Electrical Short Pipeline Potential Measurement and its Implication in Pipeline CP Management Practice

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Introduction

The most important performance indicator for cathodic protection (CP) is the structure-to-electrolyte potential [1, 2]. In most coated on-shore pipelines, the resistance between the reference electrode and the pipe-to-soil surface boundary is too significant to be ignored. [3] [4]. The IR drop caused by CP current is a measurement error. It is stipulated in many cathodic protection (CP) standards that the IR component to be evaluated and excluded while assessing the pipe-to soil potential performance in pipeline integrity management [5].

For a well-coated pipeline, the most practical monitoring technique is to use a synchronised interrupting technique by bringing the CP current to zero and to measure the potential momentary after the current source is off. By switching all sources of current to zero, the measured potential is approaching polarization potential by virtually eliminating the IR component in the CP electrical circuit [4]. This technique has been widely accepted and adopted in the pipeline industry for decades.

Most modern pipelines are electrically isolated from above ground facilities, either through a flange isolation kit (FIK) or Monolithic Isolation Joint (MIJ) [6]. This is to prevent excessive current drain to electrical earthing systems which may be uneconomical or impractical. They prevent the CP current flowing to other facilities and equipment that are otherwise electrically connected to pipeline. However, in practice, the effectiveness of these electrical joints can be compromised by deterioration, or by debris in the internal surfaces, which leads to the electrical short of the pipeline to above ground facilities and their associated electrical grounding system, from time to time. The earthing system, governed by local regulation and standards, is typically copper or copper-clad steel rod conductors. The implication of this electrical short to such earthing systems in CP measurement has not been fully explored or fully understood by the industry.

There is a general misconception in industry to use OFF instead of free potential measurements without further analysis, partially because it is not easy to measure IR free potentials as well as different sizes for coating defects. In general, this is quite difficult to evaluate, and would not generally impact the entire pipeline. This article however, describes testing on a new pipeline with little coating defects (proven by DCVG), known electrical short to earth (proven by current testing), the entire pipeline (20 Km) showing an apparent great IR drop by the INSTANT OFF technique (-1250mV ON and -500mV OFF). Due to difficulty in fixing the failed isolation, the general recommendation was to increase the current output to improve the measured INSTANT OFF potentials, to meet the -850 mV criteria.

Quick depolarisation of electrically shorted pipeline

The effectiveness of the CP relies on the efficacy of pipeline electrical isolation from connected station electrical earthing systems, achieved through MIJ and FIK. Pipeline operators experience showed that the effectiveness of electrical isolation joints (IJ) can be gradually breached. It appears that magnetic conductive particulates (mainly magnetite and pyrite) as well as hematite accumulating internally may be responsible for the electrical shorting in some pipelines. The magnetite and pyrite are good electrical conductors. Once trapped in MIJ/ FIK, they may lead to the CP current leakage through the FIK / MIJ. This results in the CP current being undesirably lost to the nearby earthing system. The anomaly is normally rectified through routine cleaning pigging practice. However, in oil and gas upstream pipelines, it is not always feasible to maintain the electrical isolation due to high fluid conductivity, design and maintainability limitations. If electrical isolation cannot be readily restored, the pipeline may suffer a long term of electrical short to local earthing systems. Therefore, it is important to understand how to manage the pipeline CP system under such electrical short conditions.

An apparently quick depolarisation of pipe potential during CP surveys using current interrupting technique for electrical shorted pipeline is often observed. For a newly built 21 Km DN 450 pipeline, while ON potential is maintained at -1250 mV, the OFF potential for the entire line can range from -1000 mV (sound electrical isolation status) to -500 mV (electrical shorting). This apparent IR drop is significantly higher than when electrical isolation was maintained even if there is no change in other conditions. It is not unusual that many operators tend to use higher output current to compensate for this IR drop and meet the “off” potential criterion. The question has been raised whether this IR drop is authentic or a measurement error. The implications for the issue are:

1) If the IR drop measured under electrical isolation failure is, authentic, then shift the pipe potential (OFF) more negative by increasing the current output is required to meet the protection criteria.

