

# **PIPELINE CATHODIC PROTECTION**

## **- A risk based technology**

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### **1 SUMMARY**

The paper addresses the risk factors in assuming that cathodic protection of pipelines will prevent their external corrosion. Common cathodic protection monitoring techniques are critically examined and nine causes of external corrosion failure on cathodically protected pipelines are discussed.

### **2 INTRODUCTION**

Cathodic protection has been a boon to the pipeline industry. It has reduced external corrosion failure rates substantially; however there is still the occasional failure. While the occasional failure was once regarded as a maintenance issue, it is now regarded as being unacceptable. This change in performance requirement has resulted in unrealistic expectations from cathodic protection. There is little consideration of the risk factors inherent in cathodic protection. At many Pipeline Risk Management Workshops the external corrosion risk is addressed by simply requiring that the pipeline be provided with an adequate coating and cathodic protection. The pipeline industry's faith in cathodic protection is so great that this decision is often made without consulting a Corrosion Specialist.

ISO15589-1 states that the application of cathodic protection will reduce corrosion rates to less than 0.01mm per year. While it does say that the potential criterion is IR free, and in a brief note in the scope says that there are special conditions where cathodic protection is not effective, there is no detailed or risk based evaluation of these matters; as a result the pipeline industry tends to ignore these risks.

There are environmental conditions where achieving cathodic protection is problematic. There are also conditions where the efficacy of the cathodic protection monitoring technique is problematic. This paper explores these issues.

### **3 CATHODIC PROTECTION MONITORING**

While there is a large number of cathodic protection monitoring techniques [1, 2], those discussed below are the ones that are in most common use.

### **3.1 On-Potentials**

Pipeline on-potentials are simply the potential of the pipeline measured with the cathodic protection energised. The errors in the interpretation of the measurement, due to the voltage gradient in the soil portion of the measuring circuit, have been documented for many years [1]. However the technique is still widely used for monitoring galvanic anode systems and on pipelines subject to variable stray direct current effects where data loggers are used to monitor the activity of the variable stray currents.

An on-potential negative of the protection criterion does at least indicate there is current flowing to exposed steel but does not quantify the current density due to the unknown soil resistivity profile from the exposed steel and the unknown geometry of the defect.

### **3.2 Off-Potentials**

Pipeline off-potential is the potential of the pipeline measured the instant after the cathodic protection current has been interrupted. This technique is based on the assumption that turning off the cathodic protection current prevents all direct current from flowing onto or off the pipeline at coating defects and therefore corrects for the soil voltage gradient error. While this is obviously incorrect in stray traction current areas and on telluric affected pipelines, it is also problematic on a pipeline that has coating defects that may be of different size or where the coating defects may be in soils of different resistivity. [3, 4] The different degrees of polarization cause equalisation current to flow between the defects immediately the cathodic protection current is interrupted providing an electrolyte voltage gradient that can be of the same magnitude as the on-potential error [3]. While standards require that the pipeline potentials be IR free to determine protection status, there is no practical rigorous way presented of achieving this.

### **3.3 Polarization Probes**

A polarization probe [3] is comprised of a steel coupon that is attached to the pipeline via a test point, and a system for locating a reference electrode close to the coupon. The coupon behaves as a coating defect on the pipeline. In having the reference electrode close to the coupon the voltage gradient in the soil portion of the measuring circuit is minimised and thus gives a potential that more represents the polarized potential of the coupon. The reference electrode system can either be built into the coupon housing or can be a portable reference electrode that is located in a plastic tube that terminates adjacent to the coupon. The coupon also allows the monitoring of current density.

The issues with using polarization probes are:

- the long term reliability of the reference electrode system
- whether the size and shape of the coupon represent actual defects on the pipeline
- whether the probes are compacted in the same backfill as the pipeline
- whether the probes are located in the area of maximum stray current activity and in the area of highest and lowest soil resistivity.

### **3.4 Coupon Off-Potentials**

A steel coupon can be attached to the pipeline via a test point. The coupon behaves as a coating defect on the pipeline in the same manner as the polarization probe and has the same constraints except that as there is no buried reference electrode there is no issue with its reliability. The

potential is measured at ground level the instant after the coupon is disconnected from the pipeline. This disconnection prevents all current from flowing onto or off the coupon, including that from stray traction current and telluric effects, thus removing the error in the interpretation of the measurement due to the voltage gradient in the soil portion of the measuring circuit.

The coupon off-potential represents the protection status of a coating defect of the coupon's size and shape in the pipeline backfill at that location. It is more robust, more reliable and less expensive than polarization probes. Errors may arise where there is current flowing to or from an adjacent defect in the pipeline coating that creates a voltage gradient in the soil between the reference electrode and the coupon location.

### **3.5 Resistance Probes**

A resistance probe element is similar to a coupon except that the steel is of very thin cross section. If the probe element corrodes it loses cross sectional area and as a result its longitudinal resistance increases. An instrument that is plugged into a socket in the test point can measure the increase in resistance. The instrument is very sensitive and very low rates of corrosion can be measured.

