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Estimation of Corrosion Protection Condition on Buried Steel Pipeline under Cathodic Protection with IR-free Probe

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Abstract

Buried steel pipelines are protected from corrosion by insulating coatings. When there is a coating defect called holiday on a pipeline, corrosion is occurred at the holiday, especially by direct current (DC) interference from DC railway in urban area. Therefore, a cathodic protection (CP) system is usually applied to buried steel pipelines in addition to insulating coatings. On the other hand, alternating current (AC) corrosion has been caused in many countries since the mid-1980s, although the corrosion protective potential is achieved at the pipelines under CP. A corrosion protection criterion to prevent from AC corrosion is established by some organizations, for example, DIN 50 925 (1992) and ISO 15589-1 (2003). These criteria consist of the AC current density and/or DC current density at a coupon. However, there is a possibility that the current density to keep from corrosion varies depending on each environment around buried pipelines. Consequently, in AC corrosion, the management by means of the potential such as the corrosion protective potential under CP is desired.

In the present work, an IR-free probe with a steel coupon as a simulated holiday has been developed to estimate the condition of corrosion protection from DC and/or AC interference at buried steel pipelines under CP. The IR-free probe is constructed to measure the IR-free potential, i.e., the polarized potential of the coupon easily without current interrupt methods and expensive instruments. Using this IR-free probe, laboratory and field test results have indicated that the IR-free potential can estimate the risk of AC corrosion under CP. That is, AC corrosion has resulted not to be caused when the peak-potential, which means the noblest value of IR-free potential waveform, is below -0.85 V vs Cu/$CuSO_4$. In addition, even if the peak-potential is more than -0.85 V vs Cu/$CuSO_4$, corrosion rate has resulted to achieve below 0.01 mm・$year^{-1}$ when the peak-potential is over 0.1 V less noble than the free corrosion potential of the coupon with the IR-free probe.

Furthermore, many investigation results on site have indicated that IR-free probes provide useful data for the estimation of the corrosion protection conditions under DC stray current.

1. Introduction

The use of probes to estimate conditions of corrosion and/or corrosion protection of buried steel pipelines has been adopted on site during recent years.

Many kinds of probes are mounted with a coupon, i.e., a specimen of the same material as the buried pipelines and simulated a coating defect called holiday. When it is positioned in vicinity to a buried pipeline, the probe can simulate a free corrosion condition of a holiday. Connecting between a probe and a buried pipeline under a cathodic protection (CP) will make estimating the CP effectiveness. Furthermore, it can be used for evaluating the effects of direct current (DC) and/or alternating current (AC) interference.

To estimate the CP effectiveness with such a probe, the measurements of the coupon potential and/or the coupon current is used. It should be noticeable that the measurement of the coupon potential under CP is included the voltage drop, called IR-drop, as an error. The IR-drop is caused by the soil resistance between the reference electrode and the coupon and by the electric current the flows to or out of the coupon. In order to measure the accurate coupon potential without IR-drops, the coupon instant-off method is applied in most cases. This method employs for measuring the instant-off potential, i.e., the polarized potential of the coupon taken immediately after the coupon current is stopped by disconnecting the coupon from the pipeline. In this study, such the instant-off potential of the coupon is called the coupon off-potential. Additionally, the coupon current has been used to measure the corrosion rate by DC interference, because the corrosion rate is proportional to the DC flew out of a coupon in accordance with the Faraday's Law. On the other hand, it is mentioned in some reports that AC corrosion as opposed to DC corrosion is difficult to estimate by means of the potential such as the coupon off-potential and the pipe-to-soil potential. This reason is assumed that such the potential, especially the coupon off-potential, is measured with functions to obtain the DC potential or that it is difficult to evaluate which coupon off-potentials is adopted as a criterion for AC interference because the polarized potential of the coupon has fluctuation affected by AC current. Therefore, some organizations have established criteria for AC interference by means of the AC and/or DC current density of the coupon current, such as DIN 50 925 (1992), ISO 15589-1 (2003).

