ADVANCED SYSTEMS OF OVERLINE ASSESSMENT OF COATINGS AND CATHODIC PROTECTION

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INTRODUCTION

External corrosion control of buried pipelines is achieved by a combination of barrier coatings and cathodic protection. Overall the success rate of this combination has been exceedingly good but the extremely high environmental and economic costs and the over-riding safety implications of pipeline leakage mandates that the integrity of the external corrosion protection system is regularly and properly assessed.

By reference to a recently completed coating quality and cathodic protection performance survey for a large pipeline network in North Africa the paper will detail:

- **why overline surveys are necessary**

- **the initial construction damage and the in service deterioration of pipeline coatings**

- **the related increasing demands for cathodic protection current in order to provide corrosion protection at these areas of coating deterioration**

- **the impact of third party pipeline, cathodic protection, rail and ac power distribution systems on the overall external corrosion control**

- **what overline surveys are available**

- **the use of advanced close interval potential survey (CIPS) and integrated recorded direct current voltage gradient (DCVG) survey techniques to characterise the combined coating and cathodic protection systems, to locate and assess coating defects and to determine the levels of cathodic protection**

- **the use of the integrated CIPS and recorded DCVG survey data to prioritise remedial work to both cathodic protection systems and the pipeline coating**

- **the need for International Standards**

- **a case study : SUMED Pipeline, Egypt**

- **problem areas : disbonded coatings, cased crossings, other shielded locations**

WHY ARE PIPELINE OVERLINE SURVEYS NECESSARY?

PIPELINE COATING DEFECTS AND DETERIORATION

Pipeline coatings and their performance have developed markedly in the last three decades. However they still are subject to damage and deterioration caused by factors identified in the 1970's (1):

- damage during handling and laying
- failures during commissioning and operation
- rock penetration during installation and service
- soil loading and shear failure during operation
- lack of coating integrity at elevated temperature
- disbonding through pipe movement and lack of adhesion
- disbonding due to inadequate surface cleaning
- enhanced failure at low temperatures

to which should be added

- poor coating electrical insulation properties due to improper formulation or application (e.g. poorly formulated asphaltic enamels in the former Soviet Union, "coked" hot applied enamels, thinly applied fusion bonded epoxy)
- deteriorating coating electrical insulation due to moisture absorption and/or general breakdown of coating film
- characteristic failures of particular coatings (e.g. spiral corrosion and disbondment with tape coatings with inadequate properties/overlap, disbondment of fibre reinforced coal tar and asphaltic enamels at elevated temperatures particularly in moist conditions.
- failures of inadequately designed or applied field joints and repairs
- damage due to third party interventions (e.g. deep plough or excavation damage).

As long ago as 1970 the author was responsible for surveying the electrical properties of the coating applied to a (then) recently constructed 18 in. dia. pipeline in Pakistan, as an acceptance test for the quality of the coating and the extent of construction damage. This technique used the classical attenuation calculation of pipe/soil potential from the cathodic protection drain point to points distant from it and utilised measured pipe/soil potential shifts along the pipeline to provide data from which coating conductance could be calculated. The technique was similar to that published in the late 1950's (2).

Most recently the results of a Spanish study of the number of construction coating defects detected by the analogue DCVG technique on 27 new gas pipelines coated with three layer polyethylene has been published (3). The author concludes that an average of 2 No. defects detectable by the analogue DCVG technique can be anticipated per kilometre of pipeline during construction but that the actual values for pipelines in the 3 in. – 12 in. dia. size range surveyed were between 0 and 14 defects/km.

It is well established that even the most theoretically robust coatings will be subjected to construction damage even if the coating application system can theoretically produce a defect free coating.

It is similarly well established that, for the reasons indicated above, coatings will deteriorate with time.

John Morgan in his book "Cathodic Protection" (4) presents data implying a 10 fold increase in current demand for plastic tape coatings over 30 years (0.001 to $0.01 \mu A/.m^2$) and for coal tar and bitumen enamels respectively a 100 fold increase (0.01 to $10 \mu A/m^2$) and a 10,000 fold increase ($0.1 \mu A/m^2$ to $1000 \mu A/m^2$) over the same period. These figures are based upon practical data and incorporate the effects of coating defects and not just deterioration of the coating electrical characteristics.

The result of the deterioration in electrical properties of coatings with time, due to both mechanical damage causing through-coating defects and the general reduction of coating electrical resistance due, principally, to water uptake is that:

- cathodic protection current demand will increase with time, say from $35 \mu A/m^2$ to as much as $500 \mu A/m^2$ for asphaltic or coal tar coatings in moist environments.