The resistance probe is particularly useful where there are varying stray current effects such as telluric effects and DC traction effects, and for AC corrosion. In these cases the DC potential measured at a given time may not indicate the protection status due to stray current density variations and polarity reversals. However the resistance probe still has the same issues as a coupon in terms of its size and shape, backfill material and location. Additionally because the resistance probe is of thin cross section as corrosion proceeds and perforates the element in some areas there may be errors in the current density and measured corrosion rate. The corrosion rate calculated from resistance probes assumes uniform corrosion and so any pitting and consequent penetration rates will be underestimated. Also as the element has a machined surface rather than a blast cleaned one the rate of corrosion may not reflect that of a blast cleaned surface.

## **4 EXTERNAL CORROSION FAILURE CAUSES**

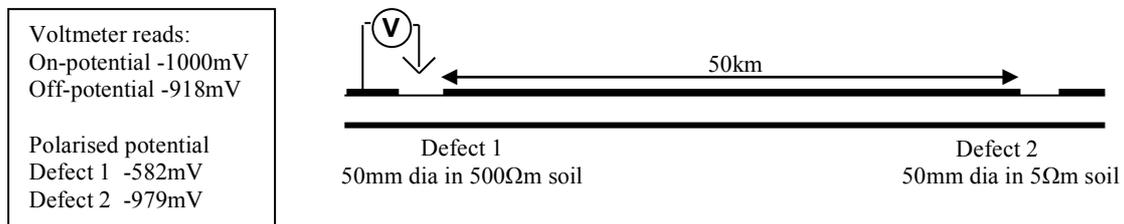
### **4.1 Differential Soil Resistivity**

This is particularly an issue with ultra-well coated pipelines [5]. Defects in high resistivity soil, which tend to be the least protected defects on the pipeline due to the lower CP current density, may not register a lack of protection even if a reference electrode is placed directly over the defect. This is because the reference electrode and meter see all of the pipeline defects in parallel. The defects that have the greatest affect on the meter are those with the lowest measuring circuit resistance. These tend to be the defects in the lowest resistivity soil that also tend to be the most protected. A calculated example is presented below.

In Figure 1 the meter reads an on-potential of -1000 mV Cu/CuSO<sub>4</sub> and an off-potential of -918mV (Cu/CuSO<sub>4</sub>), but the defect adjacent to the reference electrode has a polarized potential of -582mV (Cu/CuSO<sub>4</sub>). If the protection levels are increased to provide protection to the pipeline in the high resistivity environment (monitored using the coupon off-potential technique), the pipeline in the conductive environment may be substantially over-protected resulting in accelerated disbondment of the coating or hydrogen assisted cracking. A similar situation can occur if the pipeline is generally bedded and padded with high resistivity clean sand but there are relatively low resistivity water crossings, or areas backfilled with low resistivity spoil instead of sand.

This issue occurs when monitoring with pipeline on-potentials and pipeline off-potentials, but is overcome by the use of polarization probes, coupon off-potentials or resistance probes providing these devices are installed in the areas of highest soil resistivity. To monitor overprotection they should also be installed in the areas of lowest soil resistivity. However the monitoring is carried out the effect of differential soil resistivities is a significant risk to cathodic protection preventing pipeline corrosion.

In Australia onshore cathodic protection systems are typically set to maintain an on-potential at the cathodic protection unit of approximately -1200 mV Cu/CuSO<sub>4</sub>. While polarisation probes and coupons have been used in some areas since the late 1970s, it was not until 1990 when most new pipelines had coupons or resistance probes installed to monitor the effectiveness of the cathodic protection. They have highlighted the issue of differential soil resistivities however I don't believe we have had pipeline failures attributable to this.



**Figure 1**  
**The Effect of Differential Soil Resistivities**

***The calculation to support this is:***

If the natural potential at the defects is -500mV Cu/CuSO<sub>4</sub>, and the voltmeter at the reference electrode gives an on-potential reading of -1000mV Cu/CuSO<sub>4</sub> with the cathodic protection energized, the current density to Defect 1 would be 41mA/m<sup>2</sup> (Polarization resistance R<sub>p</sub> of 2Ωm<sup>2</sup> (1000Ω) resistance to earth of ρ/2d (5000Ω), and a driving voltage of 500mV gives a current of 0.08mA.) Similarly calculated Defect 2 would have a current density of 240mA/m<sup>2</sup> (0.47mA). The polarized potential at Defect 1 is -582 mV Cu/CuSO<sub>4</sub> (0.08mA across the polarization resistance), and similarly calculated at Defect 2 is -979 mV Cu/CuSO<sub>4</sub>.