2) If this exceptional IR drop is due to measurement error, then compensating for it by increasing CP current output may result in unnecessarily high current and possibly over-polarisation with the risk of coating damage .

Experiment

Experiments were performed using a cathodic protection system equipped with a 0-36 VDC 0-5A 80 W laboratory DC power supply with constant voltage and constant current mode. The designated buried structure was a bare steel post (1000 mm x 100 mm x 100 mm). A 500 mm x 300 mm aluminium foil was buried as temporary anode bed and located 30 metres away from steel post to minimized the anodic voltage cone effect. A 400 mm x 400 mm copper plate was submerged in a nearby fresh water pond as a local earthing. A synchronised current interrupter and data logger were used to switch the current supply and the connection between the copper earthing and the steel structure. The data logger recorded the steel/soil and copper earthing/soil potentials. Buried copper/copper sulphate electrodes (CSE) at fixed locations were utilised as reference electrodes for potential monitoring. A current clamp (clip on ammeter) was used for testing the CP current in each circuit. A 500 Ω linear (B) and single Gang 24mm potentiometer was used to simulate the variable resistance incurred by internal debris through electrical isolation joints. The experimental configuration is shown in Figure 1. A number of resistances were selected by tuning the potentiometer to simulate the gradually increasing of isolation joint short.

The pipe/soil potentials of the pipe were measured by different methods:

Method A: The Instant OFF (near IR-free) “OFF” potential of steel pipe is measured while switch K1 is interrupted and switch K2 is closed during the testing. This is to simulate the interruption techniques used in a normal survey, when it is impossible to iinterrupt between the steel pipe and pipe and local earthing;

Method B: The Instant OFF (near IR-free) “OFF” potential of steel pipe is measured while both switches K1 (power supply) and K2 (IJ to copper earthing) are interrupted simultaneously.

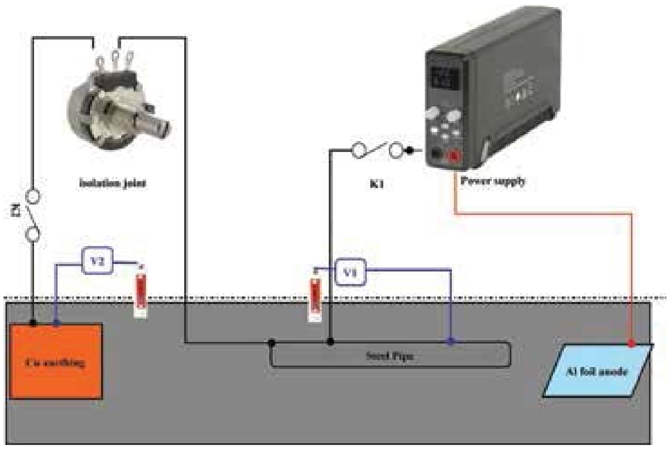

Figure 1: cathodic protection system for steel pipe short to local earthing.

Results and Discussion

Potential of pipe isolated to copper earthing

The On/Off pipe potentials are measured while the pipe is electrically isolated from the copper earthing. The average of the pipe/soil potential while on is -1263 mV and off potential is -933 mV. The loop resistance of CP circuit is an overall resistance of anode resistance, cable resistance and pipe resistance. In this case, the loop resistance is greatly impacted by the anode/soil resistance, with better compactness and increased moisture in the soil, the loop resistance is significantly reduced from 300 Ω to 150 Ω. It is intentional to keep the loop resistance at a reasonable high level, since this will maintain a constant overall resistance without being affected by the adjustment of IJ resistance.