- due to the current/potential attenuation characteristics of pipelines this increase in current demand will not only require an increase in cathodic protection current output, it will also reduce the length of pipeline that can be protected from one cathodic protection station. For the $35 \mu A/m^2$ increasing to $500 \mu A/m^2$ example, a 14 in. dia. pipeline of 0.375 in. wall thickness can be well protected at commissioning with cathodic protection installation at some 2.5 amperes spaced every 46km along the pipeline. The deterioration of coating resistance to a current demand of $500 \mu A/m^2$ will require cathodic protection installations operating at some 10.7 amperes spaced every 15km along the pipeline

- Localised coating defects may result in inadequate levels of cathodic protection at the defect even if the overall levels of cathodic protection are adequate.

THIRD PARTY DAMAGE AND INTERACTION

Concurrently with the general deterioration of pipeline coating with time there are the possibilities of other third party actions causing increased risk of corrosion damage to pipelines. These can be summarised as:

- impact damage/gouging, or notching, of the pipeline which may render the pipe vulnerable to rupture, either immediately or by a delayed failure due to stress or fatigue induced crack growth from the mechanical defect. This crack growth may be enhanced by inadequate cathodic protection at the damage site, where the coating will also have been damaged, allowing corrosion fatigue or stress corrosion cracking to proceed.

  Many pipeline failures are due to impact damage, indeed this is reported as the most frequent cause of reportable incidents on US gas transmission lines (5).

- contacts with buried metallic items, in particular unprotected pipelines. These will cause significant localised current demands and even quite small pipework systems in contact

with a "protected" pipeline may prevent adequate cathodic protection over a significant area.

Similar effects arise from steel castings at road/rail crossings failing to maintain their isolation from the carrier pipe, resulting in corrosion risk to the carrier pipe.

- third party or "second comer" pipelines installed in the vicinity of an established pipeline brings the risk of dc stray current interaction from their (new) cathodic protection system. Similarly, existing third party pipelines and their cathodic protection systems present increasing risks of interaction as their coatings deteriorate and their cathodic protection current increases.

- dc rail systems are a severe cause of interaction to buried pipelines and the effects can be detected over many kilometres from points of proximity between pipeline and rail.

Interaction can cause severe localised corrosion as relatively large currents can be collected over long lengths of pipelines in proximity to interaction sources. These currents must return to the rail earthing system or third party pipeline to complete their circuit and the point of return can be a localised coating defect close to the third party pipeline. In simple terms 1 ampere of current discharge from a pipeline for 1 year will consume 10kg of steel. Many pipeline failures are attributed to stray current corrosion; this is the second most prevalent cause of pipeline corrosion leaks (after "galvanic" or localised corrosion cells) in a US Office of Pipeline Safety study (6).

- ac power distribution systems in the vicinity of pipelines can induce significant ac current onto buried pipelines. In recent years the significance of this has become more clear. The discharge of ac current in excess of 30A/m^2 is considered to be sufficient to cause significant corrosion even if the (dc) cathodic protection levels appear to be adequate (Ref 7).

For many older pipelines there are inadequate provisions for monitoring and mitigating induced ac. Even for those pipelines where provisions were adequate, the development of greater capacity electricity transmission systems in the vicinity of existing pipelines and the practice of shared utility rights of way often result in increased ac problems during the operating life of a pipeline.

AVAILABLE PIPELINE SURVEY TECHNIQUES

The author has reviewed the available survey techniques for pipeline coatings and cathodic protection along with the criteria for protection (8). The importance of measurements that are recorded, are subject to an audit trail and accurately measure pipe/soil potential without errors due to current flows through the soil, which are termed IR errors, are detailed therein.

In summary the location of defects in pipeline coatings, due to mechanical damage, soil stress, chemical attack and "general ageing" of coatings has been widely practised using techniques such as the Pearson Survey, Current Attenuation Surveys (e.g. C-Scan) and "Direct Current Voltage Gradient" (DCVG) surveys.

These techniques all have their place in assessing coating quality but they have the following drawbacks:

- they ONLY assess the coating quality and NOT the level of cathodic protection at located defects.

- the Current Attenuation surveys produce an average coating assessment over a relatively long section of pipe, not precise coating defect location. This is excellent in prioritising subsequent survey and rehabilitation work but not in assessing local corrosion control performance.