The resistance between a defect and a reference electrode ≈ ( ρ/2d - ρ/2πa + R<sub>p</sub>/A) where ρ = local soil resistivity, d = defect diameter, a = distance between reference and defect and A = defect area. Defect 1 which is 1m below grade and adjacent to the reference electrode in 500Ωm soil will have an approximate resistance to the reference of R<sub>1</sub> = 5940Ω whereas Defect 2 which is 50km away in 5Ωm soil will have an approximate resistance to the reference electrode of R<sub>2</sub> = 1070Ω.

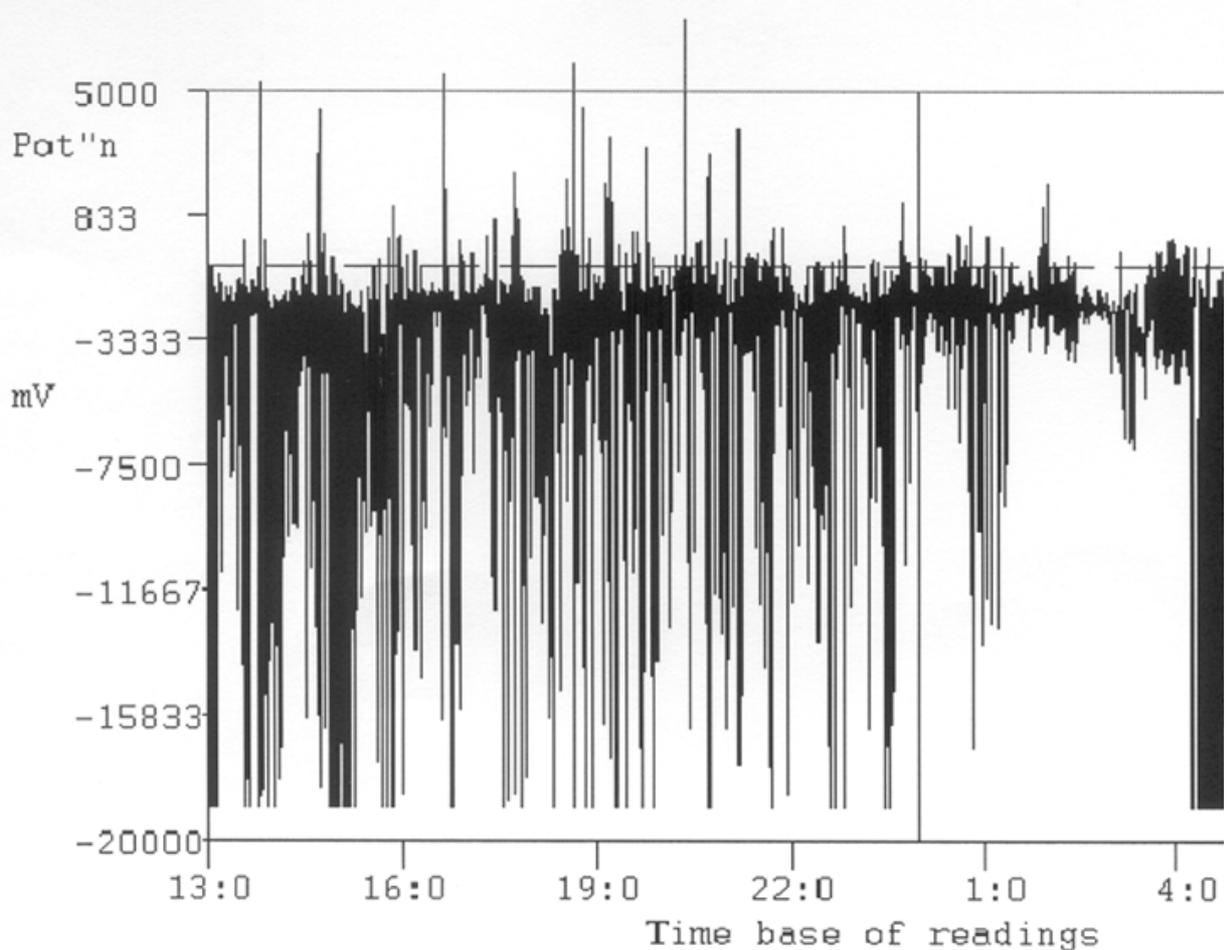
At current interruption, a current I will circulate between the two defects due to the difference in their polarized potentials (i.e. E<sub>1</sub> = -582 mV and E<sub>2</sub> = -979 mV), resulting in a residual IR component in the off-potential reading. The off-potential (ignoring other errors) the voltmeter sees can be calculated from Kirchoff's Laws:

Voltmeter reading = E<sub>1</sub> + IR<sub>1</sub> where I = (E<sub>2</sub> - E<sub>1</sub>) / (R<sub>1</sub> + R<sub>2</sub>) or  
 Voltmeter reading = E<sub>2</sub> + IR<sub>2</sub> where I = (E<sub>1</sub> - E<sub>2</sub>) / (R<sub>1</sub> + R<sub>2</sub>)  
 which calculates to an off-potential reading of -918mV Cu/CuSO<sub>4</sub>.

