacement cost. This approach is useful in providing a measure of internal corrosion activity but has several limitations. One limitation is that the process of inserting and removing coupons is labor intensive and adds to program cost over time. In order to exchange coupons, an individual must physically visit the site, extract the old coupon, and insert the new coupon. This technology utilized in a pipeline also makes the insertion of any inline device, or PIG, difficult if the coupon is not flush-mounted with the pipe wall. One other such limitation of this technology includes the inherent indirect nature of coupons, the difficulty being that they may not always represent corrosion occurring in the pipe wall itself.

In the category of intrusive corrosion monitoring technologies are several techniques based again upon monitoring the wall loss, or specifically the corrosion, of a replaceable sample. Some of these technologies include linear polarization probes (LPR)², electrochemical noise probes (ECN)³, and electrical resistance (ER) probes⁴. In the case of the latter, a known electrical current is passed through a thin metallic filament exposed to the internal process. The voltage between terminals, or end points, of the filament is then measured. Over time, as the filament wears away, the measured voltage between terminals is observed to increase as the electrical resistance rises over time due to the reduction in metal volume. This voltage is separately correlated to wall thickness using a multitude of considerations. However, as was the case with the weight loss coupon, the metal reduction of the filament doesn't necessarily indicate the remaining wall thickness of any particular location in the pipeline or vessel. It simply provides a measure of process corrosivity, or the potential for corrosion to occur. One particular recognized difficulty with this technology is the formation of conductive layers on the filament of the ER probe. As the thickness of the filament in this case is comparable to the

thickness of the conductive layer, this contribution can be significant enough that readings may require a correction factor.

Non-intrusive corrosion monitoring techniques offer an added advantage over the other category of probes described, being that there is no need for pre-fabricated access fittings. As a result, these techniques are much easier to relocate without permanently altering the pipeline or vessel. Non-intrusive online monitoring techniques operate not by monitoring the wall loss of any intrusive sensor, but instead rely on other secondary measurements to yield corrosion indicators. Some of these techniques include hydrogen permeation, ultrasound testing (UT), fiber optic (FO)⁵, and electrical resistance matrix methods⁶.

In comparison to the techniques discussed above, electrical resistance matrix methods offer the benefit of being able to cover large areas without introducing dead zones, report wall loss rates directly representative of the area of interest, and have been demonstrated to work effectively with both pitting and generalized corrosion. They can also overcome the problem associated with averaging wall loss rates over long time scales when implemented in a continuous monitoring, or online monitoring, mode. This non-intrusive approach, one example of which is the Electric Field Mapping (EFM) system, will be the focus of the remainder of this paper.

Electric Field Mapping (EFM) Measurement Principle

The Electric Field Mapping (EFM) technique was developed as an electrical resistance matrix-based method designed with enhanced flexibility. This flexibility is apparent in terms of the system's measurement capabilities, implementation methodologies and ease of installation.

From all the corrosion monitoring methods discussed, the electrical resistance (ER) probe method is the most analogous to the electrical resistance matrix method. Common in both cases is that electrical resistance measurements are made in order to determine wall loss. However, with the ER probe, the metal used as the sensing element is different than that of the pipeline. With an electrical resistance matrix, the pipe wall itself acts like the probe.

In either case, through Ohm's Law, given a constant electrical current, the voltage measured between two points is directly proportional to the electrical resistance. The electrical resistance will vary depending on the resistivity of the metal (a material property dependent on temperature), and the volume of metal that will carry the electrical current. As the charge carriers (electrons in the case of a metal) repel one another due to their like charge, the measured electrical resistance will increase as the current carrying volume is reduced. This can be understood phenomenologically as similarly charged carriers will resist being forced into tighter spaces.

However, in the case of an electrical resistance matrix based approach where the current is not confined to a filament but instead to a volume of metal, electrical current will be

diverted away from areas of reduced wall thickness. Current paths will then not be linear, but instead will follow paths of least resistance (see Figure 2).

The effect of the current paths being not always aligned with the axis of the sensor pin grid is that the voltages measured between sensor pin pairs have to be understood differently than the simplistic case of the ER probe. While it remains true that an increase in measured voltage between any given pin pair is caused by wall loss (assuming the injected current and surface temperature is constant), pin pairs adjacent to corrosion defects will experience voltage changes as well. Thus, electrical field effects must be taken into consideration during data analysis.