Anodic voltage cone effect can be measured through potential shifting of isolated structure while the CP current is interrupted. In this case, the minimum interference is preferred for meaningful comparison. This is measured by the potential of nearby isolated metallic structure while CP current is interrupted. 1 mV/ mA toward positive direction shifting is observed in nearby isolated copper earthing. For pipe potential around -1250 mV, the isolated nearby copper earthing exhibited a ~11mV toward positive direction. The potential measured here is utilised as a reference ON and OFF potential while steel structure is perfected isolated to copper earthing.

Potential of pipe shorting to copper earthing

The pipe/soil potential of the pipe shorting to copper earthing through an adjustable potentiometer was measured with the resistance ranging from 2 ~ 500 Ω. The resistance of 2 Ω is to simulate the isolation joint in a dead short status. 500 Ω is to represent isolation joint in a better isolated status. An arbitrary selected resistance of 80 Ω and 190 Ω is used to represent the isolation joint shorted at different degrees.

Table 1: Potential of steel pipe electrically shorted to local copper earthing- measured by method A, interruption of current source K1 only.

IJ resistance	Steel On potential	Steel off potential	Off potential shift than * isolated pipe
Ω	mV	mV	mV
2	-1269	-760	173
80	-1180	-735	198
190	-1229	-794	139
500	-1289	-825	108
Average	-1242	-779	155

* Off potential in “Potential of pipe isolated to copper earth” section, ON -1263, OFF -933

The average of steel pipe off potentials by interrupting of K1 under different IJ shorting status (resistance), are listed in Table 1. This is to replicate the interrupting technique used in pipeline CP survey, while the IJ electrical isolation is compromised. It is identified, while the on potential is maintained at around the same level (-1250 mV), the off potentials measured are more positive than when it was isolated from the copper earthing. The average of positive shifting is 155 mV.

Table 2: Potential of steel pipe electrical short to local copper earthing – measured by Method B: interruption of both current source and IJ.

IJ resistance	Steel On potential	Average of Steel off potential	Off potential shift than * isolated pipe	ΔOff - steel pipe
Ω	mV	mV	mV	mV
2	-1272	-899	34	139
80	-1163	-884	49	148
190	-1221	-879	54	85
500	-1287	-872	61	47
Average	-1236	-884	50	

* ΔOff - steel pipe” as Table 1.

The average of steel/pipe off potentials by interruption of K1 and K2 simultaneously are listed in Table 2. Although the on-potential are maintained at the same level , the steel pipe off-potential showed significant negative shift compared to those measured by method A. It is evident that, by interrupting K1 only, and leaving the short circuit to the copper earthing in place, the pipe potential moves toward more positive range than when measured by interrupting of both K1 and K2.

On and off potential of copper earthing short to steel pipe

Off potentials of the copper earth to soil are measured simultaneously with steel pipe potential by both methods (Table 3). It is evident that the off potential of copper earthing measured by method A (by interrupting of K1 only) is more negative than when measured by method B (by interruption K1 and K2 simultaneously).

It appears both shifts become more pronounced once the IJ's resistance gets smaller (Figure 2). For steel pipe, with the reduction of IJ resistance (worse short status), the steel pipe Instant OFF potential shifts to further positive values when measured by method A. For an IJ resistance in 2 Ω and 80 Ω, the difference can reach to ~ 150 mV (Figure 2). The Instant OFF potentials of copper earthing show a similar trend but in a different direction. With less IJ resistance, the copper earthing to soil Instant OFF potential is more negative when measured with method A, than it is measured by method B. This positive shift can reach to approximately ~180 mV under this testing condition (Figure 2).

Table 3: Potential and IR drop of copper earthing short to steel pipe, measured by both techniques.

