AC Corrosion of Cathodically Protected Pipelines

This doctoral thesis presents three years of research on alternating current (AC) corrosion of cathodically protected (CP) pipelines. AC corrosion has become an increasing concern to pipeline operators worldwide during the last 30 years. This is due to a growing energy infrastructure of both buried pipelines and above ground high voltage transmission lines which results in the conditions for AC interference. The electromagnetically induced alternating voltage on pipelines may cause the existing cathodic protection to become ineffective. In fact, improper adjustment of the CP system may severely aggravate corrosion on the pipeline caused by alternating current. AC corrosion is a multidisciplinary scientific field, requiring fundamental knowledge within the fields of electrochemistry and corrosion, material science and characterisation, as well as electrical engineering and basic geology. The approach of the present investigation is largely empirical and a wide range of parameters affecting AC corrosion have been investigated.

Effects of different coating defect geometries and their orientation have been investigated by electrochemical impedance spectroscopy (EIS) and electrical resistance (ER) probes for corrosion rate measurements. Effects of the chemical environment have been investigated by ER probes, scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), ion chromatography (IC), inductively coupled plasma optical emission spectroscopy (ICP-OES) and X-ray diffraction (XRD). Effects of pipeline steel grades have been investigated by polarisation scans, weight-loss coupons and ER probes. Effects of variations in AC interference levels have been investigated by ER probes. Effects of the pH level at the steel/solution interface has been investigated by pH probe measurements, ER probes and optical methods.

Investigations of the formed corrosion products and mineralogical changes of the surrounding soil environment have been made by X-ray photo-electron spectroscopy (XPS), SEM, EDS, IC, ICP-OES, XRD and light optical microscopy (LOM). All investigations have contributed to an enhanced understanding of the factors leading to and intensifying AC corrosion of cathodically protected pipelines.

The results obtained in the present research indicate that AC corrosion is largely dependent on both AC and DC current densities. It is found that increasing levels of alternating current alone does not necessarily result in AC corrosion, but that this is highly influenced by the amount of cathodic protection current. AC corrosion may be divided into two categories: "high CP" and "low CP" AC corrosion. Many of the discrepancies in literature on AC corrosion may be explained by the fact that researchers have not been aware of this fundamental difference. High CP current generates the highest AC corrosion rates. This is fully in line with present industry standards and scientific literature on the field. The importance of current densities implies that AC corrosion will be largely dependent on factors contributing to an area dependent resistance to current flow, such as coating defect size and geometry as well as soil resistivity and chemistry. A direct consequence of cathodic protection is alkalisation of the environment at the steel/solution interface. The response of a soil system to elevated pH has a large influence on the soil resistivity and thus the current densities and the AC corrosion rate. Finally, AC is found to affect DC polarisation behaviour of steel significantly, causing depolarisation of both anodic and cathodic reactions as well as a shift of the corrosion potential.

One key conclusion of the present thesis is that the Pourbaix diagram for iron may be the used to explain AC corrosion. This implies that pH and surface potential are important parameters when evaluating AC corrosion. Unfortunately, these are inherently difficult to measure in practical applications, especially pH. It is found that there is a strong link between DC current density and pH. AC often enhances the DC current and consequently elevates pH, but under special circumstances, i.e. a low galvanostatic DC current, a high levels of AC is shown to exhibit de-alkalisation properties. Furthermore, AC current density strongly affects surface potential under cathodic protection, due to the strong influence of AC on the polarisation behaviour. This explains why the traditional use of current densities to evaluate AC corrosion works, although this correlation may have been completely coincidental. "High CP" AC corrosion is related to entering the high pH corrosion region (HFeO₂⁻) and "low CP" AC corrosion is related to entering the low pH corrosion region (Fe²⁺) in the Pourbaix diagram. The alternating voltage will continuously reduce or oxidise the dissolved species, thus leading to a stabilisation of these corrosion regions. Therefore, an effective corrosion mitigation strategy depends on whether the observed AC corrosion is of the low or high CP type. Numerous investigations of AC corrosion have been made without application of cathodic protection, and these fall in the category "low CP". Historically this has lead to a widespread confusion about AC corrosion because researchers observing low CP AC corrosion tend to conclude that cathodic protection will minimize corrosion, while researchers observing high CP AC corrosion will conclude that CP enhances AC corrosion. In reality an intermediate CP strategy can be used to mitigate AC corrosion. This works because the passive film on a cathodically protected surface consists of one or more of the oxides: Fe(OH)₂, Fe₃O₄ or a green rust type. These oxides can transfer significant amounts of alternating charge via Fe(II)-Fe(III) redox reactions within the oxide, without further oxidation of the underlying steel. Alternatively, mitigation of the induced AC voltage on the interfered structure by grounding installations may lower corrosion effectively, however compared to control of the cathodic protection level, this is an extensive and costly procedure in practice.

With the publication of this thesis, hopefully researchers in the field of AC corrosion will become aware of the discrepancy between high and low CP AC corrosion, and the collective understanding of AC corrosion will be enhanced.

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