However, some of estimations with the conventional coupons have several problems as follows:

Estimations with the coupon off-potential require an expensive recorder with functions of the high-speed sampling rate and the arithmetic processing to calculate the coupon off-potential. Moreover, the coupon off-potential can not be measured continuously in the sense of the word, because a connect/disconnect function between the coupon and the pipeline is necessary to measure the coupon off-potential. In addition, if other electrical currents flow in vicinity of the coupon except the current to flow out of or to the coupon, the measurement results can cause complications. For instance, when there is a ground bed of another pipeline under CP in the vicinity of positioning a probe connecting to a buried pipeline to maintain, the coupon off-potential measurements may not be accurate, because the coupon off-potential may include the IR-drop caused by the protective current due to another CP. Furthermore, when there are multiple impressed current systems or galvanic anode systems in the same CP area on a pipeline, the coupon off-potential measurements may include the IR-drop caused by the protective currents so as to be hard to interrupt multiple current sources at the same moment.

Estimating AC interference with the coupon current under CP, unexpected results may be derived due to the differences of each environment buried coupons, such as the lack of corrosion protection or the overprotection. This reason simply comes from the fact that the protective current required for cathodic reactions to decrease the polarized potential of a coupon below the protection potential varies depending on a surrounding environment of the coupon. For example, when the amount of dissolved oxygen to reach a coupon surface is much more in a rainy season, the protective current to achieve the protection potential is required more than in other seasons. This indicates that each protective current for all environments surrounding buried pipelines can not be obtained and that an estimation result with the coupon current has the risk to give false judgments.

In addition, calcareous deposition mainly composed of $CaCO_3$ and $Mg(OH)_2$, called electro-coating, is deposited on the surface of a coupon under CP over the long term. Such the coupon is usually replaced by new one during periodic intervals, because the coupon current density can not be measured accurately due to the uncertain surface area of the coupon as if the electro-coating acts as the coating with resistance. On the other hand, the electro-coating does deposit at many of holidays of the actual pipelines. This means that the estimation result with the coupon current of a bare coupon may have difficulties to evaluate the actual protective condition at a holiday deposited the electro-coating.

Therefore, it should be noticeable that the estimation with conventional coupons has a limitation in management of corrosion protection conditions of buried pipeline under CP.

To resolve these problems, we have developed an IR-free probe with a coupon. The IR-free probe has a structure to take an accurate measurement of the polarized potential of the coupon without the coupon instant-off method. The IR-free probe has been improved variously since its prototype was developed in 1999 and used for the maintenance of our buried pipelines under CP.

2. Basic Structure and Evaluation of IR-free Probe

2.1 Basic Structure of IR-free Probe

To remove an effect of IR-drops, it is important to install a reference electrode near a coupon, whereas, it can be difficult installing the reference electrode near the coupon in a buried condition. Therefore, architecture to measure the coupon potential without IR-drops has been developed, which has a large salt bridge with a coupon at the bottom. The basic structure of the IR-free probe will be detailed below.

A coupon in the same material as a buried pipeline to investigate is embedded in an insulated resin plate. There is a drilled hole penetrated through from the coupon surface to the back of resin plate. The wall surface of the hole is insulated with an insulating material, for example, insulating coating, resin tube and so on. This hole employs the potential measurement hole to measure the potential of the surface of the coupon from its back side. This resin plate embedded the coupon is attached to the bottom of an insulated resin pipe employed as the Luggin capillary tube. Inside the probe, i.e., the inner portion of both the tube and the potential measurement hole are filled with an electrolyte prepared to a specific conductivity. The coupon is equipped with a shielded lead wire, which is pulled from the open end through the inside of the tube, so that it can measure the coupon potential and connect to a pipeline. The basic structure of the IR-free probe is shown in Fig. 1.

