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CORROSION PROTECTION | CMI METHOD

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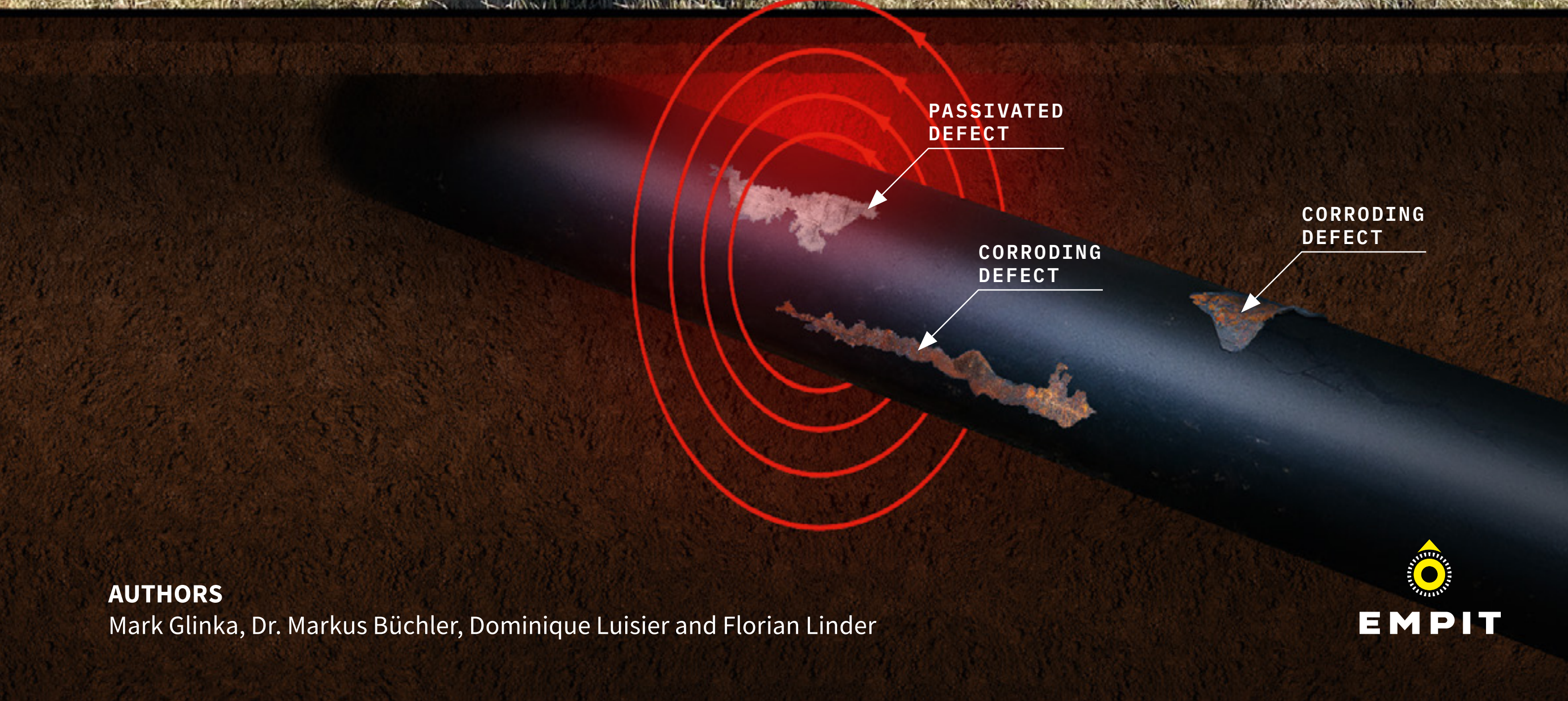

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Evaluation of the Corrosion Protection of Buried Pipelines: The Use of Current Magnetometry Inspection (CMI)

By Mark Glinka, Dr. Markus Büchler, Dominique Luisier and Florian Linder

For the assessment of external corrosion protection, coating integrity evaluation methods are often carried out on buried pipeline systems. In contrast to the commonly used Direct Current Voltage Gradient measurement (DCVG), the newly developed Current Magnetometry Inspection (CMI) offers significant advantages. For the operator, the question arises regarding the comparability of the methods. Therefore, measurements were carried out with both DCVG and CMI to draw conclusions about the transferability of the respective measurement results. These results and an evaluation are discussed below.

