STRATEGY FOR ELIMINATING RISKS OF CORROSION AND OVERPROTECTION FOR BURIED MODERN PIPELINES

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ABSTRACT

The driving force that causes metals to corrode is a natural consequence of their temporary existence in metallic form. Application of cathodic protection (CP) as measures to stop corrosion has a very long history. The first application of impressed current system for protection of underground structures took place in England and in the United States, about 1910-1912. The first criterion for CP of steel pipelines, that is, −0.850V (vs. copper sulfate electrode) with the CP applied, was proposed by Kuhn in 1933 and has since been accepted and used worldwide on steel pipelines and structures in various soils and water. Kuhn’s criterion has facilitated the application of CP for extending buried pipelines with the economic growth. Kuhn’s criterion is referred to the protection potential criterion and in the scope of direct current (DC) corrosion protection.

In the early 1900s, the effect of AC interference current on a metallic structure was known and to some degree had been quantified. In 1906, Hayden investigated to determine whether, and to what extent, AC currents passing between any metallic conductors (gas and water pipes, lead cables, etc.) and the ground would produce AC corrosion, due to the introduction of grounded AC systems using the developed single-phase railway motor. Hayden concluded iron is attacked less than lead. Up until the mid-1980s, the prevailing opinion was that, although AC current could cause corrosion of steel, the corrosion rate was a small percentage of an equivalent amount of DC and furthermore could be controlled by the application of CP in accordance with the protection potential criterion. Up to the mid-1980s, corrosion failure on a pipeline was not attributed to AC corrosion, probably because the pipelines were bare or less well coated having sufficient grounding, such that induced voltages were not a practical problem.

In 1986, corrosion failure on a polyethylene coated pipeline caused by induced AC interference currents resulting from AC powered rail transit system was first reported in Europe despite satisfying the protection potential criterion. Since then, pipeline failures caused by AC corrosion have been reported not only in Europe but in North America. Factors that contribute to AC corrosion include (1) high resistivity of pipe coating, and (2) the increased tendency to locate pipelines paralleling high voltage (HV) AC electric power lines and/or AC powered rail transit systems. It has been definitely shown by the occurrence of AC corrosion on a cathodically protected pipeline that AC corrosion cannot be prevented by CP in the presence of very high AC voltage of a pipeline.

The necessity for establishment of criterion for AC corrosion protection has been realized ever since. However, there are no agreed-on criteria for AC corrosion protection.

Recently, pipelines are being constructed in parallel with HVAC electric power lines and/or AC powered rail transit systems with thinner, high strength steel-walls, high resistivity coating with little or no corrosion allowance. This means that more attention must be paid to new threats, that is, AC corrosion and overprotection on modern pipelines.

The authors have developed an advanced instrumentation for assessing the AC corrosion risk of buried pipelines, and established the new CP criterion based on coupon DC and AC current densities (coupon current density-based criterion). The most distinguished feature of the instrumentation is the simultaneous computation in a measuring unit of 20 ms regarding coupon DC current density and coupon AC current density corresponding to the commercial frequency of 50 Hz. The criterion eliminates all corrosion risks such as AC corrosion, DC stray current corrosion, microbiologically influenced corrosion etc., and overprotection risk.

This paper details how the developed instrumentation enabled understanding of AC corrosion or protection level of a cathodically protected pipeline, and establishment of the new CP criterion. Particular emphasis in the presence of AC is placed on the necessity for understanding of (1) limitations of the protection potential criterion and CP, and (2) adverse effects leading to possible AC corrosion and hydrogen embrittlement under overprotection circumstances caused by increasing the CP level as protection measures against AC corrosion. Furthermore, the features of an advanced instrumentation for assessing the AC corrosion risk of buried pipelines are also described with an example of measured data.

1. PREAMBLE

Pipeline operators were shocked at the first occurrence of AC corrosion in 1986 and subsequent AC corrosion failures of modern pipelines in Europe and North America despite satisfying the protection potential criterion. It was proven that AC corrosion was attributed to induced AC voltage on a pipeline caused by (1) application of high resistivity coatings, and (2) the increased tendency to locate pipelines paralleling HVAC electric power lines and/or AC powered rail transit systems. To prevent a recurrence of AC corrosion, corrosion engineers have urged the necessity of a new cathodic protection (CP) criterion for AC corrosion protection. However, there are no agreed-on criteria for AC corrosion protection.

Recently, because of limitations of land, minimization of environmental effects and cathodic currents demand, high transportation efficiency, and cost reduction in pipeline construction, natural gas transmission pipelines (modern pipelines) are being constructed in parallel with HVAC electric power lines and/or AC powered rail transit systems with high resistivity coating, and thinner, high strength steel-walls.

Today it is acknowledged that, the AC corrosion risk of pipelines with high resistivity coating can be evaluated by installing steel coupons at pipe depth and measuring the DC and AC current densities when the coupon is connected to the pipe. However, there are still not concrete techniques for measuring coupon DC and AC current densities in the field.

Furthermore, special regard shall be paid to the fact that modern pipelines made of high strength steels are susceptible for hydrogen embrittlement. Thus particular care shall be excised to avoid overprotection leading to two possible adverse effects on modern pipelines. The first is hydrogen embrittlement due to hydrogen production at the pipe surface by excessive cathodic reaction. The second is stabilization of significant corrosion due to the formation of dissolved dihypoferite ions ($HFeO_2^-$) by very high levels of cathodic reaction.

Therefore, a new cathodic protection criterion must cover the eliminations of the overprotection risk as well as the AC corrosion risk, in addition to the protection potential criterion.

This paper describes strategy for eliminating risks of corrosion and overprotection for buried modern pipelines with two key points:

1) Establishment of a new cathodic protection criterion in which the elimination of the risks of overprotection as well as AC corrosion are taken into account, in addition to the protection potential criterion
2) Development of an advanced instrumentation for assessing the AC corrosion risk in the field

2. HISTORY OF CATHODIC PROTECTION

2.1 APPLICATION OF CATHODIC PROTECTION

The definition of corrosion is the degradation of a material that results from the interaction of a material and its environment. The spontaneous process by which metals convert to the lower-energy oxides is referred to corrosion. Application of cathodic protection (CP) as measures to stop corrosion has a very long history. The practice of zinc coating on steel was described in France as early as 1742. This method is application of the conception of CP. Contributions of Sir Humphry Davy to CP are very famous. The rapid failure of the copper sheathing on the hulls of ships of the British Navy provided Davy with the opportunity to apply his discoveries of the galvanic effects of dissimilar metals to the prevention of corrosion electrolytically. At that time, copper sheathing was used to protect the wooden hulls from destruction by worms and prevent the adhesion of barnacles. In 1824, Davy reported that copper is protected by zinc or iron coupled by copper in sea water. The problem regarding a balance between ‘corrosion prevention’ of copper by CP and ‘fouling development’ was not entirely solved. This led Davy to realize the necessity for control of the current required for corrosion prevention.

The first application of impressed current system for protection of underground structures took place in England and in the United States, about 1910-1912.Nowadays it is widely recognized among corrosion engineers that the most reliable methods of protecting buried pipelines from corrosion are external coatings and CP. The external coatings can degrade over time; enabling corrosion to initiate in a holiday provided that insufficient current flowing through electrolyte to the holiday. Therefore combination coating with CP is prerequisite.

2.2 PROTECTION POTENTIAL CRITERION WITH THE CATHODIC PROTECTION APPLIED

The first criterion for cathodic protection (CP) of steel pipelines, that is, −0.850V (vs. copper sulfate electrode, CSE) with the CP applied, was proposed by Kuhn in 1933 and has since been accepted and used worldwide on steel pipelines and structures in various soils and water. Kuhn's criterion has facilitated the application of CP for extending buried pipelines in order to cope with the rapid economic growth.

3. RECOGNITION OF AC CORROSION

In the early 1900s, the effect of alternating currents on metallic structures was known and to some degree had been quantified. In 1906, Hayden investigated to determine whether, and to what extent, alternating currents passing between any metallic conductors (gas and water pipes, lead cables, etc.) and the ground would produce electrolytic corrosion, due to the introduction of grounded alternating-current systems using the developed single-phase railway motor. Hayden concluded iron is attacked less than lead.

More than 50 years ago, AC corrosion on pipelines was perceived in the gas industry. Kulman cited an American Gas Association (AGA) corrosion committee survey in 1955 wherein seven of 27 pipeline respondents who had experienced induced AC also had suspected that AC current was a contributing cause of corrosion in their facilities.

Up until the mid-1980s, the prevailing opinion was that, although AC current could cause corrosion of steel, the corrosion rate was a small percentage of an equivalent amount of direct current (DC) and furthermore could be controlled by the application of cathodic protection (CP) in accordance with the protection potential criterion.