## 4.2 Stray Direct Current

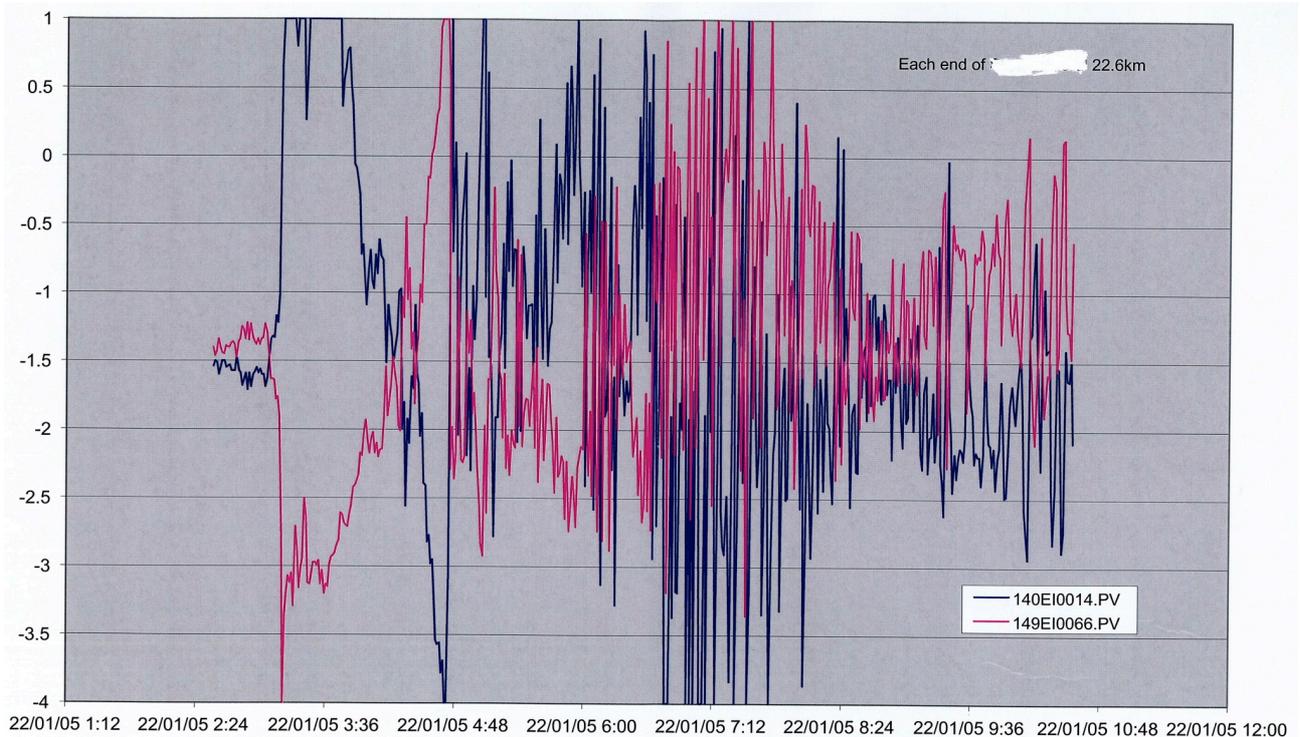
Stray direct current usually results from the operation of direct current traction systems [6] or telluric effects [7]. Both of these effects result in a fluctuation in potential of the pipeline as indicated in Figure 2 for stray traction current and Figure 3 for telluric effects. The Figure 2 stray traction chart potential varies between positive of +5V and negative of -18V. The Figure 3 telluric chart varies between positive of +1V and negative of -4V. All potentials are referred to Cu/CuSO<sub>4</sub>. While these are on-potential measurements the polarized potential also varies with time as a result of the changes in current density and polarity. Therefore spot checks of on-potential, off-potential, coupon off-potential or polarization probe potential will only present a snap-shot in time of the potential, which may not represent the potential at other times.

Recordings of on-potential can be taken but do not allow for the soil voltage gradient error component of the measurement. Polarization probe potentials, or cyclic switching of coupons to give off potentials, can provide a graph of polarized potential against time but the period of the recording may not reflect that which occurs between potential surveys. This is particularly problematic with telluric affected pipelines where the effects are not as consistent as with DC traction currents. There is also the question of how to interpret recordings of potential when they are as dynamic as the ones show in Figures 2 and 3. Does each anodic spike that may only exist for several hundred milliseconds have to be negative of the protection criterion? This could lead to substantial overprotection of the pipeline most of the time. At what stage does an anodic transient