1. Introduction

Buried pipelines are usually protected from integrity-relevant wall thickness reductions with external corrosion protection consisting of a combination of a coating and cathodic protection (CP). The effectiveness of CP must be demonstrated based on ISO 15589-1 by means of the measurement of the IR-free potential ($E_{IR\text{-}free}$) on individual coating defects by means of the Intensive Measurement (IM) that is based on a combination of a Close Interval Potential Survey (CIPS) and a Direct Current Voltage Gradient (DCVG). Additionally, the requirements of the ISO 21857 with respect to stray current interference and the ISO 18086 must be taken into consideration. The task now is that the determination of the $E_{IR\text{-}free}$ potential on modern pipelines is difficult due to the high quality of the coating and the associated small coating defects. The small voltage gradients usually prevent the calculation of the $E_{IR\text{-}free}$ on modern pipeline systems. As a result, demonstrating compliance with normative and legal requirements is often complex. This is further complicated by the often increased AC and DC interference [1]. Given these difficulties with respect to the assessment of the $E_{IR\text{-}free}$, a DCVG survey is often performed with increased potential swing (i.e. at a significantly more negative on potential) to demonstrate the absence of major coating defects on the external pipeline coating. By excavating and re-coating, a direct proof of the corrosion state and the restoration of the local defect-free condition is achieved. It is observed that only in very few cases the excavation of the thus identified coating defects was actually necessary from an operational perspective. In most cases the exposing of the coating defect reveals that CP was effective and that the metal at the coating defect did not suffer from active corrosion. Therefore, the assessment of pipeline integrity is often carried out using Inline Inspections (ILI) with Magnetic Flux Leakage (MFL) or Ultra Sonic (US) measurement. These provide direct information on wall thickness reduction and are therefore able to deliver optimized integrity assessments. Correspondingly they reduce the number of unnecessary excavations. However, ILI can only be applied on appropriately designed pipelines in the transmission network. In the distribution network or for unpiggable lines, no alternative methods exist for fault location and excavation to date. The technology developed in Germany by EMPIT GmbH for evaluating pipeline integrity based on Current Magnetometry Inspection (CMI) now offers an alternative and innovative possibility for a more in-depth assessment of pipeline integrity and the effectiveness of corrosion protection.

The corrosion protection by means of CP is based on electrical currents. These can be directly detected with electromagnetic measurements, which makes it possible to precisely locate coating defects. There is no need to increase the potential swing by shifting the on-potential (E_{on}) to more negative values. Therefore, it is possible to precisely locate coating defects without increasing the risk of alternating current corrosion and coating disbondment due to increased cathodic polarization. Furthermore, the method fundamentally offers the possibility to capture additional relevant parameters, which are necessary for evaluating effective corrosion protection at each coating defect. Thus, the procedure has the potential for a comprehensive description of the corrosion-relevant characteristics of a defect. This article presents the measuring principle as well as field experiences with its application.

2. The Evaluation of Corrosion Protection

2.1. Existing Methods

For ensuring the integrity of cathodically protected buried pipelines, methods such as DCVG in combination with exposure and repair of coating defects, IM (based on combined CIPS and DCVG), and ILI for detecting wall thickness losses due to corrosion are used. Although ILI is widely recognized as a tool for ensuring the integrity of pipelines and preventing corrosion damage, many pipelines are designed in such a way that ILI is not possible, leading to these pipelines being classified as unpiggable. These pipelines can only be assessed for the effectiveness of corrosion protection by direct evaluation of external corrosion (External Corrosion Direct Assessment, ECDA). The methods applied for ECDA typically involve connecting an external power source, with direct current (DC) or alternating current (AC) between the pipeline and an earthing system. Consequently, at the existing coating defects, there is a current transfer between the electrolyte and the pipeline. This current is associated with a voltage gradient (VG) in the soil. The voltage gradient can be easily determined by measuring the voltage between two electrodes placed on the soil surface above the pipeline. Depending on the type of source (AC or DC), the method is referred to as DCVG or ACVG.