At length, in 1967, Dévay et al. have disproved the prevailing opinion indicating the combined effect of 50 Hz AC and DC current densities on the polarization behavior of 1 cm^2 steel electrodes in a 5 % KCl solution that residual corrosion rate exceeded 0.1 mm/y despite a substantial cathodic current density of 10 A/m^2 and corresponding polarized potentials more negative than −0.90 V_{CSE}. However, at that time, pipeline engineers did not consider the experimental results obtained by Dévay et al. very important, probably because the pipelines were bare or less well coated pipelines having sufficient grounding, such that induced voltages were not a practical problem.

4. UNDERSTANDING OF AC CORROSION WITH THE CATHODIC PROTECTION APPLIED

4.1 UNDERSTANDING OF AC CORROSION

AC corrosion was not well understood for two reasons: (1) the interaction of AC and DC currents affecting the electrochemical phenomenon of corrosion is very complicated, and (2) the instrumentations used to measure the electric parameters in DC and AC with frequencies between 50 and 100 Hz were not available.

Although some investigators have attempted to explain mechanisms of AC corrosion, there is a lack of technical consensus on the mechanism and extent of the effect of AC on underground metallic structures. However, the AC corrosion on a cathodically protected pipeline is understood conceptually as follows. Figure 1 illustrates induced AC voltage on a pipeline with and without cathodic protection (CP) for a single period of a 50 Hz-sinewave. In Figure 1, the period of induced AC voltage is 20 ms corresponding to the commercial frequency of 50Hz. AC corrosion can occur on a cathodically protected pipeline only when the peak of the positive part of AC wave form is more positive than the protection potential. For the positive part of AC wave form, simultaneous reactions could occur in addition to the dissolution of steel, that is, corrosion reaction.

Probable simultaneous reactions for the positive part of AC wave form:
$Fe^{2+} \rightarrow Fe^{3+} + e^{-}$
$1/2H_2O \rightarrow 1/4O_2 + H^{+} + e^{-}$
$1/2H_2 \rightarrow H^{+} + e^{-}$
Principal anodic reaction is thought to be the dissolution of steel. Consequently, the dark shading on the AC wave form in Figure 1 refers to a strong likelihood of AC corrosion.

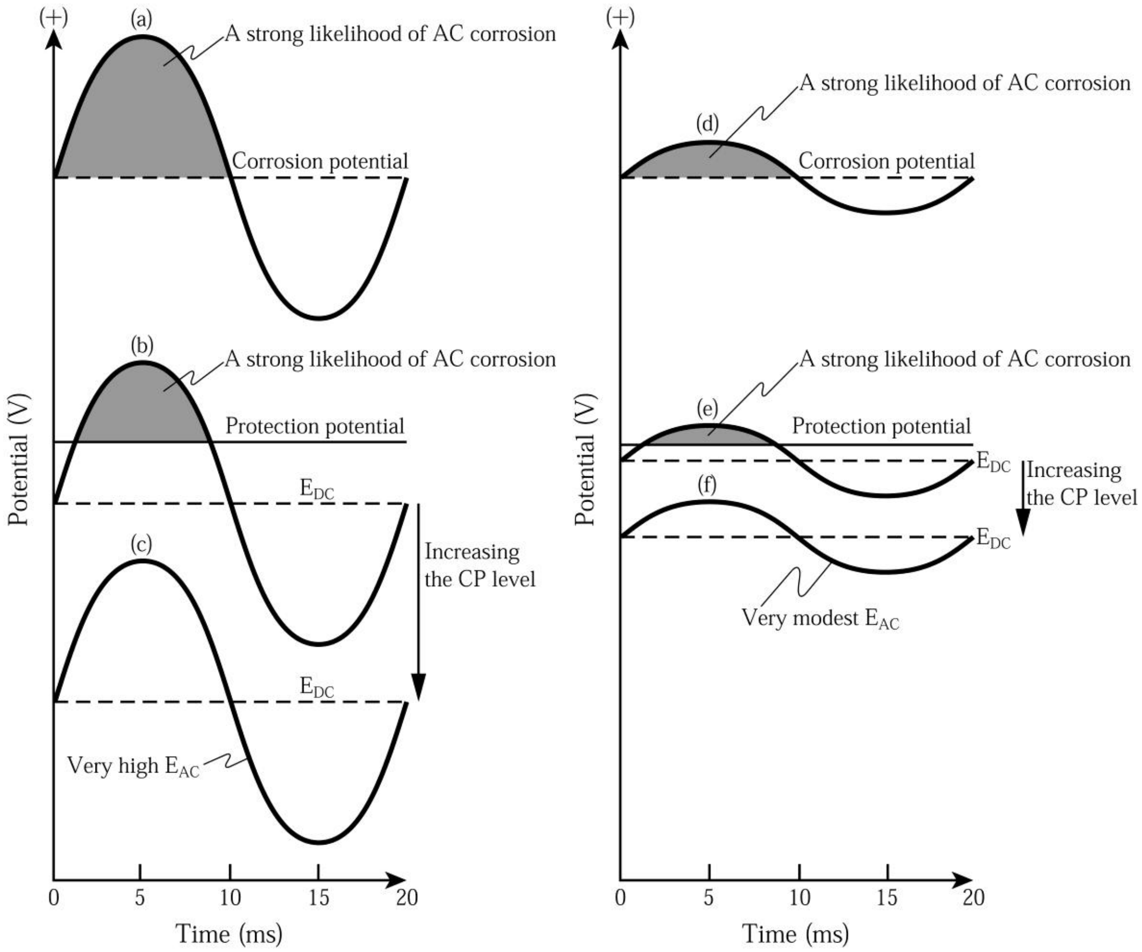

Figure 1 AC corrosion and its control by increasing the cathodic protection (CP) level.

Although increasing in the cathodic protection level so that the peak of the positive part of AC wave form can be brought below the protection potential is thought to eliminate the AC corrosion risk on a cathodically protected pipeline, AC corrosion can remain significant due to the formation of dissolved dihypoferrite ions ($HFeO_2^{-}$) which may stabilize corrosion at a very high rate at very high pH, even when the protection potential criterion is being met. This method can produce excess hydroxide ions (OH^{-}) and hydrogen produced by CP current ($1/2O_2 + H_2O + 2e^{-} \rightarrow 2OH^{-}$, $2H_2O + 2e^{-} \rightarrow 2H(H_2) + 2OH^{-}$), that is, overprotection conditions. Furthermore, overprotection may promote hydrogen damage of modern pipelines. ISO 15589-1 requires that, for high strength steels (specified minimum yield strength greater than 550 MPa), the limiting critical potential shall be determined with respect to the detrimental effects in the material due to hydrogen formation at the metal surface.

4.2 FACTORS CONTRIBUTING TO AC CORROSION

Because AC corrosion rate is related to AC current density, and then whether or not AC corrosion will occur depends primarily on the surface area of holiday and electrolyte resistivity under induced AC voltage. Assuming a circular holiday, the AC current density I_{AC} is given by equation (1) and proportional to parallel length between pipelines and HVAC electrical power lines or AC powered rail transit systems.

$$I_{AC} = \frac{8V_{AC}}{\rho \, \pi \, d} \propto \frac{I \cdot L}{\rho \, d} \tag{1}$$

where:

V_{AC} = Induced AC voltage of pipeline to remote earth (V)

ρ = Electrolyte resistivity (ohm-m)

d= Diameter of a circular holiday (m)

I = Current in HVAC electric power lines or trolley wires

L = Parallel length between pipelines and HVAC electrical power lines or AC powered rail transit systems

The formula is applicable to cases when the holiday size is greater than the thickness of the coating and resistance to earth of the holiday is ρ / (2d).

Equation (1) suggests that AC current density, that is, AC corrosion rates;

- Increase with increasing currents in HVAC electric power lines/trolley wires I;
- Increase with increasing the parallel length between pipelines and HVAC electric power lines/trolley wires;
- Increase with decreasing electrolyte resistivity; and
- Increase with decreasing holiday surface area.

5. OCCURRENCE OF AC CORROSION ON A CATHODICALLY PROTECTED PIPELINE

Rapidly growing demand for energy requires the construction of an increasing number of high voltage AC (HVAC) electric power lines and the laying of high-pressure pipelines of large diameters. In congested areas as well as rural districts, the possibilities of using different routes for HVAC electric power lines and transmission pipelines are very limited. This suggests that these lines will run parallel to each other, sometimes for long distances.

In 1986, corrosion failure on a pipeline caused by induced AC interference currents was first reported in Europe despite satisfying the protection potential criterion. Since then, AC corrosion has occurred in North America as well as in Europe.