- the Pearson and DCVG surveys are intended to locally assess coating quality and locate defects but they are generally non-recorded surveys and are therefore vulnerable to operator error and lapses in training and diligence.

It is generally accepted that the DCVG survey, if properly executed, is the best of these coating survey systems to locate and to characterise the coating defects. It is repeated that they do not adequately assess cathodic protection levels and therefore do not give a full assessment of external corrosion control.

The assessment of cathodic protection levels or efficacy is similarly widely practised using various alternative "Close Interval Potential Survey" (CIPS) techniques. These systems measure the "ON" and more accurate "INSTANT OFF" pipe/soil potential at intervals along the pipeline. It is necessary to note that:

- not all CIPS survey techniques are of equal quality or give equivalent accuracy.

- the best CIPS surveys collect accurate "ON" and "OFF" data every 1-2 metres over the pipeline. The difference between the "ON" and "OFF" value is the 'IR drop error' and is determined by the local current density and the circuit resistance, predominantly the soil resistivity.

- the worst CIPS surveys collect "OFF" data only every 5 metres or so and both the "ON" and the "OFF" data may have significant measurement errors due to poor or no synchronisation between the CIPS data loggers and the CIPS switching devices that interrupt the cathodic protection power supplies.

- International Standards are inadequate in defining the principles of CIPS surveys or the necessary data collection procedures and quality management regime to ensure accurate data and interpretation

The most fundamental change in the application of cathodic protection to buried pipelines and other structures in the last 30 years has been the widespread understanding that the applied steel/soil potential for adequate corrosion control, –0.85 volts wrt $Cu/CuSO_4$ (sat) in aerobic conditions or –0.95 volts in anaerobic conditions, MUST be measured without IR errors. Although various other correction or avoidance methods have been proposed, the only effective method of measurement without IR error is to briefly interrupt the current and measure "INSTANT OFF" values prior to any significant depolarisation caused by the cessation of the current. (Figures 1 and 2).

The magnitude of the IR drop error in simple pipe/soil potential measurements taken with the cathodic protection system switched ON is significant and may be in excess of 1 volt. The IR drop error will vary with soil resistivity, being greater at higher resistivities. The IR drop error will vary with coating defect size, being greater at larger defects. All these IR drop errors will falsely indicate a more satisfactory level of cathodic protection than actually exists. (9,10).

This matter was well understood and documented in Germany and continental Europe in the late 1960's-early 1970's (11). This knowledge was not reflected in the UK Standards in 1973

(12) but was in the period 1985-1991 (13, 14, 15). North America, which influences much of the practice in the international oil sector, was categorically and incorrectly stating that the pipe/soil/potential criteria should be assessed by voltage measurement "with the protective current applied" in 1983 (NACE RP 01 69 - 83) but (after much commercially driven opposition) revised this in 1996 with the imprecise terminology that "voltage drops other than those across the structure – electrolyte boundary must be considered for the valid interpretation of this voltage measurement". (16).

Concurrent with the understanding that IR drop errors must be eliminated from steel/soil/reference electrode potential measurements for pipelines (and other buried items such as tank bottoms) it became clear that the practice of measuring "representative" pipe/soil potentials at circa 1km spacings along pipelines, even if IR drop errors were eliminated, did not indicate adequate protection to all of the pipe. The US Office of Pipeline Safety Report (6) stated that "pipe/soil potentials measured at fixed locations (test points) may fail to indicate inadequate protection at a point between the points of measurement".

CLOSE INTERVAL POTENTIAL SURVEYS (CIPS)

Close Interval Potential Surveys of pipelines are executed by deploying some form of portable data logger connected through existing test point connections to the pipeline via a long trailing cable and measuring the pipe/soil potential at every 1-2 metres along the pipeline with respect to reference electrodes carried by the data logger operator. (Figure 3).

In order to achieve measurements of both "ON" (including IR drop error) and "INSTANT OFF" potentials (in principle excluding IR drop error), the sources of cathodic protection current require to be interrupted; typically they are switched ON : OFF in a ratio of 3-5 : 1 to avoid depolarisation during the survey. As most pipelines have more than one source of current (transformer-rectifiers, bonds to other networks, sacrificial anodes) it is often necessary to deploy multiple switching devices or current interrupters. ALL must be accurately time interlinked; the best available systems use either accurate crystal oscillator timing devices with micro-processor controlled temperature compensation or utilise terrestrial or satellite timing signals to achieve a timing synchronisation within +/- 10 milli-seconds over 24 hours. There are poor systems where the synchronisation accuracy between switching devices is +/- 100mS/24 hours or more. (Figure 4).