The schematic measurement setup is shown in ***Figure 1***. These voltage gradient-based methods have significant drawbacks. The most important is that an electrolytic contact of the electrodes to the soil is required. Additionally, other buried metallic structures as earthing systems or other pipelines influence the measured voltage gradient, leading to erroneous results. In a typical urban environment with asphalt surfaces and a significant number of buried metallic structures, conducting these measurements based on voltage gradients and interpreting the data is challenging. Furthermore, increasingly dry conditions make voltage gradient measurements difficult or even impossible. The need for electrolyte contact is overcome by the method of Current Attenuation Measurement (CAM). This method is based on measuring the electromagnetic field generated by the AC current fed into the pipeline by the signal generator. The schematic setup is shown in ***Figure 2***.

The measured electromagnetic field is proportional to the current in the pipeline and therefore allows for an assessment of the current distribution along the pipeline. Defects can be identified by a decrease in the pipeline's current. The resolution of the method is mainly influenced by the resolution limitations of the CAM and the amplitude of the leakage current from the pipeline through the defect into the soil. Large leakage currents can readily be detected with state-of-the-art CAM devices. However, the smallest defects, which are frequent in the case of high-quality coated pipelines, are generally not detectable. Additionally, CAM is significantly affected by metallic components near the pipeline that disturb the electromagnetic field, severely limiting the detection of the smallest coating defects, especially in urban areas. Accordingly, CAM solves the problems with paved or very dry surfaces, but can usually only be applied for larger coating defects remote from other buried infrastructure.

The identification and localization of coating defects is a key aspect of ECDA, and the reliability of ACVG, DCVG, and CAM is significantly affected by external conditions, especially by metallic components in the soil. However, even if these methods show very high reliability in identifying defects under ideal conditions, they do not provide information about the effectiveness of cathodic protection. The presence of a defect only indicates contact between the pipeline and the soil and thus the possibility of corrosion. But in the case of pipelines protected with CP, the increase in pH (increase in alkalinity) at the steel surface and the subsequent formation of protective films over the surfaces of the anodes reliably prevent corrosion as has been reported by Robert Kuhn [2]. The relevance of protective surface films for the effectiveness of CP has later been emphasized by Leeds [3, 4]. This accumulation of alkalinity and the associated film formation is particularly enhanced for well-bedded coating defects in sand and/or in water with increased hardness that results in the formation of calcareous deposits [5]. In the case of these ideal bedding conditions the accumulation of alkalinity and the generation of conditions conducive to passivation are ensured. This good

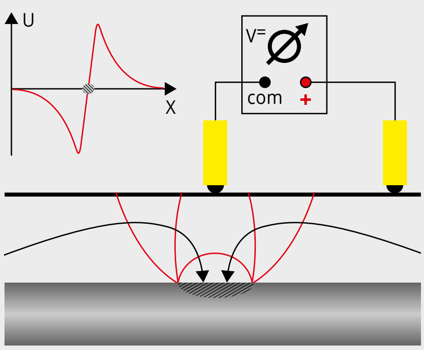

Figure 1: *Schematic measuring principle of DCVG, where the CP rectifier is used as the current source.*

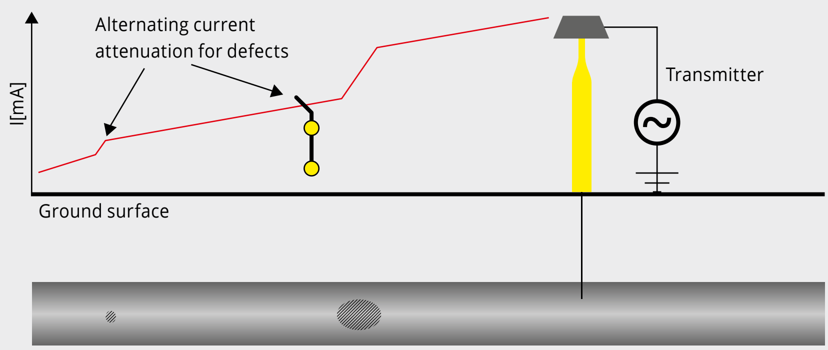

Figure 2: *Schematic measuring principle of Alternating Current Attenuation Measurement (CAM), where in addition to the CP, a transmitter/signal generator injects the alternating current signal into the pipeline.*