The primary conclusion stemming from the literature survey on AC corrosion with the CP applied is as follows: (1) Short-term perforation or severe corrosion has been observed, (2) The pipelines had high resistivity coatings such as fusion bonded epoxy, (3) The pipelines were laid paralleling HVAC electric power lines and/or AC powered rail transit systems for a long distance, (4) The AC corrosion protection has not been taken into account in the stage of design for cathodic protection.

External pipe coatings are intended to form a continuous film of electrical insulating material over the metallic surface to be protected. The function of such a coating is to isolate the metal from direct contact with the electrolyte, interposing a high electrical resistivity so that electrochemical reactions cannot occur. Pipe coatings are not perfect forever, natural and third party degradation of pipe coating could occur. Therefore, combination of pipe coatings and cathodic protection is prerequisite. Pipe coating industries have endeavored to develop coatings with high resistivity and a high level of damage resistance.

Since its first use in New Mexico in 1960, fusion bonded epoxy (FBE) coating has remained the external pipe coating of choice in North America. The 1980s saw the introduction of three-layer polyethylene or polypropylene coatings in Europe. Both the fusion bonded epoxy coatings and three-layer polyethylene coatings have raised induced AC voltages on pipelines.

The AC corrosion risk of modern pipelines is increasing, due to the technological advancements in pipe coating materials which provide increased pipe coating resistance values and furthermore the increased tendency to locate pipelines paralleling HVAC electric power lines and/or AC powered rail transit systems.

6. LIMITATIONS OF THE PROTECTION POTENTIAL CRITERION

As illustrated earlier in Figure 1, if induced AC voltage is very high, the AC corrosion can occur even the protection potential criterion is being met. In other words, despite satisfying the protection potential criterion, coupon DC potential E_{DC} cannot indicate whether the AC corrosion occurs or not. This suggests that a coupon DC potential satisfying existing protection potential criterion does not necessarily eliminate the likelihood of AC corrosion.

A 1992 report by Funk, Prinz and Schöneich described the test results of steel coupons with respect to corrosion versus AC and DC (cathodic protection) current densities as follows:
- For AC current densities greater than 30 A/m^2
  The maximum corrosion rate is in excess of 0.1 mm/y despite a constant cathodic protection current density of 2 A/m^2. In this case, the protection potential criterion is not applicable.
- For AC current densities less than 30 A/m^2
  There is no AC induced corrosion at cathodic protection current density of about 1 A/m^2.

Funk et al. also reported that measurement of AC current density on steel coupons provides information on the risk of corrosion and corrosion prevention for AC current densities greater than 30 A/m^2.

Kajiyama and Nakamura have carried out a field study, with coupons in monitoring stations, on a 6.6 km length of polyethylene coated 323.9 mm outside diameter pipeline that paralleled a 66 kV, 50 Hz electric power transmission line. They have reported that, despite a substantial coupon DC (cathodic protection) current of 10.8 A/m^2 and showing polarized potential of −1.12 V_{CSE}, coupon AC current density was 184 A/m^2. This indicates that AC corrosion on a holiday is very likely to occur despite high level of cathodic protection.

ISO 15589-1 prescribes for the AC corrosion risk and CP as follows: If the a.c.current density on a 100 mm^2 bare surface (e.g. an external test probe) is higher than 3 A/m^2 (or less, in certain conditions), there is a high risk of corrosion. Risk of corrosion is mainly related to the level of a.c.current density compared to the level of CP current density. If the a.c.current density is too high, the a.c. corrosion cannot be prevented by CP.

7. OVERPROTECTION AS THREAT TO PIPELINE INTEGRITY

In Figure 1, E_{DC} indicates polarized potential. If induced AC voltage on a cathodically protected pipeline is very high as shown (b), the method of increasing the CP level ((b) → (c)) may be thought so that the positive part of AC wave form can be neglected; Thereby satisfaction with the protection potential criterion is achieved. The aim of increasing the CP level is not to mitigate induced AC voltage but to lower the peak of the positive half cycle of the sinusoidal AC wave form more negative than the protection potential. However, particular care shall be exercised to avoid overprotection, which can result in two adverse effects on modern pipelines. In overprotection conditions, excess hydroxide ions (OH^-) and hydrogen are produced by excess CP current ($1/2O_2 + H_2O + 2e^- \rightarrow 2OH^-$, $2H_2O + 2e^- \rightarrow 2H(H_2) + 2OH^-$). The first possible adverse effect is hydrogen embrittlement due to hydrogen production at the pipe surface by excess cathodic reaction. The second possible adverse effect is stabilization of significant corrosion due to the formation of dissolved dihypoferrite ions ($HFeO_2^-$) at the alkalized steel interface as a result of accumulation of hydroxide ions (OH^-) by very high levels of cathodic reaction as illustrated in Figure 2 showing Pourbaix diagram. In Figure 2, potential E is expressed in terms of standard hydrogen electrode (SHE). In the domain of $HFeO_2^-$, potentials are shown between about −1115mV_{CSE} and −1345mV_{CSE} at pH above about 13.5. ISO 15589-1 stipulates that the limiting critical potential should not be more negative than −1200 mV referred to CSE, to avoid the detrimental effects of hydrogen production and/or a high pH at the metal surface.

Therefore, in the case of high induced AC voltage, increasing the CP level shall be prohibited. It should be noted that overprotection is regarded as threat to pipeline integrity.

In the case of very modest induced AC voltage, increasing the CP level (f) is probably effective.

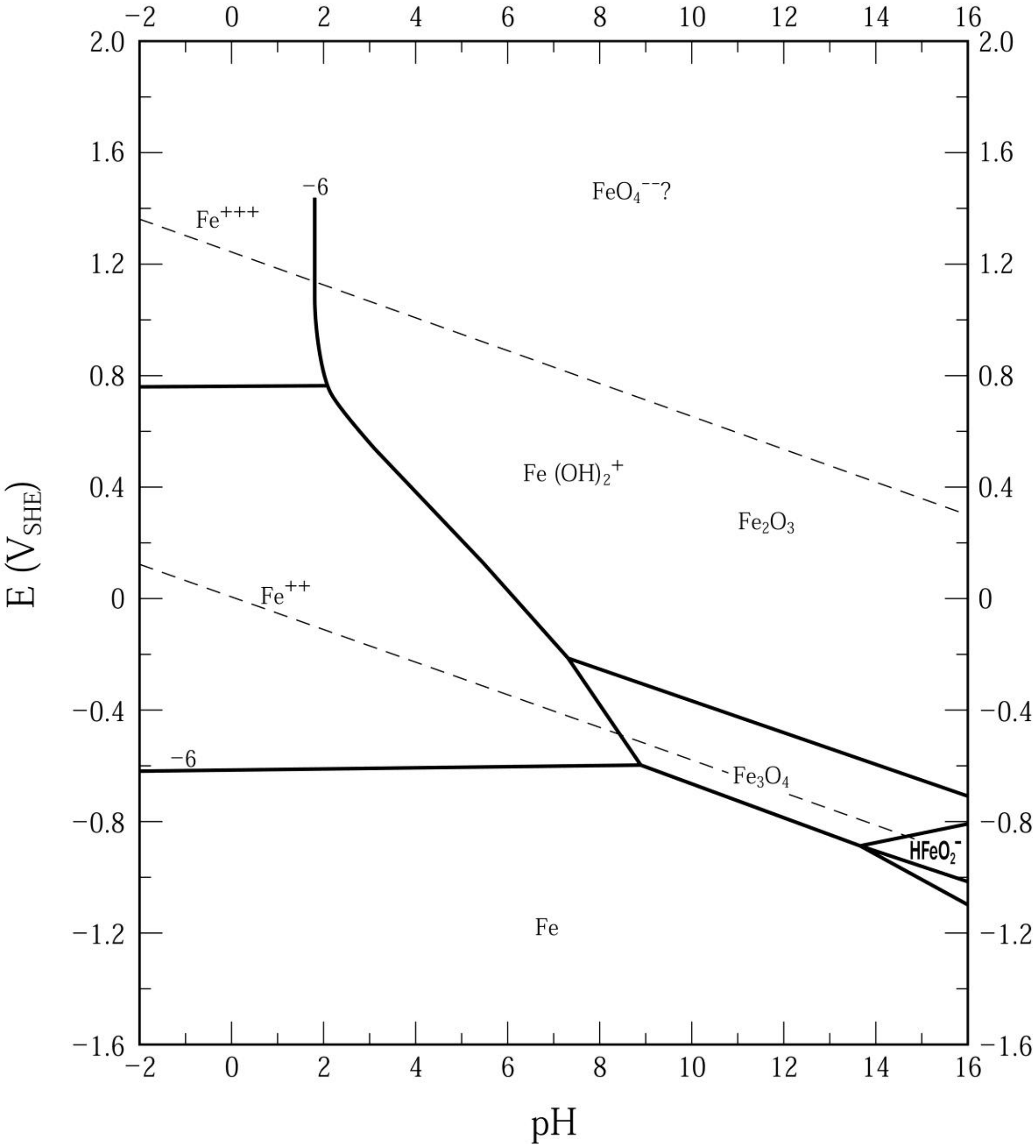

Figure 2 Pourbaix diagram showing $HFeO_2^-$ region with respect to AC corrosion at very high pH.