The IR-free probe structured in this way is positioned at a hand hole as shown in Fig.1 and connected to a buried pipeline. In measuring the polarized potential of the coupon, a reference electrode is positioned at the open end of the tube in the hand hole. This structure helps eliminate an effect of IR-drops caused by any currents outside the probe, because the accurate polarized potential of the coupon surface is measured through the electrolyte inside the probe. Therefore, the polarized potential of the coupon can be measured continuously so as not to use the coupon instant-off method and obtained accurately even under anodic or cathodic interferences. In addition, there is no need to replace the probe where electro-coating is deposited, because of criteria with the polarized potential for CP with IR-free probe described in section 3. In this study, such the polarized potential of the coupon measured with the IR-free probe described above is called the IR-free potential.

External appearances of IR-free probes positioned on site are shown in Fig. 2. Figure 2(a) shows the IR-free probe developed for the purpose of installing at the same time as a pipeline construction or repair with excavation. The coupon made from carbon steel, the surface area of which is 10 cm^2, is embedded to the bottom of the polyvinyl chloride pipe (PVC) with 5 cm in diameter. Figure 2(b) shows the type to position in an existing hand hole. This type of the IR-free probe is pushed into a hole made by a guide bar in the hand hole. The tip of the PVC pipe with 25 mm in diameter is equipped with a steel coupon with 20 cm^2 in surface area. Figure 2(c) shows the entirely buried type which has a permanent reference electrode inside it, for example, a copper/copper sulfate permanent reference electrode and/or other metal electrodes. Many kinds of IR-free probes have been positioned for various investigations of buried pipelines in our service area.

2.2 Basic Evaluation of IR-free Probe

The IR-free probe as shown in Fig. 2(a), the tube length of which was 30 cm, was immersed in 20 $mS\cdot m^{-1}$ purified water containing Na_2SO_4, then the anodic and cathodic polarization curves were measured with sweep rate of 20 $mV\cdot minute^{-1}$. The polarization curves shown in Fig. 3 indicate that the Tafel Slope of hydrogen generation and of active dissolution of iron are approximately 0.118 $V\cdot decade^{-1}$ and the 0.039 $V\cdot decade^{-1}$, respectively, that correspond to values in the literature 1). Therefore, it is confirmed that the IR-free potentials can be measured without IR-drops using this structure of the IR-free probe.

3. Criteria for Buried Steel Structures under Cathodic Protection with IR-free Probe

Criteria for buried steel structures under CP with IR-free probes utilized in Osaka Gas Co., Ltd are described below.

3.1 Basic Criterion for Corrosion Protection

As a criterion of corrosion protection for buried steel structures, less noble potential than -0.85 V_{CSE} without IR-drop has been adopted to the corrosion protection potential. V_{CSE} means the measurements using a saturated copper/copper sulfate reference electrode. Therefore, as for the IR-free probe, the basic criterion for corrosion protection has been adopted as follows:

$$E_{IR\text{-}free} \leqq -0.85\ V_{CSE} \qquad (1),$$

where $E_{IR\text{-}free}$ is IR-free potential measurements. $E_{IR\text{-}free}$ can be measured easily on site without specific instruments and techniques. Consequently, it is possible to judge immediately on site whether the equation (1) is achieved.

3.2 Criteria for AC interference

Criteria for AC interference under 60 Hz in frequency have been derived from experimental results with IR-free probes in laboratory and in field tests. They are described as follows $^{2)}$:

$$E_{peak} \leqq -0.85\ V_{CSE} \qquad (2)$$

$$E_{peak} - E_{corr} \leqq -0.1\ V \qquad (3),$$

where E_{peak} is the noblest value of the IR-free potential waveform, called the peak potential, and E_{corr} is the free corrosion potential of IR-free probe after disconnecting a pipeline.