Resistance btw Cu/Steel	Copper earthing potential measured with Method A		Copper earthing potential measured with Method B		Difference in "off potential" measured between Method A & B
	On	Off	On	Off	ΔOff
Ω	mV	mV	mV	mV	mV
2	-1238	-746	-1238	-568	-178
80	-658	-529	-628	-393	-136
190	-501	-438	-496	-346	-92
500	-360	-345	-366	-323	-22

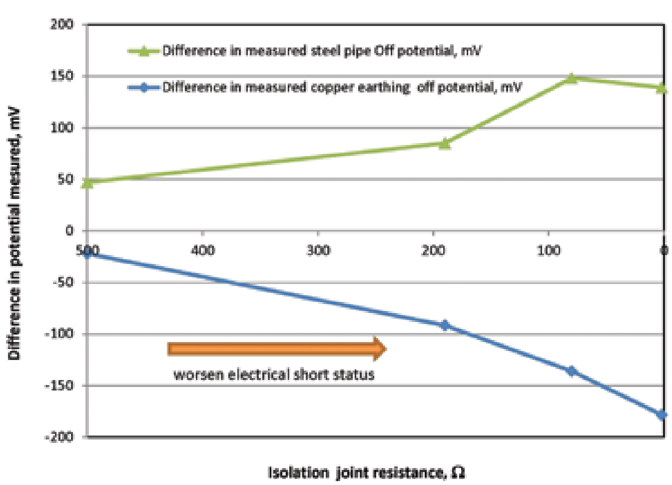

Figure 2: The difference of off-potential measured by two methods.

Current demand for steel pipe short to local earth

It is observed that there is no change of the current demand for the steel pipe no matter which method is utilised for potential measurement as long as ON potential is maintained at the same level. This strongly suggests that positive potential shift observed in the electrical shorted pipe is not caused by the polarisation status of pipe (Figure 3). Also, there seems no linear function between IJ resistance vs the steel structure potential shift observed. It appears that with the decrease of IJ resistance, the CP current is disproportionally attracted to the copper earthing. Therefore, even if the overall output current increases, there is no significant change for the portion contributed to steel structure polarisation.

The build up of deposits in gas pipelines is not uncommon. It can eventually result in shorting of steel pipeline to local station earthing. It is not surprising that the total current demand of the system increases with the further shorting of the IJ (smaller R). The copper earthing received most of the extra CP current while the steel on-potential was maintained at the same level. This has been observed in the pipeline CP operation. While the Transformer Rectifier (TR) is under auto potential mode, even there is no apparent on-potential change for pipeline, the total current demand for the pipeline could be exceptional higher than it was in electrical isolated status. The excessive CP current is picked up by local copper earthing and returns through the shorted IJ. This is easily confirmed by applying Swain Clamp in both sides of IJ. The operational experience also showed that the short of IJs is aggravated gradually with time with the indication of CP current ramping up during this period while in auto potential mode. The CP output current drops to a lower level while on-potential is maintained at the same level whenever the pig cleaning is performed (Figure 4). This strongly suggested that excessive CP current flows to copper earthing have been stopped when electrical isolation is restored.

While a TR is operating at constant current mode for pipeline in shorted status, the pipe/soil potential level will move in more positive direction. It is not uncommon that pipe/soil potential values deteriorate by ~ 300 mV for pipelines suffering a long term electrical short. When the short is rectified, the protection level of pipe is restored.

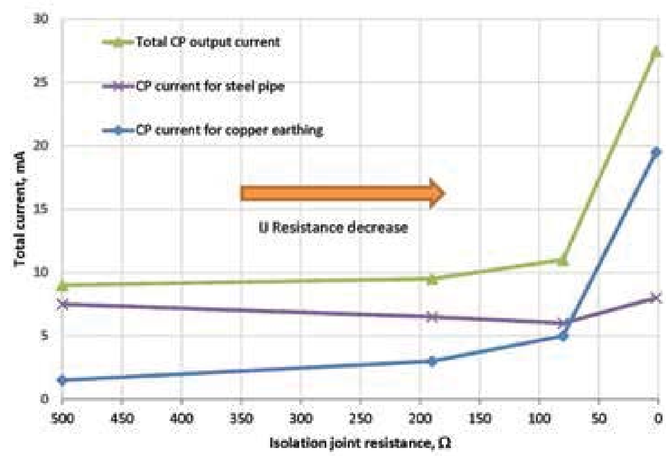

Figure 3: Current demand change while IJ is compromised steel pipe on-potential keeps constant.