8. EVALUATION METHOD OF THE AC CORROSION RISK

Because the AC current density at a holiday on a pipeline cannot be measured directly, the current density and therefore the risk of AC corrosion must be evaluated indirectly. The AC current density can be determined by installing steel coupons at pipe depth and measuring the AC current when the coupon is connected to the pipe. A coupon and reference electrode are placed as close to the pipe as possible to minimize the IR drop. Thereby coupon DC potentials E_{DC} can be considered as polarized potential. Figure 3 shows measuring systems for the coupon current densities (I_{DC}, I_{AC}) and coupon potentials (E_{DC}, E_{AC}). In Figure 3, the dark shading on the coupon is a bare steel surface simulating a holiday.

Nowadays there appears to be a tacit agreement that the AC corrosion can be evaluated by coupon DC and AC current densities, I_{DC} and I_{AC}, respectively.

Coupon currents can be measured by the voltage drop across an internal shunt resistor between a coupon and a pipe. For coupon current measurements the value of the internal shunt resistor should sufficient low to avoid significant disturbance of the system.

Though coupon DC and AC potentials, E_{DC} and E_{AC}, are not adopted for determining the CP level. However, these values are very useful to understand the CP condition of buried pipelines. Plotted data taken from over-the-line coupon DC potentials, tops (the most positive direction) in the plot indicate locations to be suspected as holidays and/or metallic connections. Using the reference electrode instead of remote earth, coupon AC potentials E_{AC} are used to determine the levels of AC interference roughly.

The method for acquisition of data on coupon current densities (I_{DC}, I_{AC}) and coupon potentials (E_{DC}, E_{AC}) is detailed in **12**.

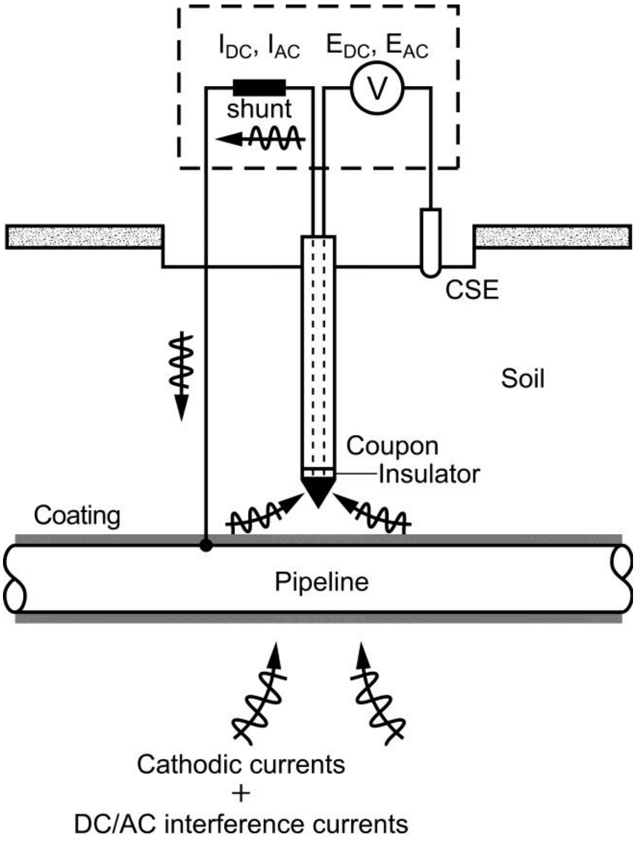

Figure 3 Measuring systems for the coupon current densities (I_{DC}, I_{AC}) and coupon potentials (E_{DC}, E_{AC}).

9. AC CORROSION PROTECTION CRITERION

After the first corrosion perforation on a polyethylene coated gas pipeline in Germany, attributed to AC corrosion despite satisfying the protection potential criterion, in 1986, the AC corrosion protection criterion DIN 50 925 as described as below was established, in 1992.

The AC corrosion protection criterion was established on the concepts as follows:

At present, there are two criteria related to the control of AC corrosion. These can be applied after coupon DC and AC current densities are measured.

Equation (1) suggests that, even with very modest induced AC voltage, AC corrosion rate would be very high at very small holidays in contact with the electrolyte with very low resistivity. Therefore AC corrosion rate is affected not by induced AC voltage but by AC current density. This is the reason why CP criteria related to the control of AC corrosion are prescribed based on coupon current densities (coupon DC current densities and AC current densities).

The two criteria defined are:

- DIN 50 925 (in the year 1992)

AC current densities less than about 30 A/m^2, when cathodic protection current densities shall be maintained at about 1 A/m^2

- ISO 15589-1 (in the year 2003)

AC current densities less than 30 A/m^2 (or less, in certain condition)

The two CP criteria, however, do not document how coupon AC current density can be measured in the field, and the frequency at which AC corrosion shall be prevented.

There are no agreed-on criteria for AC corrosion protection.

10. NEW CATHODIC PROTECTION CRITERION FOR THE ELIMINATION OF ALL CORROSION RISKS AND OVERPROTECTION RISK

Kasahara has presented that the minimum coupon DC current density of 0.1 A/m^2 should be adopted.

According to BS 7361 : Part 1, for thick film coatings, such as reinforced coal tar enamel in high resistivity soil, an instant-off potential more negative than −3.0 V_{CSE} could be acceptable. Kajiyama et al. have reported that, in the case of thick polyethylene coatings (coating thickness > 5 mm) without holidays with an average coating resistance of higher than 10^5 ohms-m^2, the maximum coupon DC current density of 40 A/m^2 corresponding to instant-off potential more positive than −2.5 V_{CSE} should be adopted.

Nakamura and Kajiyama have assessed the relationship between DC and AC current densities and corrosion rate by performing laboratory studies using 10 cm^2 steel specimens with constant DC and AC currents. Laboratory results are shown in Figure 4. Corrosion rate obtained from weight loss was reduced to less than 0.01 mm/y as long as the data was plotted inside the protection area designated by thick solid lines.

Kajiyama and Okamura have stated that, the cathodic current density, required to achieve CP of pipelines buried in microbially active soils containing sulfate-reducing bacteria or iron bacteria in Tokyo metropolitan areas in Japan, is greater than 0.1 A/m^2 corresponding to the residual uniform corrosion rate less than 0.1 mm/y. Therefore the above-mentioned CP criterion is effective to control microbiologically influenced corrosion (MIC).

Kajiyama has carried out field observations to assess the above-mentioned criterion established by laboratory studies using the coupons buried for 2～3 years in various environments having potential corrosion risks. After removing the coupons from the soils followed by cleaning and weight loss measurements, corrosion rates were obtained to be less than 0.01 mm/y. The final values of coupon current densities are shown by square symbols in Figure 4. Therefore the new CP criterion is also verified by field observations.

Taking the above-mentioned discussions into account, the authors have established the new CP criterion based on coupon DC and AC current densities (coupon current density-based criterion) as follows:

Ⅰ. $0.1\ A/m^2 \leqq I_{DC} < 1.0\ A/m^2$, $I_{AC} < 25\ I_{DC}$

Ⅱ. $1.0\ A/m^2 \leqq I_{DC} \leqq 40\ A/m^2$, $I_{AC} < 70\ A/m^2$
where:
I_{DC} = time-averaged coupon DC current density
I_{AC} = time-averaged coupon AC current density

Positive values in DC current density indicate the current flowing through electrolyte to the coupon (i.e. cathodic current flowing).

Graphic expressions of the new CP criterion (Ⅰ and Ⅱ) established by the authors together with DIN 50 925 and ISO 15589-1 are illustrated by Figure 5. The criterion eliminated all corrosion risks such as AC corrosion, DC stray current corrosion, microbiologically influenced corrosion etc. and overprotection risk.