EFM Measurement System

A two-dimensional sensor grid used to form the electrical resistance sensor matrix allows the possibility of differential voltage measurements along the direction of current flow ($V_{||}$), perpendicular to the direction of current flow (V_{\perp}), and diagonally (V_{DIAG}). Voltage measurements taken between pin pairs perpendicular to the current flow, generally speaking, will produce near zero voltage as there is no component of current flow. Those in the direction of current flow yield data pertaining to the remaining wall thickness in the region surrounding each pin pair while diagonal measurements offer additional insight into defect size, as these measurements provide additional directional information (see Figure 3). These latter diagonal measurements are a novelty of the EFM technique. This method effectively improves the system's ability to detect small pitting defects, in addition to providing a mechanism for even better differentiation between lateral corrosion growth, and pitting depth.

The voltage signals measured by an EFM system will depend on wall thickness but also metal temperature. In order to compensate for temperature variations over time, two design modifications were made in comparison to the conventional electrical resistance matrix method. In the conventional approach, a single temperature reference plate (a sample of metal of constant wall thickness in thermal equilibrium with the sample under test) is used to compensate for both changes in surface temperature, and small variations in electrical current. In the EFM system, temperature reference plates are eliminated and replaced with a series of surface thermocouples mounted using a specialized mechanism. In some applications where significant thermal gradients are observed, up to one thermocouple per sensor pin can be used; this provides a thermal map of the area of interest (see Figure 4) which can in many cases offer additional insight into the corrosion mechanism and thermal behavior of the asset. In addition, a software-based thermal calibration is applied across the sensor matrix. Early in project commissioning, the voltage response to temperature for each individual sensor measurement is closely monitored and calibration curves are generated in order to thermally calibrate the entire sensing area.

Remote System Setup

The EFM system was designed as primarily a wall loss process monitoring tool, and not as an inspection tool. For this reason, the ability to measure remaining wall thickness on a timescale relevant to the corrosion process was a requirement. While the timescale relevant to corrosion will vary dramatically depending on the mechanism(s), it was recognized that the majority of circumstances caused corrosion rates to vary on a daily basis or quicker. In order to make the EFM system practical for pipelines, it had to be capable of remote and autonomous corrosion monitoring. The electronics involved in acquiring and transmitting data are referred to as a Remote Monitoring Station (RMS). A photo of the RMS used in this application is shown below in Figure 5.

The Remote Monitoring Station (RMS) serves several purposes, including:

- Capturing solar power and storing of power using a built-in high capacity battery;
- Generating low voltage, high excitation current used to generate an electric field in the pipe metal;
- Switching through hundreds of combinations of sensor pins while acquiring precise voltage measurements for each in order to map out the electric field;
- Measuring dozens of surface thermocouple sensors;
- Logging all data with a capacity to store several months of daily data in the event of a communication disruption; and
- Data upload and download capabilities through a variety of protocols, most typically cellular communication.

FIELD INSTALLATION PROCEDURE

Field Installation of the Sensor Array

The EFM system was installed on a recently repaired section of a NPS 8 welded carbon steel pipe with a 4.0 mm wall thickness. This section of pipeline is not equipped with the facilities required to run any inline tools. ILI is only possible through the use of a tether. As the repair had only just been conducted, the pipe was already excavated and access to the surface was available. The purpose of the installation in this application is primarily to validate the chemical inhibition program recently formulated and executed, and to provide insight into the corrosion mechanism. Chemical inhibitor is applied upstream using an injection quill. The location was selected following the discovery of internal corrosion as part of a dig program in the area just upstream of a header valve. The mechanisms suspected to be responsible at the time of this publication are underdeposit corrosion and microbially influenced corrosion (MIC). In order to acquire the differential surface voltage readings described earlier, Ohmic contact is required between the matrix of sensor pins and the pipeline surface. Depending on the project goals, this can be achieved using one of two methods: capacitor discharge stud welding of sensor studs; and spring-loaded electrical probes mounted in a removable sleeve. The former

method is typically the less expensive option of the two as little prefabrication is required, while the latter allows for a quicker installation and the ability to remove and reuse the sensor array.