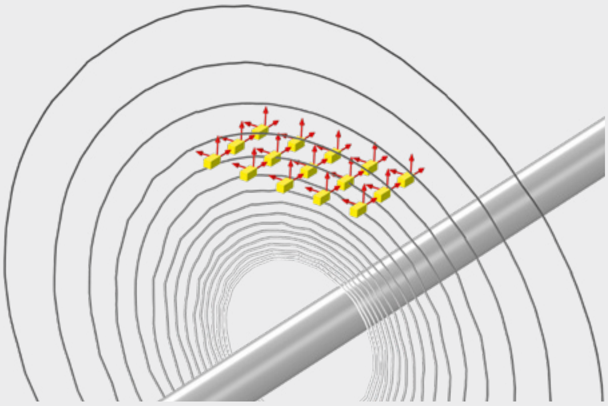

Figure 3: *The magnetic vortex field generated by a signal generator around the pipeline is concurrently measured by up to 70 sensors in three spatial directions. Consequently, the vectorial components of the electromagnetic field are captured with time synchronization allowing for determining the phase shift.*

bedding and the formation of protective oxide layers in the form of passivation steel as a result of the installed CP significantly contribute to the corrosion protection of defects. Accordingly, it is not economically sensible in pipeline operation to eliminate all coating defects through excavation and coating repair. Instead, a method is required that not only allows for the identification of coating defects but also provides further information about bedding conditions, the presence of calcium carbonate layers, the increase in pH, the formation of protective oxide layers, the size of the defects, and their spread resistance. Based on this information, a comprehensive assessment of the corrosion situation can be made, and the number of excavations can be significantly reduced.

2.2. Description of CMI

The newly developed CMI (Current Magnetometry Inspection), like CAM, is based on alternating currents. These currents are generated using a measurement technique controlled by AI and an intelligent signal generator. Therewith, dynamically adjusted frequencies are then applied to the pipeline. This offers improved possibilities for evaluating corrosion protection, summarized as follows:

- The signal generator uses at least four frequencies ranging from 2 to 2000 Hz, allowing for frequency-dependent capture of spread resistance and phase shift, which provides insights into ohmic and capacitive contributions to current flow from the pipeline through the coating defect into the soil. These data can provide relevant information with respect to the formation of protective layers on the steel surface.
- Magnetic field detection is not limited to a few parallel sensors; multiple sensor arrays are used, capturing vec-

Figure 4: *Measurement setup for the CMI. The trailer on the left contains the signal generator. The sensor arrays are integrated into the portable detector (yellow), and above the detector is the Starlink antenna, which sends the large amount of data directly to the cloud for immediate processing.*

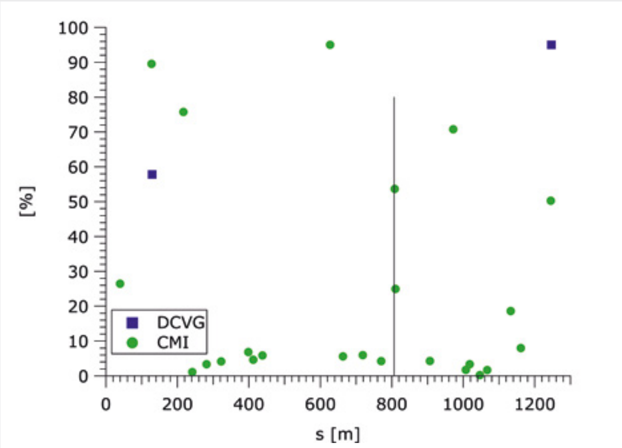

Figure 5: *Results of defect localization with CMI and DCVG, with the signal strength normalized to the highest value. The vertical line at about 800 meters marks the position of the test coupon.*

Figure 6: *Defects identified with CMI. Left: Excised 3LPE coating. Right: Close-up of the defect with the disbonded area.*

torial components of the field in all three spatial directions (***Figure 3***). This allows for precise 3D location and depth determination of the pipeline, and detection of small field components perpendicular to the pipe with high precision.