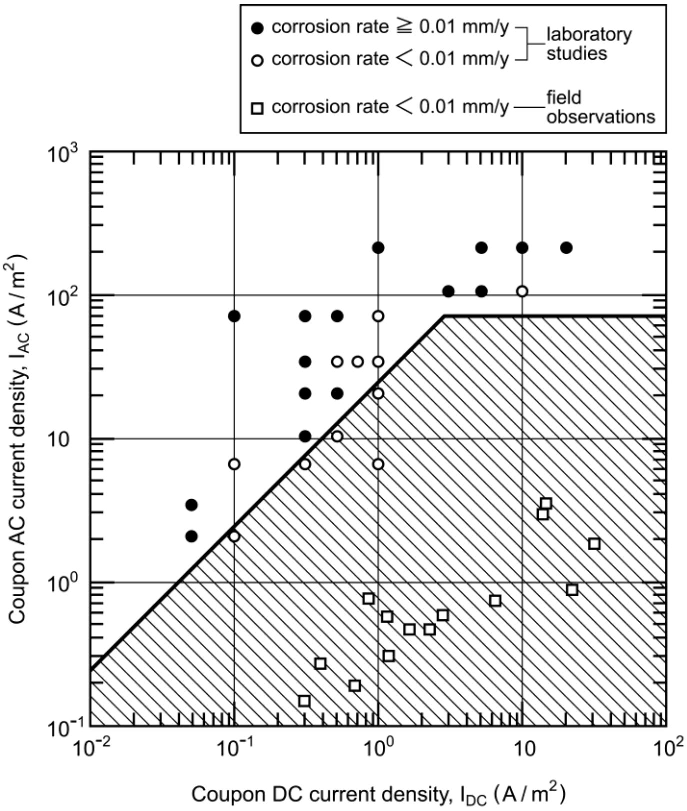

Figure 4 The data on DC and AC current densities on test specimens and coupons in consideration of corrosion rate obtained from laboratory studies and field observations.

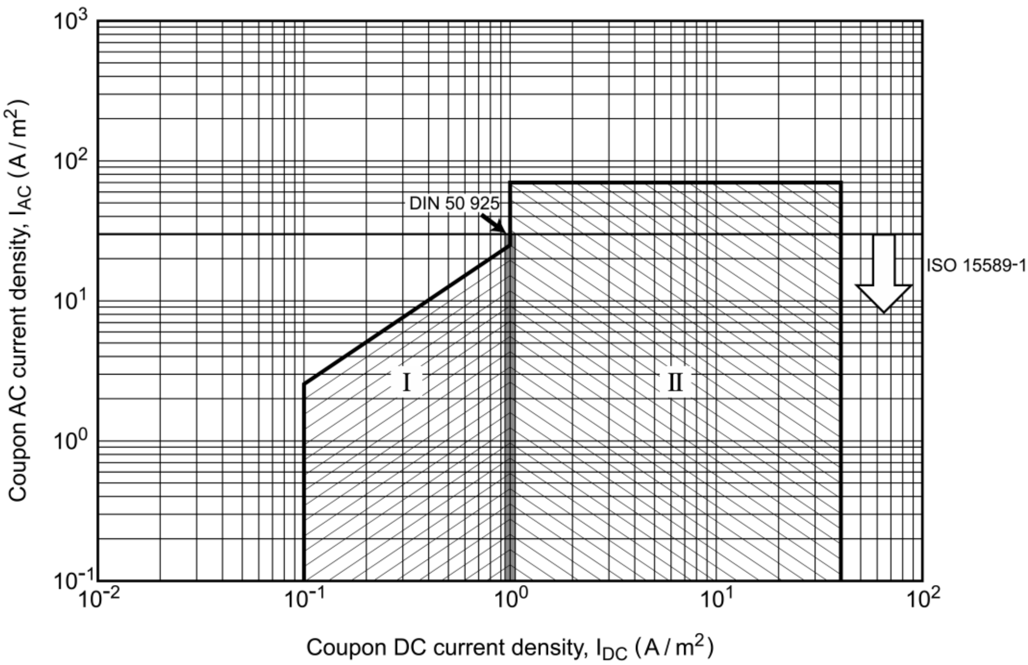

Figure 5 Graphitic expressions of the new CP criterion (Ⅰ and Ⅱ) established by the authors together with DIN 50 925 and ISO 15589-1.

11. AC VOLTAGE OF PIPELINE

So far AC mitigation is mostly driven by safety considerations. According to NACE SP0177, the AC voltage should need to be mitigated below 15 V with respect to local earth for steady-state conditions on above-grade portions, where personnel could readily come in contact with the pipeline or appurtenance. On the other hand, in Germany, the same threshold is 65 V.

European Standard CEN/TS 15280 explains that reducing the AC corrosion likelihood on a buried pipeline means that pipeline AC voltage does not at any time exceed 10 V over the entire pipelines, or 4 V where the local soil resistivity measured along the pipeline is less than 2,500 ohm-cm. Kajiyama has suggested that, for the case of a 100 mm^2 holiday on a pipe in 1000 ohm-cm soil, the AC corrosion risk on a pipeline presents if pipeline AC voltage is in excess of 3.0 V.

Induced AC voltage is well below the safety potential. Mitigating the induced AC voltage on pipelines to the recognized maximum safe AC voltage of 15 V used in NACE SP0177, does not necessarily eliminate the likelihood of AC corrosion.

Many commercially available voltmeters that can measure both DC and AC voltage are hand-held, battery-powered, and well suited for field applications. Measurement of voltage between a pipeline and a reference electrode is probably the most frequently made for determination in corrosion and CP testing works. If the AC corrosion risk can be evaluated based on induced AC voltage, it is very simple and prompt to detect the location where AC corrosion likelihood is present using hand-held voltmeter in the field. As has been previously indicated, though assessment of AC corrosion likelihood based on AC voltage can be misleading, it is effective to measure AC voltage to evaluate AC corrosion likelihood roughly.

12. PROTECTION MEASURES AGAINST AC CORROSION

As has previously been mentioned, recently, concern for AC corrosion mitigation has been increasing.

Protection measures against AC corrosion should be achieved through the following measures:
- Reduce the induced AC voltage

To reduce induced AC voltage, the following methods should be considered.
1) Install pipeline grounding equipped with suitable devices in order to let AC current, but not DC current, flow.
2) Add grounding systems to provide potential equalization at local areas.
These grounding systems can be constructed using a wide variety of electrodes (galvanized steel, zinc, magnesium, etc.). To reduce induced AC voltage, the method of adding grounding systems is widely used to discharge the induced AC current resulting in reduction of the potential on the pipeline. If grounding systems are used, they can have an adverse effect on the effectiveness of the CP due to a load to the pipeline's CP systems. To avoid adverse effects on the CP, (1) the electrode (e.g. magnesium) whose potential is close to the CP potential of the pipeline should be used, or (2) the grounding systems should be connected to the pipeline via appropriate devices (e.g. DC decoupling devices in order to let AC current, but DC current, flow).
3) Increase the CP level so that the peak of the positive part of AC wave form can be brought below the protection potential.
This method is previously described with special regard in **4**.

13. AN ADVANCED INSTRUMENTATION USING INNOVATED MEASURING TECHNIQUES

13.1 CONCEPTS FOR THE DESIGN

The authors named an advanced instrumentation "CP MONITOR" in this paper. "CP MONITOR" with a coupon was designed on the concepts as follows:

1. Surface Area and Shape of a Coupon

Literature suggests that the most severe corrosion occurs at holiday surface area of 1 cm^2, and then a 1 cm^2 coupon is recommended to be installed at the pipe depth for the purpose of measuring AC current density. In the present field observations, however, conical shaped coupons having a surface area of 10 cm^2 were used in order to ensure good contact of the coupon with electrolyte. From the extensive field observations, no possibility of significant non-uniformity of the current distribution (i.e., the current density is higher at the edge of the coupon where current lines emerge or arrive from a greater range than at the middle of the coupon) was confirmed. A bare steel coupon permitting accurate weighing to judge whether or not CP level is acceptable was installed in a monitoring station. The monitoring stations were installed above the pipeline at intervals not greater than 1 km along the pipeline.

2. Simultaneous Measurements on Coupon Current Densities and DC potentials with High Rate Data Sampling Rate

As shown in Figure 3, measuring systems for coupon DC and AC current densities, and coupon DC and AC potentials are illustrated. I_{DC} stands for coupon DC current density, I_{AC} coupon AC current density, E_{DC} coupon DC potential (polarized potential), and E_{AC} coupon AC potential, respectively. The measurement was typically performed during a period of 24 hours in each monitoring station installed in Tokyo metropolitan areas in Japan. In areas frequency of electric power transmission lines is 50 Hz, AC powered rail transit system is operated at frequency of 50 or 60 Hz. The measurement of coupon current densities should be carried out for a period of at least 24 hours, to assess the level of permanent or short-term interference on a pipeline. Figure 6 shows that block diagram for an advanced instrumentation "CP MONITOR" developed by the authors. The data on coupon current densities and coupon potentials were continuously measured with resolution of 16 bit at the interval of 0.1 ms in each monitoring station. In areas where DC/AC interference currents induced by the passing of a high speed DC/AC train are suspected, this measuring technique with high data sampling rate of 0.1 ms enables an engineer to asses the corrosion risk. Coupon DC current density I_{DC}, coupon AC current density I_{AC}, coupon DC potential E_{DC}, and coupon AC potential E_{AC} were obtained, every sub-units of 20 ms corresponding to the frequency of 50 Hz, from equations (2), (3), and (4), respectively using a low pass filter with a cut-off frequency of 73 Hz to avoid abnormal electrical spikes and harmonic currents.