**Figure 2**  
**DC Traction Affected Pipeline (mV Cu/CuSO<sub>4</sub> / time in hours)**

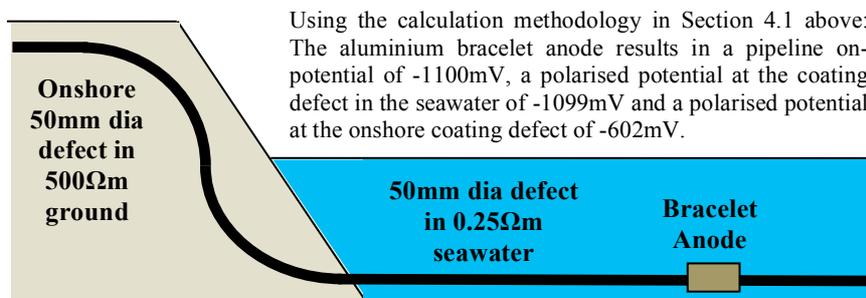
affect the polarised potential or the pH at the interface? Resistance probes are the only monitoring system that will provide a continuous monitor of protection status, but they have to be installed in the areas of maximum stray current exposure and comply with all of the requirements indicated in section 3.5 above. Stray current is a significant risk to cathodic protection preventing pipeline corrosion.



**Figure 3**  
**Telluric Affected Pipeline (V Cu/CuSO<sub>4</sub> / time)**  
**[The two curves represent the two ends of the 22.6km long pipeline.]**

### 4.3 Tidal Areas

Tidal areas on offshore pipelines present a specific challenge. The offshore pipeline is typically protected with aluminium alloy bracelet anodes. However the driving voltage of the anodes may not be sufficient to protect the tidal area when the tide is below a given section of pipe. This is particularly the case if the tidal area is in sand or rock so that when the water drains from that area the environment has a very high resistivity [8]. An example is shown in Figure 4. This matter is also addressed in Australian Standard AS2885.4: 2010 “Submarine Pipeline Systems” Appendix A.



**Figure 4**  
**Effect of Shore Crossings on Pipeline Potentials**

The installation of magnesium anodes or a remote impressed current system onshore is unlikely to have any significant effect on the protection level of the pipeline. This is because most of the current will flow along the low resistance path to the offshore bracelet anodes. For example 50 mA from a magnesium anode will divide its current output between say a 500  $\Omega$  defect onshore ( $R = \rho/2d$  for a 50 mm diameter coating defect in 50  $\Omega\text{m}$  soil) and 0.001  $\Omega$  for all of the offshore bracelet anodes (10 km of DN500 pipeline with 400 mm long bracelet anodes every 8<sup>th</sup> of the 12 m long pipe lengths). This will result in a cathodic swing in potential of the pipeline of about 0.05 mV ( $V = 0.0001 \text{ mA} \times 500 \Omega$ ).

Protection of the onshore section may be achieved by using an impressed current system with distributed anodes creating a field along the pipeline, however this is not likely to be effective because most current will still flow offshore via the lowest resistance path applying cathodic protection to the bracelet anodes. This will increase the pH at the anode surface. Aluminium is an amphoteric metal and will self corrode rapidly at pH in excess of 9 to form aluminate ions. Therefore applying cathodic protection to the onshore section of pipeline will result in increasing the rate of self-corrosion of the bracelet anodes whenever the pH rises to above that required for aluminium corrosion.

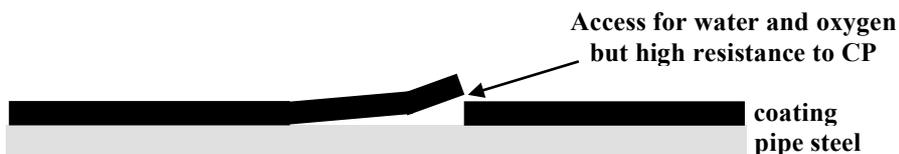
To protect the onshore section of the pipeline an isolation joint needs to be installed as close as practicable to the upper tidal level so that the onshore pipeline can have its own cathodic protection system with the required higher driving voltage. However this does not address the tidal area at low tides. If the coating is not perfect and does not remain perfect for the life of the pipeline, or the coating cannot be readily surveyed and maintained in the tidal area and cathodic protection cannot be achieved, then other protection options must be considered. Concrete encasement may be an option in that it may retain a high pH environment adjacent to steel at coating defects during low tides and have the alkali concentration replenished at high tides when the cathodic protection becomes effective. However the effectiveness of concrete preventing corrosion is dependant upon whether its resistivity is low enough to pass cathodic protection current, its ionic conductivity is low enough to prevent long cell corrosion, its oxygen diffusion rate is low enough to prevent local cell corrosion and/or whether water is able to flow along the pipeline/concrete interface reducing the pH at coating defects. Tidal areas present a significant risk to cathodic protection preventing pipeline corrosion.

In the tidal area and the onshore section of the pipeline on-potentials will not indicate any lack of protection because they will monitor the low resistance path to the offshore bracelet anodes. Off-potentials cannot be carried out because the bracelet anodes cannot be interrupted. Coupon off-potentials, polarization probes and resistance probes can be used to indicate the cathodic protection status of the onshore pipeline.