» Communication between the signal generator and detector allows for targeted variations in frequency and amplitude at identified defects, to provide further descriptions of bedding conditions and pH values in the soil.

CMI enables high-precision identification of coating defects without having to shift the E_{on} in negative direction in order to increase the potential swing. In the case of CMI this is possible thanks to significantly increased use of up-to-date technology with respect to the signal current generation, the number and precision of the sensors as well as the data storage and processing. This is evident from the required equipment as shown in ***Figure 4***. Instead of a signal generator of the size of a battery-operated briefcase for SAM, an entire trailer is needed. Additionally, the geometrically defined arrangement of numerous sensor arrays requires a much larger detector. This detector provides exact position data in relation to location, distance from the ground surface, and inclination. The CMI data assessment and evaluation is performed with a lateral resolution of one centimeter at a measurement frequency of over 100 kHz along the pipeline. The resulting big data volumes are sent via a Starlink antenna to the cloud for direct processing.

Therefore, CMI represents an advancement of CAM, utilizing all most advanced technologies available today. This new approach is expected to provide for the first time the information required to significantly reduce the number of operationally unnecessary excavations. This not only leads to cost savings but can also greatly reduce excavation work in urban areas and the associated noise emissions and traffic disruptions.

3. Field experience with CMI

3.1. Comparative Measurement with DCVG and CMI

In order to evaluate the reliability of both DCVG and CMI, measurements were carried out on a section of the Transitgas AG pipeline (Figure 4) using both methods. This pipeline section, built in 1973, runs from the southern bank of the Rhine River to the Wallbach station, with a length of about 1,433 m. The pipeline has a nominal diameter of 36” (914.4 mm) and a wall thickness of 12.7 mm. The corrosion protection consists of a bituminous coating with a thickness of about 5.5 mm.

The E_{on} was approximately -2 V_{CSE}. A reduction of the E_{on} in the negative direction was not performed in order to prevent any negative effects with respect to AC corrosion or disbondment of the coating. For objective control of the reliability of both methods, a coupon with 1 cm^2 was installed at a depth of about 80 cm.

The data provided by the CP contractor are shown in Figure 5. It is clear that CMI identified a significantly larger number of coating defects including the 1 cm^2 coupon (vertical line at about 800 m in ***Figure 5***). The two coating defects identified by means of DCVG are confirmed by CMI. However, a number of additional coating defects as well as the 1 cm^2 coupon were not detected by means of DCVG under the given measurement conditions.

3.2. Experience with Excavations

The results in Figure 5 demonstrate CMI’s high resolution in localizing defects without increasing the potential swing by significantly shifting the E_{on} in cathodic direction. To verify the plausibility of the measurement results, an excavation of a defect on a pipeline with 3LPE coating in Switzerland was carried out. This defect was identified by CMI but was not confirmed by DCVG. The results of the excavation are shown in ***Figure 6***.

Figure 7: *Pipe bend in the vicinity of the defect (at the red cross).*

Figure 8: *Hand-held CMI detector in use. The red circular lines around the pipe illustrate the magnetic field generated by the signal generator.*

It was found that the CMI indicated the presence of two distinct coating defects, each with size of about 0.1 cm² (Figure 6, left). After removing the coating, it became clear that there was a large-scale disbondment of the coating with a surface of about 12 cm². Based on the available information the minor metal loss associated with the local corrosion effects, the voluminous corrosion products, and the disbondment of the coating are associated with AC corrosion. The visual appearance of the corrosion site is consistent with the typical effects described in [6], [7], [1] and DVGW GW 28 B1 [8] in the case of a pipeline exposed to AC interference.

The corrosion effects at smallest coating defects, the formation of voluminous corrosion products, the large-scale disbondment of the coating, and limited corrosion are characteristic for AC corrosion.