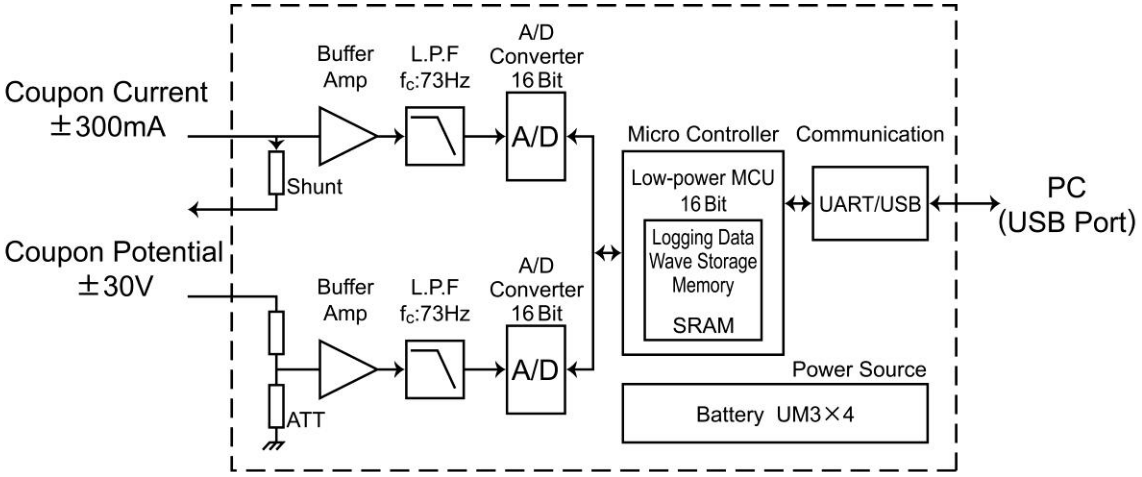

Figure 6 Block diagram for an advanced instrumentation.

Coupon current measurements must be made using a data logging device programmed to acquire the precise coupon DC current in a period.

$$I_{DC} = \frac{1}{A} \cdot \frac{1}{200} \sum_{t=1}^{200} I(t) \tag{2}$$

$$I_{AC} = \frac{1}{A} \cdot \sqrt{\frac{1}{200} \sum_{t=1}^{200} \{I(t) - I_{DC}\}^2} \tag{3}$$

$$E_{DC} = \frac{1}{200} \sum_{t=1}^{200} E(t) \tag{4}$$

$$E_{AC} = \sqrt{\frac{1}{200} \sum_{t=1}^{200} \{E(t) - E_{DC}\}^2} \tag{5}$$

where:

A = Surface area of a coupon (= $10cm^2$)
I(t) = Instantaneous coupon current at t ms in each sub-unit of 20 ms
I_{DC} = Time-averaged instantaneous coupon current in each sub-unit of 20 ms
I_{AC} = Coupon AC current in each sub-unit of 20 ms
E(t) = Instantaneous coupon potential at t ms in each sub-unit of 20 ms
E_{DC} = Time-averaged instantaneous coupon potential in each sub-unit of 20 ms, that is, polarized potential
E_{AC} = Coupon AC potential in each sub-unit of 20 ms

Higher the data sampling rate, higher the accuracy of obtained I_{DC}, I_{AC}, E_{DC}, and E_{AC}. By taking the transference rate of measured data from "CP MONITOR" to a client PC and consumption of battery for measurement into consideration, data sampling interval of 0.1 ms was determined. Even if E_{DC} satisfies the protection potential criterion, the positive part of AC wave form more positive than the protection potential which indicates a strong likelihood of AC corrosion cannot be recognized without high rate data sampling measurement techniques as mentioned above.

Each unit containing 500 sub-units was set to 10 s. The average, maximum, and minimum values of I_{DC}, I_{AC}, and E_{ON} were obtained every units by analyzing 500 sub-unit data. The schematic representation of the measurement for I_{DC}, I_{AC}, and E_{ON} is shown in Figure 7.

For field measurements, the value of 0.1 ohm was determined as shunt resistor. Coupon current measurements must be made using a data logging device programmed to acquire the precise coupon DC current in a period. Coupon DC current is acquired as an average of coupon currents over a period according to equation (2). Based on equation (3), coupon AC current in a period can be obtained. By using a low pass filter with a cut-off frequency of 73 Hz and equation (3), the frequency of coupon AC current densities can be regarded as 50 Hz or less.

Instantaneous coupon potential at t ms in each sub-unit of 20 ms, E(t), is measured by placing a copper sulfate electrode (CSE) as close to the pipe as possible to minimize IR drop. So time-averaged E(t) in each sub-unit of 20 ms, E_{DC}, can be considered as polarized potential. By using E_{DC}, E_{AC} in each sub-unit of 20 ms is obtained according to equation (5).

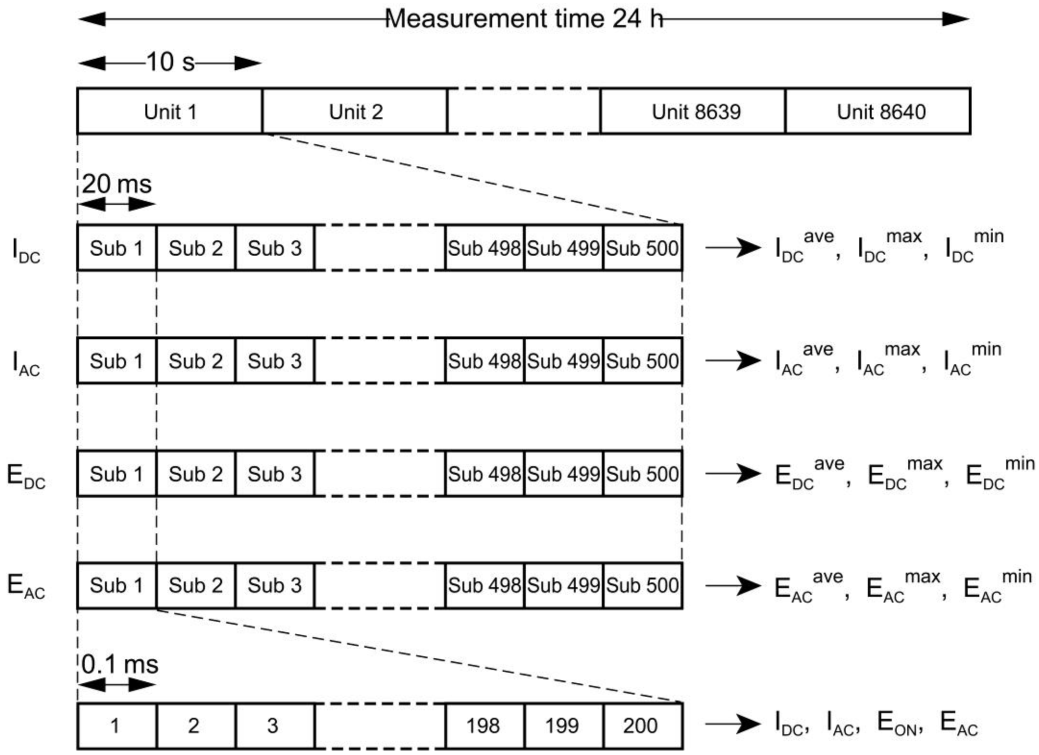

Figure 7 The schematic representation of measurement for coupon DC current density I_{DC}, coupon AC current density I_{AC}, coupon DC potential E_{DC}, and coupon AC potential E_{AC}.

3. Controlled by the "CP Management System"

The schematic representation of the procedures of periodic inspection using a developed instrumentation "CP MONITOR" controlled by the "CP MANAGEMENT SYSTEM" is illustrated in Figure 8. The authors named cathodic protection management system "CP MANAGEMENT SYSTEM" in this paper. Information on CP maintenance activities of pipelines and monitoring facilities is centralized in "CP MANAGEMENT SYSTEM".

Measurement conditions such as start time, measuring time, weather are set from the client PC to the "CP MONITOR" using USB (Universal Serial Bus). The client PC has the same information as web server via an internet.

The measurement of coupon current densities, coupon on potentials, and coupon AC potentials are carried out using "CP MONITOR" installed in a monitoring station. After ascertaining that the remaining capacity of battery is enough to measure coupon current densities and on potentials throughout the measuring time, the measurement starts up. The average, maximum and minimum of coupon DC and AC current densities and on potentials are obtained through computation every units. The data on every units together with the waveform of the maximum coupon AC current density in the measurement time are then stored in the SRAM (Static Random Access Memory) with high-speed access and low battery consumption.