It is critical for accurate and discrete ON and INSTANT OFF data sets that each measurement designated as, for example, INSTANT OFF, is measured in a period when ALL sources of cathodic protection current are switched off and when inductive and capacitive "spikes" which follow switching have decayed. The best systems can typically wait 100mS after the nominal switch off point to accommodate the +/-10mS synchronisation errors and the circa 50mS spike decay period and then count or measure over the next typically 100mS. (Figures 5 and 6).

In order for this precision to be achieved, the data logger must also have the capability to be synchronised to the same +/-10mS accuracy. These factors were well established in the mid 1980's (15) but many CIPS surveys are still undertaken with inadequate equipment, to poor specifications that do not reflect the requirement to collect accurate data. It should be noted that "INSTANT OFF" data collected in a period where there is some element of current on will falsely show a better level of cathodic protection; under-protected areas at corrosion risk may not be located.   (Figure 7). Many simple CIPS survey systems use low cost inaccurately timed switching devices and low technology data loggers that are not accurately time synchronised to these switchers. The data loggers are programmed to simply detect and record the "most negative" pipe/soil potential within a selected period as "ON" and the least negative as "OFF". This lack of precision timing or synchronisation between switching devices and loggers can introduce significant errors as both the "most negative" and the

"least negative" value can contain errors due to switching spikes, reactance effects and due to the logger measurement period incorporating a partial period of out of synchronisation switching by one or more of the switching devices.

CIPS surveys with inadequate instrumentation executed to inadequate specifications produce inadequate and inaccurate data but cost very little less than CIPS surveys with properly time synchronised equipment used to appropriate survey specifications, producing a complete and accurate record of pipeline cathodic protection efficacy.

In stray current areas the pipe/soil potential will vary with time and the best CIPS systems with precision synchronisation between data loggers and switching devices will be able to deploy "static" data loggers that will record the overall pipe/soil potential changes due to stray current (interaction or geomagnetic). They will also be able to measure soil potential gradients on both sides of the pipeline to determine the magnitude of the stray current flowing on and off the pipe. It may be appropriate to use this data to "correct" the CIPS data plots of pipe/soil potential vs. distance, but only if all 3 channels of individual data sets from the "mobile" CIPS data logger, the soil potential gradient and the "static" data logger can be correlated at the same time. This is possible with the precision synchronisation +/-10mS of the best equipment. This technique can be further enhanced by using more than one "static" unit so that the distance between the "mobile" and "static" units is minimised, a procedure sometimes termed "proximity static" recording. (Figure 8).

This use of accurately time synchronised data loggers (both static and mobile with soil potential gradient measurements) and accurately time synchronised switchers is now being termed an "Enhanced CIPS" survey as it ensures accurate data and a true detailed recorded record of the extent of cathodic protection of the pipelines. (Figure 9).

Although these "Enhanced CIPS" surveys constitute the most accurate and detailed cathodic protection assessment over the length of a pipeline it is appropriate to note that there are other factors that do introduce errors into the data recorded. These are the dc equalisation currents that flow between coating defects on the pipeline when the cathodic protection current is switched OFF and also the effects of ac interference both on the measured potential and on corrosion at coating defects.

Additional calculations can correct measured OFF potentials to true IR free data (17, 18) and measurements can be undertaken, in particular by using coupons and very fast data logging techniques, to resolve ac interference issues (19).

DIRECT CURRENT VOLTAGE GRADIENT (DCVG) SURVEYS

A complementary pipeline survey system to CIPS is the Direct Current Voltage Gradient (DCVG) survey, although some proponents consider DCVG to be an alternate to CIPS. Whereas a properly executed CIPS survey, with precision synchronisation between data loggers and switching devices, will categorically define the level of cathodic protection on a pipeline and the data will indicate the location and severity of coating defects, it is not principally a coating defect survey.

A DCVG survey will not categorically define the level of cathodic protection on a pipeline but will provide different data to better locate and characterise coating defects than CIPS. To date, DCVG surveys have not recorded their data and are therefore particularly sensitive to operator quality, motivation and training. Even when supplemented with local cathodic protection measurements at defects, analogue DCVG surveys do not provide a full record of cathodic protection performance.

DCVG surveys also suffer from a lack of an accurate distance measurement system and from the problems arising from pegging or paint marking defects for subsequent approximate location recording. These problems can, to some extent, be resolved by integrating GPS positional data at the locations of detected defects.