In this case, due to the desire to quickly backfill the excavated site and put the pipeline back in service, a welded sensor pin array was the quickest option available and the installation was performed within a week of project initiation. In order to facilitate electrical contact with the pipe surface using an array of sensor pins, a capacitor discharge (CD) stud welder is used to stud weld each individual sensor stud to the pipeline surface. The pipeline surface is first prepared using an angle grinder and a light-buffing wheel. This removes any surface coating in the area of interest as well as surface debris and oxides present on the surface. The voltage, spring pressure, and capacitance of the CD stud welder must be carefully set depending on the stud size, and the metallurgy of both the stud and the host surface. These settings constitute the parameters to be specified in the Welding Procedure Specification (WPS). Following each weld, each stud needs to be visually inspected for proper flash, and some studs destructively tested by bend testing, torque testing, or tensile testing. In practice, the bend test is the easiest to perform and can be used to check for defects such as cold / hot welds, late or cold plunges, and misfires. The resulting properly welded stud when sectioned, examined under a microscope, and hardness tested reveals a heat-affected zone (HAZ) that penetrates less than 0.005" into the host material.

In order to monitor for internal corrosion on the entire lower half of the buried sweet shallow natural gas pipeline, 84 sensor pins arranged in a 12 (circumferential) x 7 (axial) grid were used as shown in Figure 6 below.

After stud welding 84 sensor pins covering the full lower half of the pipeline as well as the current feed (excitation) pins, all connections are resistivity tested and compared with expected readings for continuity and a high quality connection. A pre-fabricated stainless steel shroud is then fitted over the sensor array. The annular space in between the mechanical cover / shroud and the pipeline is then filled with a re-enterable encapsulant gel that prevents any moisture / water from gaining access to the pipe surface. This forms a final layer of waterproofing, as the shroud itself is separately made waterproof using seals. The end flanges on the shroud are used to merge with any existing coatings and / or pipe wrap, as shown in Figure 7 below.

Installation of the Remote Monitoring Station (RMS)

Cables are routed from the buried sensor array through flexible conduit to the surface and connections are made to the RMS. The RMS is programmed to run a diagnostic scan while staff remain on-site, and communication is confirmed. A cellular data connection is used and the cellular modem is assigned an IP address by the network provider. This IP address is then used for remotely downloading new scanning routines, if necessary, and for uploading data to a secure data server.

Automated Data Analysis and Presentation

As mentioned before, the current paths in the case of an electrical resistance matrix approach are often not straight paths and as a result can't be simply modelled. For generalized corrosion / erosion where reporting of average wall loss on the order of the pin spacing (typically 1") is representative, diagonal measurements do not need to be used and relatively simple conversions between changes in electrical resistance and wall loss can be applied using scaling laws.

However, in the case of localized pitting corrosion, a more complex analysis is required and the analysis of diagonal measurements assists in yielding accurate results. This often entails modelling of the electric field to determine how it is affected by all defects within a range of influence. This model is used to create proportionalities between the recorded temperature-corrected voltages near and around defects and remaining wall thickness. Baseline wall thickness data is required in the case of monitoring isolated pitting and is incorporated into the analysis model using data typically acquired using an ultrasound C-Scan. All the voltage mapping and baseline ultrasound data, compared against a database of modelled and empirically verified pitting patterns, differentiate between pitting and generalized corrosion.

Data are analyzed using a software package known as the Database Management and Analysis Tool (DMAT). DMAT is a PC- and server-based software package used to manage large volumes of data created by hundreds of voltage and temperature measurements per scan, with up to dozens of scans per day. In this project scans are taken daily.

PRESENTATION OF CORROSION DATA VIA A WEB INTERFACE

In order to provide the pipeline operating company's staff with rapid access to data without the need to purchase, configure, or install any software, the DMAT software application is left to reside on a DMAT Data Analysis server. This server also functions as a secure web server which clients can use to log into remotely from virtually any location with internet access. Using a common web browser, stakeholders can access the latest recorded corrosion and remaining wall thickness data (in this case delayed by a maximum of 24-hours given the scan frequency). Available information includes background data including a full description of the asset and the installed monitoring system, diagnostic and system health information, and most importantly up-to-date corrosion data.