The measured data are transferred from the “CP MONITOR” to the client PC.

Immediately after the transference, the CP level is assessed by comparing the obtained time-averaged coupon DC and AC current densities to the new CP criterion based on the coupon current densities using the client PC in the field. When the CP level is not met the CP criterion, the detailed investigations shall be performed based on the inspection results and pipeline history. A benefit of CP MANAGEMENT SYSTEM-based inspection is to certainly and efficiently implement periodic inspection of the CP system with large quantity information, resulting in minimizing human errors.

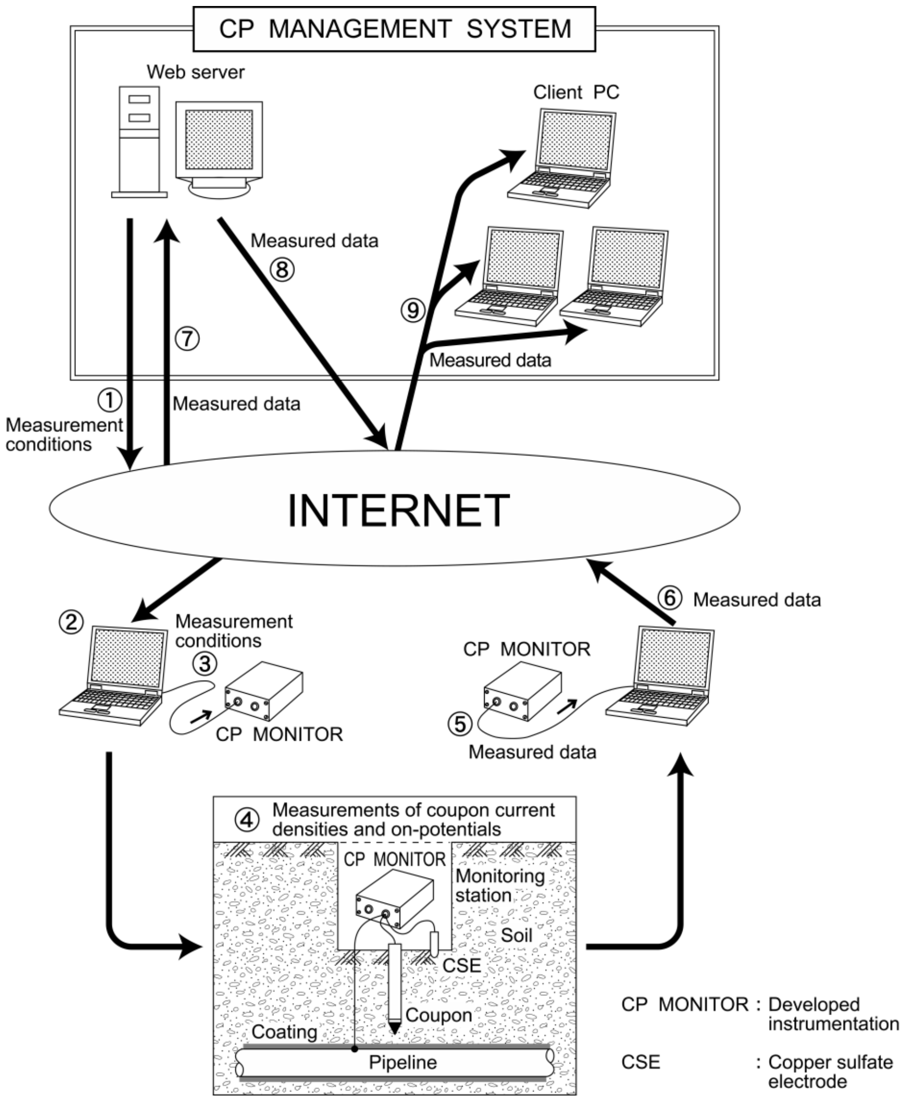

Figure 8 The schematic representation of the procedures of periodic inspection using a developed instrumentation “CP MONITOR” controlled by “CP MANAGEMENT SYSTEM”.

4. Identification of I_{AC} (50Hz)

In this paper I_{AC} (50Hz) is defined as the coupon AC current densities, corresponding to the frequency of 50 Hz. The frequency of 50 Hz is regarded as coupon AC current density having the difference within 10 ms ± 1 ms (i.e. 45.5 Hz − 55.6 Hz) in appearance time between and minimum value in a sub-unit (a single period of 20 ms).

5. Display of the waveform of the maximum coupon AC current density

After the measurement, the waveform of the maximum coupon AC current density in a sub-unit is displayed. Thereby the frequency and current level can be confirmed visually.

13.2 AN EXAMPLE OF MEASURED DATA

Figure 9 demonstrates the data on coupon DC potentials E_{DC} and coupon DC and AC current densities, I_{DC} and I_{AC}, respectively, measured during a period of 24 hours for the polyethylene coated 300 mm diameter pipeline paralleling two 66 kV, 50Hz overhead electric power lines and neighboring a 1500 V DC powered rail transit system. The environment in which the pipeline is laid suggests that there is the possibility of AC corrosion and DC stray current corrosion. The DC powered rail transit system was not operated after midnight until early morning (1:30 – 4:00). The fluctuation of coupon DC potentials and coupon DC and AC current densities varied corresponding to the demand for electric power and the operation condition of the DC powered rail transit system. During no operation of DC powered rail transit system, stable and more positive coupon on potentials were observed, together with stable and lower DC current densities, indicating no DC interference currents induced by the passing of DC powered train. Variations in coupon AC current density between 1.06 – 5.00 A/m^2 were measured, the most severe effect occurring at 9:57. From 3:00 through 5:30, lower coupon AC current densities were observed, suggesting the decrease in electric power transmission currents due to the lower electric power consumption. The AC level was satisfactorily mitigated using Mg electrodes as earthing electrodes.

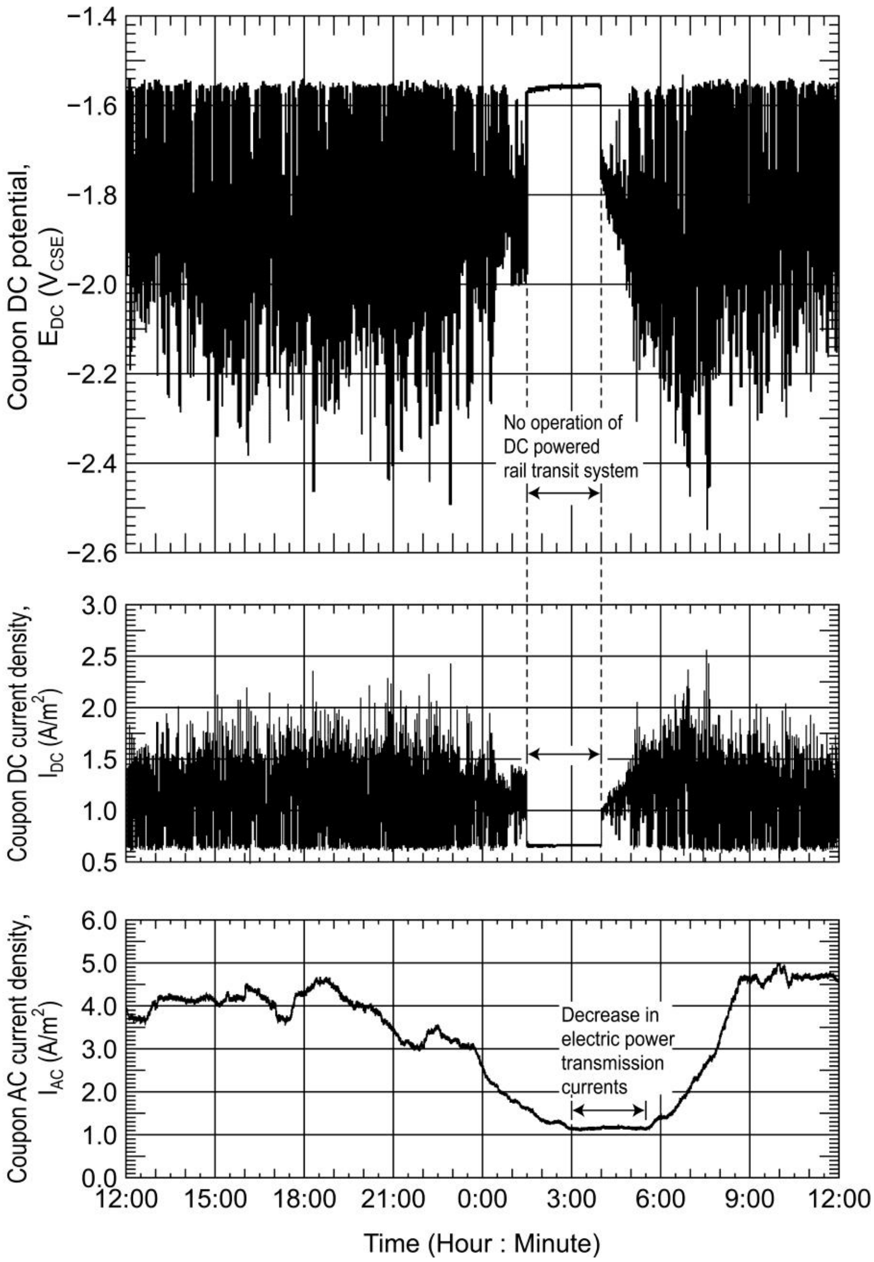

Figure 9 The data on coupon DC potentials, and coupon DC and AC current densities measured during a period of 24 hours for the polyethylene coated 300 mm diameter pipeline paralleling two 66 kV, 50 Hz overhead electric power lines and neighboring a 1500 V DC powered rail transit system.