A DCVG survey is executed by switching the cathodic protection system (all or part) ON/OFF and recording the dc voltage gradient between two reference electrodes a nominal 1.5m apart above the pipeline. (Figure 10). The technique does not connect to the pipeline for measurement, does not measure pipe/soil potential (but this is normally done at test posts as a supplementary activity), but does measure the voltage gradient in the soil in the vicinity of the pipeline due to the cathodic protection current flow. (Figure 11). It can therefore be used, measuring maximum and minimum voltage gradients, to locate and characterise coating defects and other high current density demands such as contacts to other metallic services. (Figure 12).

DCVG surveys have been demonstrated, when executed by properly trained and motivated personnel to be more sensitive in the location of defects than the ac Pearson survey that has been used for many years for this purpose. However, the Pearson survey can be relatively easily recorded and some operators will prefer the reduction in operator error risk and the ability to quality audit the recorded data from the recorded Pearson survey to the non recorded, operator sensitive, DCVG survey. Conversely the DCVG technique, when used by a specialist, is a fine technique for coating defect location as part of a small scale and detailed fault investigation.

COMBINED CIPS AND DCVG SURVEYS

Some CIPS survey equipment can now accommodate the recording of DCVG data concurrently with the CIPS data. This not only provides the advantages of both systems, a full cathodic protection performance record and better location and characterisation of defects, but it also provides for a more rigorous defect sizing calculation technique. In a similar manner to the importance of IR drop error free potentials being understood at an early date in Germany, the value of data collected by combined CIPS and DCVG surveys was well established in the late 1960's – early 1970's in continental Europe (11) but is only recently being transferred beyond that region. (Figure 9).

The well established German Standard DIN 50 925 specifies what is generally known in those countries influenced by German standards as an "Intensive Survey". (17). This Intensive Survey technique has been widely practised by pipeline operators such as Rhurgas since the early 1970's and "comprises measurement of structure/electrolyte potentials and potential gradients both when the protection current is on and when it is switched off". The Intensive Survey is a combined CIPS and DCVG survey. The DIN 50 925 Standard recommends that these surveys are undertaken at least every 10 years or at shorter intervals if excavation or other construction work has taken place near the pipeline or if the pipeline is subjected to movement. The leading German text on this subject (18) recommends these surveys every 1 – 2 years for pipelines with a high necessity for safety.

DIN 50 925 states that "Assessment of corrosion protection ….. is based solely on the IR free (INSTANT OFF) potential". It describes in detail the voltage gradient measurements necessary to detect and characterise coating defects. This characterisation can extend to quantifying the size of the defects by a simple calculation method that has been in the public domain since 1977. (11).

The DIN 50 925 Intensive Survey has historically been undertaken very slowly using un-synchronised switchers and recording instruments.

The recent advances in combined CIPS and recorded DCVG instrumentation now make it possible to undertake these surveys in a strictly equivalent method to DIN 50 925 to provide the following survey parameters :

- Combined CIPS and DCVG as the "Intensive Survey" to DIN 50 925.

- Accurate INSTANT OFF pipe/soil potential every 1-2 metres over the pipeline, ensuring measurements at all coating defects.

- ON pipe/soil potential every 1-2 metres over the pipeline.

- Recorded DCVG (potential gradient) every 1-2 metres over the pipeline

- Coating defect location and characterisation (approximate size) recorded every 1-2 metres over the pipeline, where present.

- Accommodation of stray current/geomagnetic pipe/soil potential changes during survey by using measured soil potential gradient from both sides of the pipeline and static data loggers time synchronised to mobile data loggers to +/–10mS.

- accuracy of pipe/soil potential data can be ensured by time synchronisation between data loggers and current switchers to +/–10mS.

- survey speed of between 1-2 km per hour or 6-12 km per day including deployment of equipment.

- accuracy of defect location recording to within 1 metre by calibrated trailing wire, subject to terrain; it can be integrated with GPS data and GIS plotting if required.

These surveys produce the definitive record of BOTH coating defect location/size and cathodic protection levels, i.e. they fully measure and record the external corrosion control system parameters. (Figures 13 and 14).   They may be supplemented where necessary with additional calculations to determining the absolute IR free potentials from the Instant OFF values at defects (18) and by coupon measurements to determine ac corrosion risk. (19).

NORTH AFRICAN CASE STUDY

An integrated CIPS and recorded DCVG survey recently completed by the author's team is representative of a typical in service survey of this type and demonstrates many of the previously discussed features.