#### **4.4 Cathodic Protection Shielding by Disbonded Coating**

The most common cause of external corrosion failures on cathodically protected onshore pipelines is disbonded coating. The disbonded coating is an insulator that does not allow cathodic protection current to flow through it to reach the steel exposed in a crevice beneath. Corrosion can occur if the crevice under the coating is wide enough to allow water access but is so narrow that the electrical resistance to cathodic protection current is so high that sufficient current cannot pass to create an alkaline environment and provide protection. This is indicated in Figure 5. It is not normally an issue with offshore pipelines due to the highly conductive seawater that can fill the crevice, but onshore the higher resistivity of the groundwater restricts the current. Additionally onshore the groundwater can periodically dry out allowing rapid oxygen access to the mouth of the crevice and the moist area within the crevice; this can provide very rapid corrosion rates.

The problem occurs with all linepipe coatings although tape wraps and asphalt enamel have probably provided the greatest number of shielded cathodic protection corrosion failures [9].



**Figure 5**  
**Disbonded Coating Causing Shielding of the Cathodic Protection**

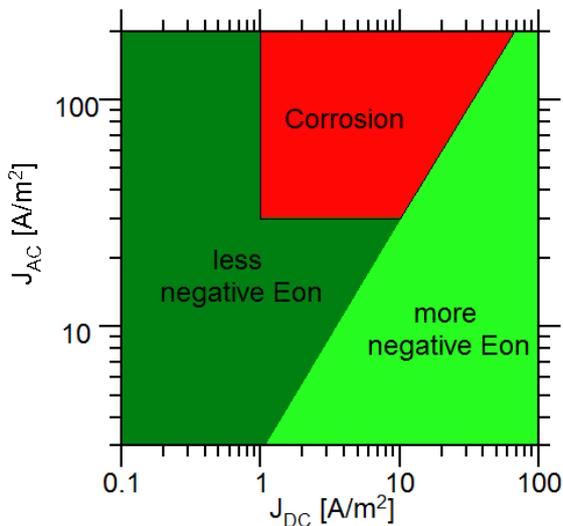
It is claimed by some that FBE does not exhibit this form of failure, however the current density that would pass through the FBE coating can be calculated simply. A paper from the 3M Company indicates that the volume resistivity of FBE is approximately  $10^{15} \Omega\text{cm}$  when new and approximately  $10^{13} \Omega\text{cm}$  when it has been immersed in water for some period of time [10]. Using this data the electrical resistance of a  $400\mu\text{m}$  thick film of immersed FBE calculates to  $4 \times 10^7 \Omega/\text{m}^2$ . For a 1V driving voltage the current density passing through the coating calculates to  $2.5 \times 10^{-8} \text{A}/\text{m}^2$ . This is a factor of about  $10^6$  less than the cathodic protection current density required for protection of an exposed steel surface.

Beavers & Thompson carried out tests on FBE that had a coating resistance of  $10^8 \Omega\text{cm}^2$  [9] For a  $400\mu\text{m}$  thick film and a 1V driving voltage it provides a current density of  $2.5\text{mA}/\text{m}^2$ . This may allow sufficient transport through the coating to provide the alkaline environment necessary to protect steel in an enclosed blister. However if the blister cracks under environmental stress and the steel is exposed to an oxygenated electrolyte that may contain chloride ions, the current density may not provide the required protection.

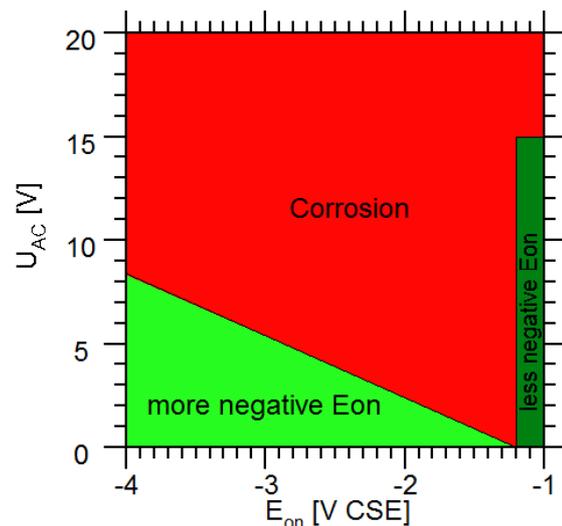
Unfortunately there is presently no cathodic protection monitoring technique that will detect corrosion initiation under disbonded coating in a field environment. Similarly there does not appear to be a proven coating defect location technique that can detect disbonded coating at present. This is a significant risk to cathodic protection preventing pipeline corrosion.