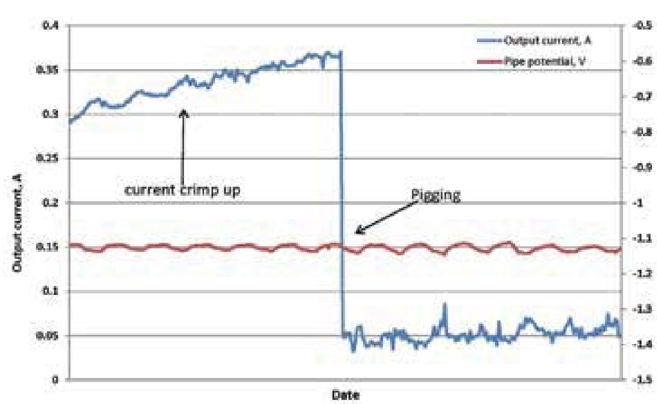

Figure 4: Step current drop after cleaning pigging for TR operating at auto potential mode.

The other interesting observation is, even with an electrical short to pipeline, the potential difference between steel pipe and copper earthing could be significant. Sometimes, the potential swing method cannot easily pick up the short status. This is believed to be due to two factors, 1) the compromised IJ is normally not a dead short, typically in its initial stage. This IJ resistance will take a portion of potential difference between pipe potential and earthing potential. 2) The ratio of polarization resistances between the copper earthing and the steel pipeline is significantly different, particularly for a well coated pipe. Therefore, the current demand to shift the copper earthing potential needs to be significant to be measured. The local electrical earthing for above ground installations or stations comprise copper earth rods and either bare or sheathed interconnecting copper cables or tapes in a low resistivity soil, therefore, a measurable potential shift requires significant current.

Copper /steel coupling effect in survey

It is evident that copper/steel coupling resulting from a shorted IJ will play an important role for the apparently quick depolarization observed in CP survey. Since K2 (IJ) is impossible to be interrupted during the survey, only method A can be deployed in CP survey for pipeline that is electrically shorted to the local earthing. However, interruption of K1 only will form a dissimilar metals Voltaic cell. The driving voltage of this cell is the potential difference between polarised copper earthing (i.e. cathode) and polarised steel pipe (i.e. anode). Electrical current flows from the copper earthing to the steel pipe through the metallic circuit including the IJ, and from steel pipe to copper earthing through soil (electrolyte) (Figure 5). In this process, it depolarises the anode (steel pipe) by shifting its potential further in the positive direction. Meanwhile, the cathode (copper earthing) is polarised toward further in a negative direction. The surface area ratio of cathodic and anodic plays a critical role here as well. A large ratio of bare copper to (largely coated) steel means more current is required before a copper potential shift can be easily detected. The steel pipe, particularly when well coated, will experience more significant and faster depolarisation in this process (Figure 5). This explains the quick depolarisation in steel pipe measured through method A. This voltaic cell won't occur if K2 can be interrupted as proposed in method B. unfortunately, it is impossible to achieve this in field test.