The pipeline network comprises twin 42 inch dia. pipelines running parallel for approximately 320Km between terminals. The pipelines carry crude oil. The terrain incorporates desert, mountain, sabkha (wet, saline desert), an industrial region, heavily irrigated farmland, fresh water crossings and salt water crossings. The pipelines are circa 25 years old and were originally coated with a butyl rubber/polyethylene tape system with an outer wrap for rock protection.

The network was originally provided with impressed current cathodic protection using transformer-rectifiers at approximately Km 0, KM 105, Km 137 and Km 320. Intermediate solar powered/battery cathodic protection installations were installed at approximately Km 52, Km 176, Km 220, Km 271 and Km 284. In summary cathodic protection stations were every circa 50Km.

Subsequent to construction, between 1974 and 1975, fluctuating stray current from a dc rail system constructed in 1988 at around Km 105 dictated the installation of a potential controlled (potentiostatic) powered rail bond to limit the severe potential discursions.

In 1993 a conventional analogue DCVG coating defect survey was undertaken by a team with considerable commitment and expertise, overseen by one of the most highly respected corrosion engineering consultancy groups in the UK. This survey located, manually characterised and pegged some 3,500 defects along the pipeline.

Subsequently a coating repair programme was instigated and many of the more significant defects were repaired.

Due to the increasing current demand of the pipeline, current output from the cathodic protection installations were increased significantly and additional solar/battery powered cathodic protection installations were constructed at Km 40.5, Km 66 and Km 82. These reduced the spacing between cathodic protection stations to circa 25Km over the first half of the line.

In 2000 the owner/operator sought proposals for a re-survey of the pipeline utilising techniques to the latest standards. Initially the expectation was that a CIPS (close interval potential survey) would represent the appropriate advance over the DCVG survey undertaken some 7 years earlier. However, after review of the available systems the Client selected the CIPS and integrated recorded DCVG survey on both technical and value for money grounds.

The contract was awarded in July 2001 with a requirement to commence the survey in August 2001 and complete before the end of November 2001.

Prior to deployment of the survey team a pipeline failure occurred at around Km 300 that was subsequently attributed to impact damage to the coating and the pipeline by a mechanical excavator, followed by corrosion.. Due to the considerable concern caused by this incident a series of survey activities were executed in the Km 320 – 280 region as soon as the team deployed.

The routine survey procedures for each day are summarised as follows:

- synchronisation of all switching devices and data loggers for use in the survey section

- switching of at least 2 No. cathodic protection stations behind the survey commencement point (except at the terminal) and 2 or 3 No. ahead of the survey to ensure that at the end of each section of work at least 2 No. switching cathodic protection stations were ahead of the survey.

- calibration checks of all equipment, data loggers and reference electrodes, against traceable standards, daily.

- synchronisation checks using an oscilloscope, to confirm that all switching actions and related "spikes" were occurring within the 100mS "wait" period selected for the equipment.

- the measurement of bond currents between the two parallel pipelines and interrupting them, synchronously with the cathodic protection station switching bond currents, where in excess of 20mA. If below this figure the bonds were considered of marginal importance and were left open circuit during the survey.

- the survey team deployed two mobile time synchronised (to $\pm$ 10mS/24 hours) data loggers, one for each pipeline.

- each mobile data logger was utilised to record 3 channels of data for each pipeline

  - channel 1 or "mobile 1" to record ON and INSTANT OFF pipe/soil potential data at the leading point of the survey team. This is the CIPS data.

  - channel 2 or "mobile 2" to record ON and INSTANT OFF pipe/soil potential data AGAIN over the same pipeline some 10 metres (or 10 – 20 seconds) behind the leading point of the team. This is the quality check data.

  - channel 3 directly measuring the dc voltage gradient between the leading point ("mobile 1") and the 10 metre trailing point ("mobile 2"). This is the DCVG data.

- The "mobile 2" data represents a quality assurance and audit trail for the other data channels as the "mobile 2" ON and INSTANT OFF pipe/soil potential data should replicate the "mobile 1" data. Further, the "mobile 1" minus "mobile 2" should replicate the DCVG data measured on channel 3.

- This quality audit provision is essential in the provision of pipeline integrity data with confidence as all CIPS and DCVG systems miss some data, or collect some erroneous data, due to poor reference electrode/soil contact, particularly in stony or dry desert conditions.