The occurrence of AC corrosion shown in Figure 6 clearly indicates that the pipeline section under investigation could be at risk due to AC interference. It has been reported [6] that more negative E_{on} potentials can accelerate the corrosion process. Therefore, from the perspective of pipeline integrity, it is ideal to perform high-resolution coating defect detection without further accelerating alternating current corrosion and coating disbondment at more negative E_{on}.

3.3. Further Evaluations with CMI

The setup shown in Figure 2 is not only capable of detecting coating defects. More importantly, the continuous measurement of the electromagnetic field with high lateral resolution also enables the high-precision localization of the 3D position of the pipeline as well as its burial depth. Since the measurement resolution with CMI is significantly enhanced in terms of the number of sensors, data acquisition rate, lateral measurement interval, and the use of multiple frequencies, the method also allows for a precise determination of pipeline position and associated anomalies.

The excavation shown in Figure 6 was not only undertaken due to the detected coating defect. Rather, CMI identified a pipe bend that should not be present at that location according to the pipe book. During the excavation, this pipe deformation was indeed confirmed, as can be seen in ***Figure 7***.

The slight deformation of the pipe in Figure 7 clearly demonstrates the high measurement resolution in terms of pipeline positioning that can be achieved with CMI, due to the large number of sensor arrays and the high lateral measurement resolution of 1 cm along the pipeline. These measurements illustrate that CMI significantly surpasses the capabilities of DCVG and provides additional important information regarding pipeline integrity assessment. The accurate capture of the pipeline's exact position and the determination of changes in position and geometry over the years are just some of the key advantages of CMI.

Mechanical stresses in the pipe resulting from shifts in pipeline position are particularly relevant when repurposing pipelines for hydrogen transport. With CMI, it is possible to estimate mechanical stress and locate defects in a single measurement run. This allows operators to efficiently assess and document the condition of the facility for its transformation, a crucial element for safe continued operation with hydrogen.

The method which is shown in use in ***Figure 8***, in combination with appropriate numerical simulation, allows for the quantification of the current passing into the soil through the defect and the calculation of the pipe to soil potential. This immediately allows for calculating the spread resistance of the identified coating defects for the various applied frequencies, providing crucial insights into the corrosion-relevant conditions at each defect. Notably, these methods enable a further evaluation of the large number of identified defects without the need for their costly excavation. These capabilities of CMI will be further investigated in a research project funded by the German Gas and Water Association (DVGW) starting in March 2024.

4. Conclusion

The measurements performed with CMI allow for important conclusions regarding the capabilities both in terms of defect localization and further evaluation of pipeline integrity. The discussed results can be summarized as follows:

- CMI enables high-resolution localization of coating defects on pipelines without shifting the E_{on} potential in a cathodic direction. This allows for maintaining optimal CP conditions during measurement, which is significantly advantageous for corrosion protection: increased risk of alternating current corrosion or enhanced coating disbondment can be prevented.
- CMI's reliability in defect detection under normal CP conditions is significantly higher than that of DCVG. The defects detected by CMI were confirmed by DCVG indications, in the excavation, and with the test probe/coupon.
- The number of defects identified with CMI is typically significantly higher than those of DCVG. While this may seem unfavorable from an operational perspective, CMI's capability for further evaluation of the corrosion protection of the defects leads to a more reliable identification of defects, better assessment of the state of external corrosion protection. Correspondingly the assessment of further corrosion relevant parameters does not require additional excavations. Instead, the identification of the most corrosion relevant coating defects usually allows for more targeted excavations.
- The additional determination of the seamless 3D pipeline position and geometry provides an important means to verify existing data and obtain digitized XYZ coordinates.
- From the pipeline trajectory the pipe displacements can be directly calculated. This allows for deriving mechanical stresses, which may be particularly relevant when using the pipeline for hydrogen transport.

Based on the available results, CMI is a reliable method that provides essential integrity-relevant information, extending far beyond the mere identification of coating defects.

5. Literature

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KEY WORDS: cathodic corrosion protection, current magnetometry inspection, intensive measurement, intensive defect detection, non-piggable pipelines, defect detection, coating defects, pipeline integrity

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