## 4.5 Alternating Current Corrosion

In spite of a substantial amount of research there is no simple criterion as to when AC induced into a pipeline will cause AC corrosion. (Refer to EN 15280 Clause 7.) It appears that the criterion will be based on AC and DC current densities at the coating defect [11] however at the pipeline design stage induced voltage calculations give us a voltage. Translating this voltage into current density involves making risk based assumptions. Figure 6 presents a current density criteria map for AC corrosion from EN 15280 Appendix E. Figure 7 presents an AC and DC on-potential AC corrosion criteria map, also from EN 15280 Appendix E. As the relationship between current density and on-potential is a function of soil resistivity and coating defect size and shape Figure 7 is based on certain assumptions. However it is apparent that AC corrosion can occur at any pipeline on-potential depending on the AC current density. Therefore this is a significant risk to cathodic protection preventing pipeline corrosion.



**Figure 6: AC Corrosion Current Density Diagram**



**Figure 7: AC Corrosion On-Potential Diagram**

When a section of a pipeline is subject to significant AC induction under powerline load conditions the use of on-potentials or off-potentials will not indicate the probability of AC corrosion without making assumptions about soil resistivity and coating defect size and shape. Polarization probes and coupons allow the determination of AC and DC current densities, however the research is yet to provide definitive current density criteria. The resistance probe will indicate if corrosion is occurring as its measurement is independent of potential and current density. However there is an assumption in relating the size of the resistance probe to that of the coating defects and how this affects current density.

Figure 7 does indicate that AC corrosion will not occur at a DC on-potential of -1200mV Cu/CuSO<sub>4</sub> and potentials less negative if the AC is less than 15V. This may explain the lack of AC corrosion issues in Australia where we tend to set our impressed current systems to a drain point of -1200mV Cu/CuSO<sub>4</sub>.

#### 4.6 Shielding by Adjacent Structures or Objects

A pipeline can be shielded from receiving adequate cathodic protection current by either [12]:

- a) Close proximity to an insulated surface such as may be caused by:
  - A second pipeline laid in the same trench where there is a coating defect on one of the pipelines,
  - A plastic conduit installed in the same trench where there is a coating defect on the pipeline,
  - A horizontal directional drill where coating is removed by pulling the pipe against a high resistivity rock surface and that rock surface remains close to the steel at a coating defect, or
  - A stone in the trench penetrates the pipeline coating to the steel surface and remains close to the steel surface.
- b) Close proximity of a cathodically protected surface such that the cathodic protection fields of the two cathodically protected structures overlap. The cathodic protection shielding can

occur between structures at greater separation distances than is the case with an insulated surface shielding mechanism. The degree of shielding is dependent upon the soil resistivity, the cathodic protection driving voltages and the separation between the two structures [11]. It may be caused by:

- Two pipelines laid in the same trench with the coating on each of the pipelines damaged at the same location, or
- A pipeline approaching a cathodically protected facility such as a wharf, jetty or a plant where the earthing is included in the facility cathodic protection system.

In either case on-potentials or off-potentials will only monitor the remote condition and not the conditions in the shielded geometry. Polarization probes, resistance probes and coupon off-potentials will only monitor the situation if they are located in the shielded geometry. This presents a significant risk is a significant risk to cathodic protection preventing pipeline corrosion.

#### **4.7 Sulphate Reducing Bacteria**

Some international standards, including ISO 15589-1, indicate that a potential of  $-950\text{mV Cu/CuSO}_4$  is the protection criterion if active sulphate reducing bacterial are suspected of being present. There are a number of issues with this as a protection criterion:

- Most pipelines will encompass anaerobic soils at some locations along their length. Most soils contain sulphate reducing bacteria, although they may be dormant due to the environmental conditions. Testing for the bacteria can make them active therefore the default protection criterion for most pipelines can become  $-950\text{mV Cu/CuSO}_4$ . However the field sampling and handling procedure for the soil samples can result in the bacteria being killed and therefore areas that do contain active bacteria may not be detected.
- There is sufficient work published indicating that even  $-1000\text{mV Cu/CuSO}_4$  is inadequate to prevent bacterial induced corrosion [13].
- Once the bacteria form nodules it is unlikely that any cathodic protection potential will prevent the corrosion due to the high resistance shell that forms part of the nodule. The high resistance shell is also likely to prevent any cathodic protection monitoring techniques indicating that bacterial corrosion is occurring. They will just reflect what is occurring at exposed steel and on the surface of the nodule.

This presents a significant risk to cathodic protection preventing pipeline corrosion.

In Australia I am not aware of any cases of external pipeline bacterial induced corrosion. This may be due to the practice of installing temporary cathodic protection as soon as pipe is installed. The temporary cathodic protection should increase the pH of the environment at all coating defects to a level in excess of pH 10 before bacterial slimes can form. This should inhibit further bacterial activity. As the bacteria are not active the  $-850\text{mV Cu/CuSO}_4$  protection criterion should be adequate.