- The trailing DCVG measurements, with the "mobile 1" and "mobile 2" both directly over (each of) the pipeline(s), located by pipe locators in front of the survey team, were dictated by right of way and access limitations along significant portions of the route. Although, theoretically, measurement of field gradients at right angles to the pipeline can provide advantageous data, particularly in stray current areas, this was not practical for this survey.

- As the survey team proceeded, the trailing connection wires to a test post on each pipeline were automatically deployed and the cumulative distance over the pipeline measured. Identification features were keyed into the data.

- During the survey all cathodic protection station operating parameters were recorded and other data including soil resistivity, pH and redox potential were collected.

- In locations where ON pipe/soil potentials at test points were noted as varying in excess of $\pm$ 10mV, presumably due to fluctuating stray current, a third static synchronised data logger was deployed during each survey day at a location within the limits of the survey that day.

Working in this detailed and quality managed manner, the survey of the entire 640Km of pipelines was completed, including surveys by boat across water courses and lakes, in less than 14 weeks. This averaged over 7.5Km of survey per working day.

All data sets were reviewed and the raw data were plotted on a daily basis for combined Client and survey team review in order to ensure that the data sets were accurately collected and, in particular, that the comparisons between "mobile 1", "mobile 2" and the DCVG channel confirmed the quality of the data. Some 10Km of survey were repeated due to very dry conditions during the afternoon sun, despite watering the points of reference electrode/soil contacts.

It is suggested that International Standards should reflect the data collection practice and Quality Management regime described above, without which the data collected may incorporate serious errors and omissions and are not suitable for a definitive quality audit.

DISBONDED COATINGS, CASINGS & OTHER SHIELDED AREAS

As noted earlier, pipeline coating may suffer disbondment due to poor material selection, surface preparation, application or extremes of operation and environment. Thin film coatings, such as fusion bonded epoxy (FBE), liquid applied epoxy, modified epoxy and polyurethane have advantages of very strong bond to properly prepared and pre-treated steel. Further, if disbondment does occur, their film integrity is sufficiently fragile that the coating film will generally fail and be disbursed at the steel/soil interface as flakes. Such failures may not result in shielding of the underlying steel surface from cathodic protection and resultant corrosion. Areas of coating damage and deterioration of this type can be located by the survey techniques described above.

Conversely, there is a considerable track record of both fibre reinforced coal tar and bitumen enamel coatings and adhesive/mastic/rubber lined plastic tapes disbonding from pipelines yet remaining as intact films that shield the steel from cathodic protection. Corrosive micro-climates are established under the disbonded coating, allowing the un-protected steel to corrode. The author has concerns that even the most robust 3-layer polyethylene coatings may exhibit such disbondment and corrosion damage to pipelines in future. Those areas of disbonded coating, with corrosion under the coating but no through coating defects, can not be located by the electrical survey techniques described above.

The only certain method of monitoring corrosion damage under disbonded coatings is the use of those on line inspection tools (intelligent pigs) of the appropriate type, sensitivity and data interpretation sufficient to detect the external pitting that can occur under disbonded coating. These surveys have a very high cost and not all pipelines can accommodate them.

It may be possible to determine the risk of such disbonded coating and associated corrosion by detailed investigation of different categories of coating defects located by the combined CIPS + recorded DCVG technique described above. Areas of disbonded coating are likely to have some through coating defects, exposing steel, within their boundaries so expert assessment of located defects may indicate the extent, if any, of disbonded coating and associated corrosion.

Cased crossings of roads, railways, rivers etc. present considerable problems and risk to the external corrosion control of pipelines.

If the casing is insulated from the carrier pipe and is properly sealed there is little corrosion risk to the carrier pipe. However, many pipe/casing insulating centralisers and insulating end seals fail during construction and in service, allowing contact between casing and pipe and/or the ingress of corrosive ground water into the casing/carrier pipe annulus. If the annulus is flooded there is a corrosion risk to the pipeline that may not be monitored by an overline survey.

If the casing remains electrically (metallically, electronically) isolated from the pipe, despite there being (ionic) continuity through the water in the annulus, the attenuation surveys and the CIPS + DCVG techniques may detect submerged coating defects on the carrier pipe within the casing and may measure representative pipe/groundwater potentials within the casing. Cathodic protection current will flow through the casing (corroding the inner surface where it discharges into the electrolyte in the annulus) and adequate cathodic protection may be afforded to the carrier pipe. All data from within flooded casings should be treated with caution unless collected with reference electrodes introduced into the casing for a dedicated investigation.