The original waveform of the maximum coupon AC current density is demonstrated in Figure 10. The difference in appearance time between the maximum and minimum values exhibited 10 ms (3.2 ms − 13.2 ms), therefore the frequency of coupon AC current density was regarded as 50 Hz corresponding to the power-line frequency. As a result, the maximum I_{AC}^{max} was considered as I_{AC} (50 Hz).

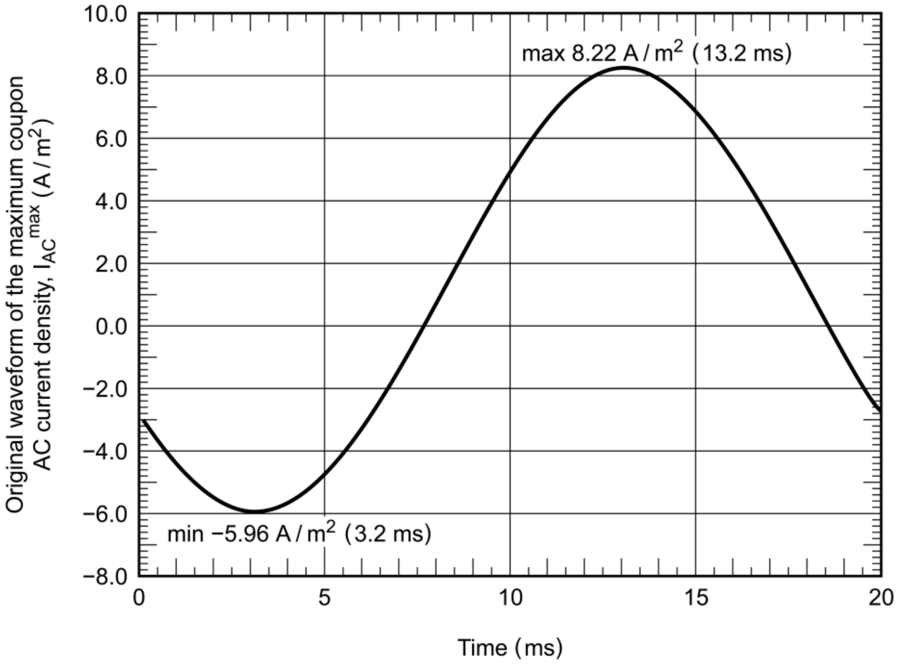

Figure 10 Original waveform of the maximum coupon AC current density in the measurement time.

Average values of coupon DC and AC current densities were assessed with respect to the new CP criterion as shown in Figure 11. The result satisfied the CP criterion.

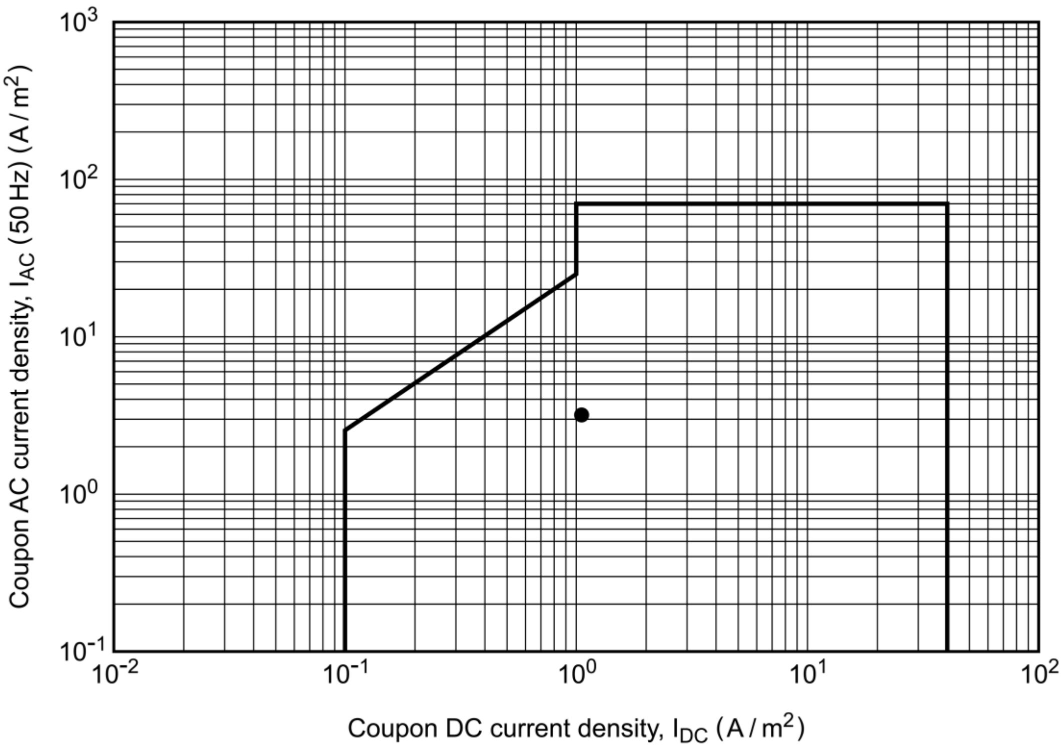

Figure 11 Result of the measured average values of coupon DC and AC current densities.

14. CONCLUSIONS

In this paper, modern pipeline is defined as high strength steel pipeline (specified minimum yield strength greater than 550 MPa) with high resistivity coating. Recently, modern pipelines have been used worldwide in response to the growing energy demand.

Modern pipeline is thought to be susceptible for hydrogen embrittlement induced by cathodically-formed excess hydrogen under overprotection condition. The technological advancements in pipe coating materials which provide increased pipe coating resistivity values and the increased tendency to locate pipelines paralleling high voltage AC (HVAC) electric power lines and/or AC powered rail transit systems have made the AC corrosion risk more severe. This means that more attention must be paid to new threats, that is, AC corrosion and overprotection on modern pipelines.

Conclusions can be drawn as follows:

1. Even if coupon DC potential (polarized potential) satisfies the protection potential criterion, the positive part of AC wave form more positive than the protection potential which indicates a strong likelihood of AC corrosion cannot be recognized without high rate data sampling measurement techniques.

2. AC corrosion can occur in high alkaline environment produced by cathodic protection that is perfectly passivating if AC currents are absent. This is a special feature of AC corrosion.

3. There is a lack of technical consensus on the mechanism and the extent of the effect of AC densities on cathodically protected underground metallic structures, particularly AC corrosion in soils. There are no agreed-on criteria for AC corrosion protection. Furthermore, the effect of hydrogen formed by cathodic protection on a modern pipeline is not well understood. In spite of these situations, pipeline corrosion engineers shall struggle to eliminate risks.

4. Based on accumulated-experience and knowledge for many years, the authors have developed an innovated instrumentation for assessing the AC corrosion risk of buried pipelines, and established the new CP criterion based on coupon DC and AC current densities (coupon current density-based criterion). The most distinguished feature is the simultaneous computation in a measuring unit of 20 ms regarding coupon DC current density and coupon AC current density corresponding to a period of the commercial frequency of 50 Hz. The criterion eliminates all corrosion risks such as AC corrosion, DC stray current corrosion, microbiologically influenced corrosion etc. and overprotection risk.

5. The new CP criterion established by the authors is the second revolutionary criterion following the protection potential criterion proposed by Kuhn in 1933. From now on, for the case of no AC interference, the protection potential criterion continues to be accepted and used on steel pipelines and structures in various soils and water.

6. Pipeline corrosion engineers shall be aware of the changes in materials (pipe and coating) and conditions of environments where the pipeline is laid (AC interference current), then eliminate predictable risks of all corrosion including AC corrosion and overprotection to manage and maintain the integrity of their pipelines; thereby engineer's primary responsibility is achieved.

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