As mentioned previously, underdeposit corrosion was observed in this pipeline previously and is feared to reoccur if the current corrosion mitigation program, mainly consisting of chemical inhibition, is inadequate. Current corrosion data acquired over the last five months using the EFM system indicate that while some internal corrosion continues to occur the long-term average corrosion rate is low and is much less than 0.1 mm per year (see Figure 9).

In addition to the time-based data shown in Figure 9, which can ultimately be used to link mitigation efforts to corrosion rates, a surface plot showing new wall loss to-date over the entire monitored area also provides insight into where the new wall loss is occurring (see Figure 10 below). In this case, new wall loss, while very small, seems concentrated near the six o'clock position of the pipe as expected in an underdeposit corrosion scenario.

CONCLUSION

The Electric Field Mapping (EFM) system described has demonstrated the ability to non-intrusively monitor internal corrosion on a remote pipeline right of way while rapidly delivering data to stakeholders via the internet. The system components have been briefly discussed and an overview of other corrosion monitoring strategies mentioned. This system has successfully monitored an underdeposit corrosion mechanism with extremely high sensitivity, yielding daily corrosion rates for new wall loss within the 3:00 to 9:00 area on the bottom of the pipe.

This case study also demonstrates that the opportunity is available to correlate with corrosion mitigation efforts by examining time-based data. These results demonstrate the growing need for online continuous monitoring systems in changing process environments, or those undergoing corrosion mitigation, as a means to intelligently optimize mitigation efforts and ultimately extend the lifetime of assets.

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FIGURES

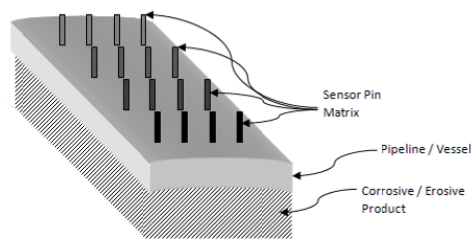


FIGURE 1 - Illustration of the operation of an electrical resistance matrix. Current injection not shown.

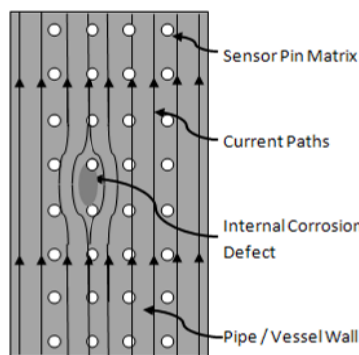


FIGURE 2 - Diagram showing how current paths are diverted around internal corrosion defects, along with an overlay of sensor matrix pins.

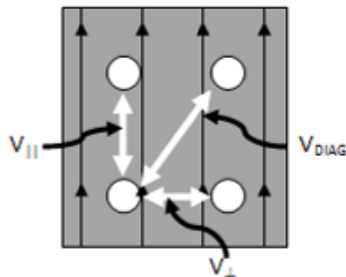


FIGURE 3 - Diagram showing the possibility of differential voltage measurements parallel to the direction of current flow ($V_{||}$), perpendicular to the current flow (V_{\perp}), and diagonally (V_{DIAG}).

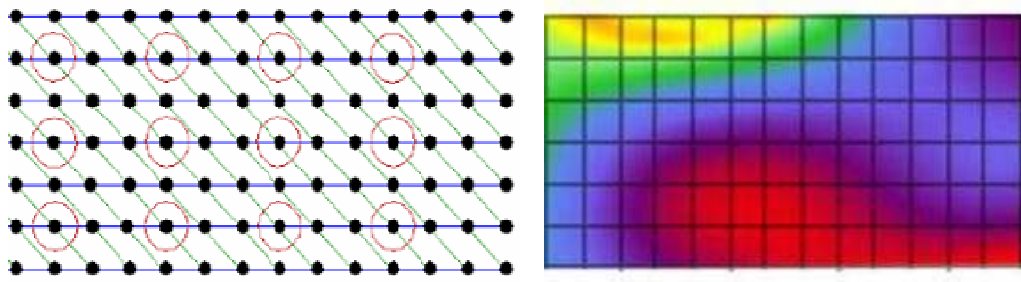


FIGURE 4 - Correlation between various sensor elements (left) and thermal map (right). (LEFT) Sensor pin matrix (black dots), $V_{||}$ measurement directions (blue lines), V_{DIAG} measurement directions (green lines), and thermocouple locations (red circles). (RIGHT) Interpolated thermal map where different colors are used to represent different temperatures.