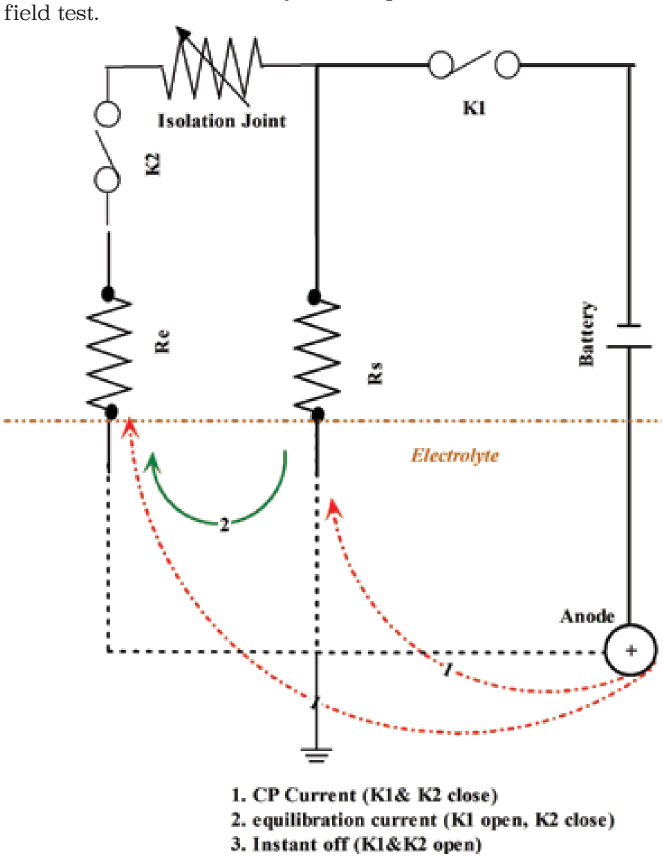

Figure 5: equivalent CP diagram to explicit the quick potential depolarization observed by method A.

CP Management Practice Implications

The implication of this voltaic current and its impact on CP monitoring is profound in managing the CP of a pipeline shorted to local electrical earthing.

TR unit operating management

IR errors in the soil need to be evaluated carefully in cases where the pipeline is shorted to a local copper earthing system while using conventional current interruption techniques. This investigation has proven that the pipe/soil potential IR errors measured by conventional current interruption techniques are contributed by two aspects, a) IR caused by soil/metal interface resistivity, and b) potential caused by re-circulation of equalisation currents in Cu/Steel voltaic cell. The IR drop caused by this voltaic cell current is a measurement error. In practice, to meet this falsified "off-potential" by forcing more CP current will be inefficient and may adversely put the coating under stress and may cause pre-mature failure of the coating. This is particularly important for some susceptible coating types, e.g. Fusion Bonded Epoxy (FBE) coating. The alkaline environment caused by very negative CP potential (over-polarisation) will lead to the increase of pH and coating disbondment. For this reason, the CP levels on pipelines should be managed in such a way to exclude this measurement error .

Another often omitted challenge for TR units operating under auto potential (potentiostatic) mode with an electrically shorted pipeline is the reference cell location. The TR units are often located at above ground installations or stations, proximate to the local electrical earthing system. High CP current flow to the earthing system due to the short to pipeline will cause a localised voltage gradient, i.e., cathodic voltage cone, around the bare copper. The reference electrode or cell located within this voltage gradient will falsely set its reference point more negative to the remote earth, and lead to higher current output and over-protection. This voltage gradient needs to be mapped and the reference electrode should be relocated out of the adversely affected location for a pipeline prone to electrical short; of course, if possible, the electrical short should be remedied.

IJ management

Isolation Joints (IJs, or MIJs) and Insulated Flanges (IFs or FIKs) need to be carefully managed for cathodic protection operation.

The effectiveness of the CP relies on the efficacy of pipeline electrical isolation from related above ground installations (or stations) earthing systems, achieved through MIJs and FIKs. Pipeline operators' experience has shown that the effectiveness of electrical isolation joints can be breached by internal conductive debris [7]. This results in the CP current undesirably discharging to the nearby earthing system. The anomaly is normally remedied through routine cleaning pigging practice. However, in oil and gas upstream assets, to maintain the electrical isolation by pigging is not always practical due to high fluid conductivity or design limitation. It is often identified that resistance in IJ deceases gradually with the accumulation internal deposit, until it reaches to dead short.

a) Design IJ installation so that electrical shorts to local earth can be readily rectified

In practice, it is not uncommon that in pipelines designed in such a way, that electrical shorts cannot be removed easily, this includes but not limited to:

- IJ located in a non-piggable path;
- the IJ cannot be removed /replaced without depressurising the entire pipeline;
- the IJ cannot be removed /replaced till the shut down of the entire gas facility.