#### **4.8 Hot Pipelines**

Increasing pipeline temperature increases the rate of the cathodic protection reaction (the cathodic protection current density) and the cathodic protection criterion becomes more negative which further increases the current density. While calculations to determine the protection criteria and

current density for hot onshore pipelines can be carried out such significant assumptions have to be made that standards for onshore pipelines tend to ignore the issue. The efficacy of the cathodic protection can be further complicated by the elevated temperature of the pipeline drying out the soil in the vicinity of the pipeline thus substantially increasing its resistivity and making the provision of the high level of current density problematic.

If the cathodic protection monitoring is to be carried out with coupons or resistance probes they need to be installed immediately adjacent to the pipe to ensure they experience the effect of the increase in resistivity of the soil, and may need to be installed on the pipe surface so that they are at the temperature of the pipe.

Pipelines at elevated temperatures present a significant risk to cathodic protection preventing pipeline corrosion.

#### **4.9 Backfill Voids**

While all pipelines laid in Australia are provided with bedding and padding of sand or fine graded backfill, there have been occasions on steep slopes where the trench breakers were insufficient to prevent water flowing in the trench and washing out the fine backfill material. The resultant voids are areas where cathodic protection is ineffective and corrosion can proceed due to the very humid environment allowing condensation on the pipe surface. A similar example has occurred where a pipeline in a rock trench backfilled with sand exhibited significant pitting even with a measured pipeline on-potential of  $-1500\text{mV Cu/CuSO}_4$ . This issue also applies carrier pipes installed inside casings where there is no annular fill.

Areas where the pipeline is not in electrolytic contact with the bulk electrolyte present a significant risk to cathodic protection preventing pipeline corrosion.

### **5 CONCLUSIONS**

Cathodic protection is being presented as a technique for preventing pipeline corrosion. This is not always the case. There are practical conditions where it is ineffective, however this risk is not adequately addressed by the pipeline industry. The forward in the Australian pipeline cathodic protection standard says:

“While cathodic protection can prevent corrosion there are circumstances where it may not be effective, even if protection is indicated by potential monitoring techniques carried out at test points. Therefore the determination that cathodic protection is achieved is a risk based judgment dependent on an evaluation of a number of parameters.”

ISO15589-1 says in a note in the scope:

“Special conditions sometimes exist where cathodic protection is ineffective or only partially effective. Such conditions can include elevated temperatures, disbonded coatings, thermal-insulating coatings, shielding, bacterial attack and unusual contaminants in the electrolyte.”

However these words do not give pipeline owners / operators / regulators the information needed for input into a risk evaluation methodology that allows for a realistic evaluation of the risks associated with relying on cathodic protection and coatings to prevent corrosion of pipelines. More work is required in this area.

## 6 REFERENCES

1. Martin B, "Potential measurement on buried pipelines", Cathodic Protection Theory and Practice (Editors V Ashworth & C Booker), Ellis Horwood, England, 1986, 276-292.
2. Martin B & Brinsmead H. "A method for determining pipeline polarised potentials in stray current areas using linear regression analysis", Industrial Corrosion, (ICorr) 3(3) (1985) 10-14
3. Martin B, "The ohmic component of potential measurement - laboratory determinations with a polarization probe in aqueous environments", Materials Performance (NACE) 20(1) (1981) 52-57.
4. Barlo T & Fessler R. "Interpretation of the true pipe-to-soil potential on coated pipelines with holidays", Proceedings NACE Corrosion 83, Paper 292, April 18-22, 1983, Anaheim USA
5. Martin B & Brodribb R, "Cathodic protection issues with ultra-well coated pipelines", Proceedings Australasian Corrosion Association Conference 2007, Lead Paper 15, Nov 25-28, 2007, Sydney, Australia
6. Martin B, "Stray current corrosion", Proceedings Australasian Corrosion Association Conference 2001, PFT Memorial Lecture, Nov 19-21, 2001, Newcastle, Australia.
7. Martin B, "Telluric effects on a buried pipeline", Corrosion (NACE) 49(4) (1993) 343-349.
8. Martin B, "The limitations of cathodic protection", Proceedings Australasian Corrosion Association Conference 1985, Nov 11 - 15, 1985, Newcastle, Australia
9. Beavers J & Thompson N, "Corrosion beneath disbanded coatings", Proceedings NACE Corrosion 96, Paper 208, 1996, Denver, USA.
10. Kehr J et al (3M Company), "Fusion-Bonded Epoxy and Dual-Layer FBE Materials Provide Enhanced Performance for Pipeline Installation", Proceedings ASME India Oil and Gas Pipeline Conference 2007, October 15-18, 2007, New Delhi, India.
11. Buchler M & Schoneich H, "Investigation of alternating current corrosion of cathodically protected pipelines - development of a detection method, mitigation measures, and a model for the mechanism", Corrosion (NACE) 65 (9) (2009) 578-586.
12. Martin B, "Cathodic protection shielding of pipelines", Materials Performance (NACE) 21 (2) (1982) 17-21.
13. Romero M et al, "Cathodic protection efficiency in the presence of SRB: state of the art", Proceedings NACE Corrosion 2009, Paper 9407, 2009