FIGURE 5 - Remote Monitoring Station (RMS) shown with the cabinet door open. Electronics are housed in a NEMA 4X enclosure and are connected to a solar panel and cellular antenna.

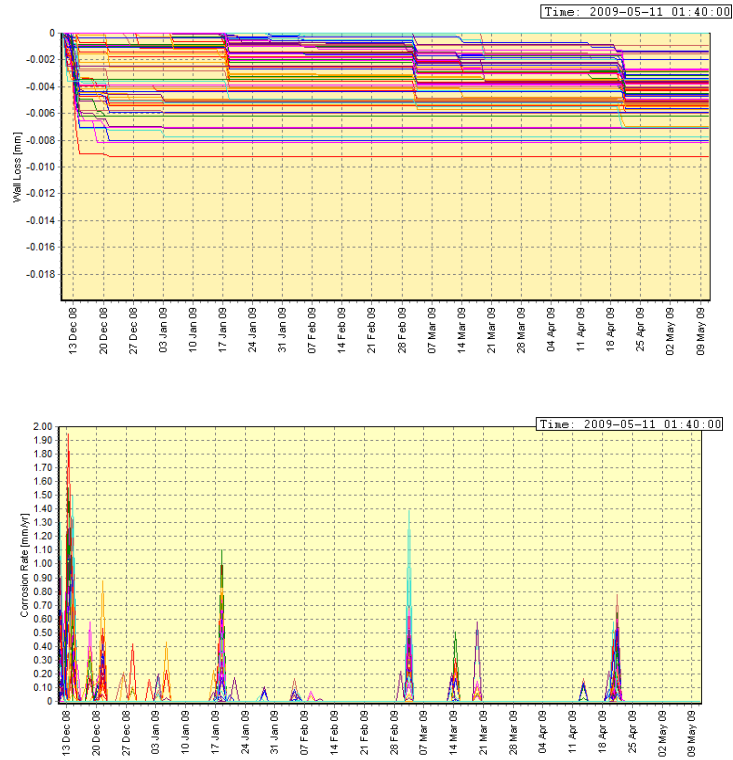


FIGURE 9 - (TOP) Wall loss versus time graph. Each colored graph represents a different location in the sensor pin array. (BOTTOM) Short-term corrosion rate versus time graph, calculated from the data in the top graph.

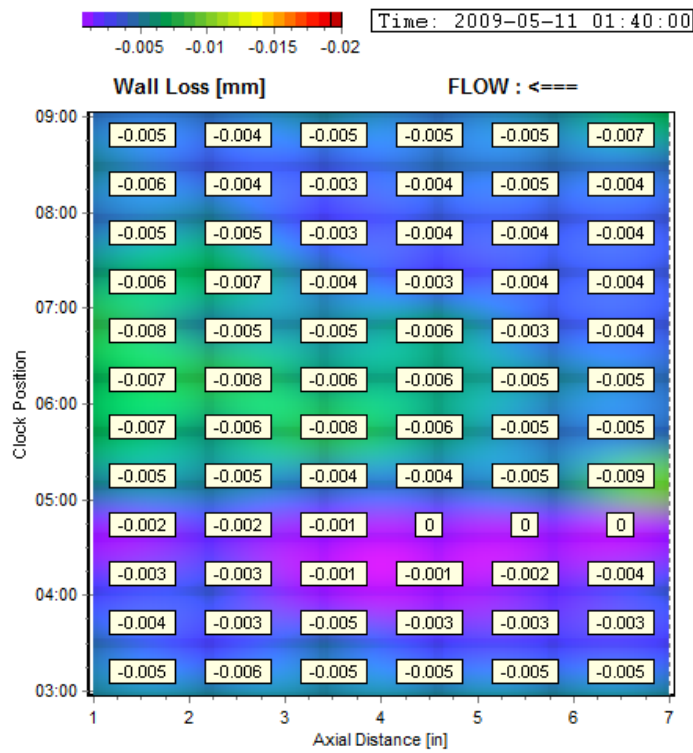


FIGURE 10 - Surface map showing new wall loss on the bottom surface of the pipeline.