In these cases, the CP has to be managed in an electrical short condition.

b) Specify effective methods of IJ or IF integrity measurements:

It is noted that most used field methods to check the integrity of IJ are the potential difference and potential swing method. Although these are simple, for a pipe shorting to a large local copper earthing system, these methods may not sensitive enough to pick up indications of the current leakage.

The use of a Swain Clamp to measure current flow in the pipeline adjacent to the IJ or IF is much more effective in detecting shorted joints. This technique will also locate partially failed (conducting) spark arrestors that are often fitted across IJs and IFs and are often not effectively tested.

c) Current monitoring for auto potential TR unit

Monitoring the current output is very useful in assessing the IJ's isolation status. A gradual increase in current demand from the TR operating in auto-potential mode is normally a sign that electrical isolation between pipeline and electrical earthing system been breached.

d) Integrity of IJ due to the stray current from earthing to pipeline through faulty IJ (internal stray current through faulty IJ)

There is always a concern that the resistive IJ with current jump can be associated with internal metal loss. Appropriate NDT and in line inspection technique have to be incorporate into the inspection regime to identify the metal loss [8].

Monitoring techniques

This study has demonstrated that, without interruption of current flowing through IJs or IFs simultaneously, the measured "off-potentials" will be erroneous. Unfortunately, it is impossible to interrupt the current flowing through IJs and IFs during CP surveys. Alternative monitoring techniques should be deployed for pipelines prone to electrical short.

a) Coupon off potential measurement

There is some controversy related to monitoring CP 'Off" potentials by coupon local disconnection [9]. Some argue that localised cathodic or anodic voltage cone can distort the coupon "off-potential" reading and mispresents the true pipeline protection status. However, the author supports this methodology to be used in a cautious manner. Although the local anodic and cathodic voltage cone caused by coating defects is realistic, the measuring error can be assessed by taking the pipeline measurement in a current interruption "on-cycle" and "off-cycle". This is more or less similar to interrupting both the K1 and K2 simultaneously to exclude the interference from voltaic current. The most effective method utilises a pre-synchronised interrupter inserted between this probe /coupon to pipe circuit to measure the off potentials concurrently with the 'general pipeline' OFF period.

b) Deployment of IR free coupons

There are reports for the use of IR free coupons (steel coupons with an integrated very close reference electrode) being used in the field successfully to assess the pipelines subject to telluric influence [10]. The benefit of IR free coupon can be utilised to assess the pipeline protection level without interrupting the current source [9]. In such a way, the voltaic current interference of bi-metal coupling can, theoretically, be eliminated. The size and shape of the probe or coupon influences the validity of the data collected [11].

c) ER probe method

By using ER probes, the electrical resistance can be measured, and is related to the corrosion rate. This is one of the accepted protection criteria in the Australian Standard [1]. The ER probe is connected to the buried pipeline, and is thus in the CP circuit. The aggregated metal loss for a period between measurements is determined and a corrosion rate can be assessed. This is a straight forward indication of pipeline CP status. It is widely used for pipeline external corrosion monitoring, particularly for pipelines affected by fluctuating interference. Surface strip element and cylindrical element types are most common designs for underground pipeline service. The size and shape of the probe or coupon influences the validity of the data collected [11].

Conclusion

The conventional current interruption technique brings significant error in measuring IR free potential in a pipe shorted to local copper earthing. This is believed caused by the voltaic current incurred by bi-metal electrochemical cell, produced after the current supply was interrupted. Forcing more CP current to meet "OFF" potential criteria will adversely lead to the over-protection and premature failure of pipeline coating. For pipe susceptible to electrical short, the regular cleaning pigging to restore the electrical isolation is always the preferred option. While it is not achievable, managing of CP for pipelines with electrical shorting have to take this measurement error into consideration. The TR unit operating management, Isolation joints management and suitable monitoring techniques are keys for the success in CP management for the electrical shorted pipeline.

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