If the casing is in metallic contact with the pipeline cathodic protection current will not reach the carrier pipe and it will be at risk of corrosion if the casing seals have allowed the ingress of groundwater. No overline survey technique will indicate the corrosion status of the carrier pipe within a casing in contact with the pipe. All overline survey techniques will indicate status of the external casing if shorted to the pipe; the casing may be bare and un-protected. This may cause substantial problems to the protection of the carrier pipe beyond the casing, due to excessive current demand from the cathodic protection system. All too often the risk of corrosion to the pipe within the casing is ignored while attempts are made to improve protection to the nearby buried pipeline.

Casing isolation and, where possible, the environment within the casing should be assessed during overline surveys. Electrical contact between casing and pipeline can be easily established using all of the above survey techniques, if they are properly adapted for this purpose at casings.

Other, localised, shielding caused by rocks or other non-conductive media in close proximity to the pipeline may cause localised protection difficulties that, associated with coating damage, may result in corrosion of the pipeline at locations that are not detected by the electrical survey techniques described above. The only effective monitoring of these unusual conditions is the use of on line inspection tools (intelligent pigging) as summarised above.

Even uncased road crossings can present particular hazards to pipelines. Roads represent possible concentrations of third party activity, pipelines and cables; all are sources of potential mechanical or stray current damage to an existing pipeline. In northern climates the soil at road sides can be particularly corrosive due to de-icing salt runoff from the roads in winter. Road safety considerations, particularly in countries where road traffic discipline is not good, may prevent safe surveys of the pipeline under roads. The road construction, particularly asphalt and some geotextile membranes, may present a barrier to accurate pipe/soil potential measurement.

The author has often seen surveys 'completed' without the survey team collecting data from the last few hundred meters of pipeline at the terminals; access 'was not permitted by the Client' or 'there was no time to arrange a hot work permit'. As the conditions within terminals are often at least as corrosive and at risk of mechanical damage, stray current from terminal cathodic protection systems, local electrical earthing and steel/concrete steel/soil galvanic corrosion couples at valve pit entries it is clearly necessary to survey these areas.

In planning overline surveys, it is necessary to consider the effects of casings, shielded areas and other localised features, in order to collect the most appropriate data in these high risk and difficult to survey areas, and to interpret these data correctly.

CONCLUSIONS

- A variety of survey techniques are available to assess the quality of buried pipeline external coatings and cathodic protection systems.

- The different survey techniques produce data of varying accuracy, detail and cost. The selection process for the appropriate survey technique will take into account the known history of the pipeline, its coating, its cathodic protection system, its environment and the intended future operations and maintenance activities. A combination of different techniques may be the technical and commercial optimum.

- CIPS surveys that are properly specified and use accurately time synchronised data loggers and switchers produce a definitive record of cathodic protection performance, external pipeline corrosion risk and give an indication of coating defect location and severity.

- DCVG surveys that are properly specified and executed are able to locate and characterise coating defects but do not produce a definitive record of cathodic protection performance. They are normally non-recording and therefore subject to operator error.

- Pearson surveys similarly locate coating defects and are easily recorded. The advantages of recorded data are offset by interior detection and characterisation of defects compared with DCVG surveys.

- Combined CIPS and recorded DCVG surveys can economically produce recorded data of definitive cathodic protection performance and coating defect location and approximate size – thus characterising the overall external pipeline corrosion control system.

- It may be necessary to supplement even combined CIPS and recorded DCVG surveys with additional data calculations to correct for equalisation currents and with switched and with rapidly data logged coupon data to assess ac corrosion risk.

- Combined CIPS and recorded DCVG surveys should be a routine feature of pipeline maintenance. They should be repeated at intervals of no longer than every 10 years and at shorter intervals for pipelines presenting a significant safety or environmental risk.

- None of the overline surveys can detect disbonded coatings or any corrosion caused by shielding of cathodic protection from the steel by the coating. If there are through coating defects in the areas of disbondment, they can be located and characterised by the combined CIPS + recorded DCVG surveys. Subsequent expert exposure, inspection and interpretation may allow a risk assessment of the disbonded coating and associated corrosion to be made. Only an appropriate intelligent pig survey can be certain to locate and characterise corrosion under disbonded coating.

- Cased crossings represent potential corrosion risks to pipelines; these risks require assessment as part of any comprehensive pipeline corrosion survey. The overline survey techniques described can all be used to indicate contact between casing and pipeline; expert interpretation is required to assess corrosion risks within casings.

- Shielding by rocks or other non-conductive media can cause similar problems to disbonded coatings.

ACKNOWLEDGEMENTS

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