In the evaluation of AC interference, firstly, it is estimated if the criterion in equation (2) is achieved. Even if not, the criterion in equation (3) is estimated. Equation (3) is developed from the experimental results that the corrosion rate calculated from weight loss is less than 0.01 $mm \cdot year^{-1}$ and the maximum corrosion depth of localized corrosion is less than 100 μm after buried tests. If criteria described above are not achieved, the result indicates that this measuring point has the risk of AC corrosion. In these equations, the peak potential can be measured easily on site with the use of a commercially available portable oscilloscope, or digital tester, or digital recorder, and so on. Notice that, in equation (3), the threshold value of 0.1 V may be changed in another frequency and soil environment.

4. Introduction Examples on Site under Cathodic Protection

4.1 Estimation of DC interference

IR-free probes as shown in Fig. 2(b) were positioned at each hand hole for investigating a buried gas pipeline with 600 mm in diameter under CP by multiple impressed current systems. This pipeline is affected by the stray current from DC railway. In addition to the IR-free potential measurement, the pipe-to-soil potential was measured simultaneously at each hand hole. In measuring, DC potential recorders developed in our company were used. The specifications of the DC potential recorder is shown in Table 1.

Figure 4 shows the relationship between the IR-free potential and the pipe-to-soil potential at the same hand hole, which tends to be at their worst under rainy weather, for an entire month of continuous measuring. The data in Fig. 4 indicate that the pipe-to-soil potential has quite a change due to the IR-drop caused by the DC stray current, whereas, that the IR-free potential has a little change. In addition, the IR-free potential is less than the corrosion protection potential, i.e. -0.85 V_{CSE}. The measurement result on this site indicates that the polarized potential of the pipeline may be barely changed as the IR-free potential under rainy weather and achieved the protection potential.

4.2 Estimation of AC Interference

The same type of IR-free probes described in section 4.1 were positioned at each hand hole of another buried gas pipeline with 600 mm in diameter under CP by an impressed current systems, where the effects of AC induced current have been confirmed. The coupon current in addition to the same measurement items as described in section 4.1 was measured simultaneously at each probe. In measuring, AC potential recorders developed in our company were used. The AC potential recorder has 3 recording units in it to measure the pipe-to-soil potential, the IR-free potential and the shunt voltage for the coupon current. Each data can be recorded per 10 kHz, simultaneously, and saved at three SDXC memory cards. This recorder has the input impedance with over 10^{12} ohm at each unit and the continuous measuring period is for more than 30 days. The measurements in each SDXC card is analyzed with the dedicated software at a personal computer.

Figure 5 shows the waveform with 60 Hz taken from the analysis after low-pass filter processing. 60 Hz is the frequency used in our service area. Comparing the IR-free potential with the pipe-to-soil potential as shown in Fig. 5, the pipe-to-soil potential shows large fluctuation from -11.4 to +0.6 V_{CSE} due to the greater IR-drop caused by AC, whereas, the IR-free potential shows a little fluctuation from -1.4 to -0.9 V_{CSE} affected by AC. The peak potential, i.e., -0.9 V_{CSE} is achieved the protection potential. Therefore, it is confirmed that this measuring point has no risk of AC corrosion due to the criteria described in section 3.2.

5. Conclusion

An IR-free probe equipped with a coupon has been developed for estimation of corrosion protection condition on buried pipeline under cathodic protection. The IR-free probe has advantages in comparison with conventional coupons as follows:

(1) The polarized potential of the coupon with the IR-free probe can be measured easily without the instant-off method and estimated with time continuously for a long term.

(2) Its polarized potential can be measured accurately, even though there are any currents surrounding the IR-free probe, for example, uninterruptable direct current sources in vicinity of its installation.

(3) AC interference can be evaluated by means of the noblest value of the polarized potential waveform of the coupon with IR-free probe whether the corrosion rate is less than 0.01 mm・year^{-1}.

References

1) John O'M Bockris and Amula K. N. Reddy : Modern Electrochemistry, Vol.2, Plenum Press, New York, 1080 (1970).

2) Aiichiro Kashiwagi, Hidemasa Nonaka, Akinobu Nishikawa and Akira Kinoshita, Zairyo-to-Kankyo, 52 (11), 1180 (2004).

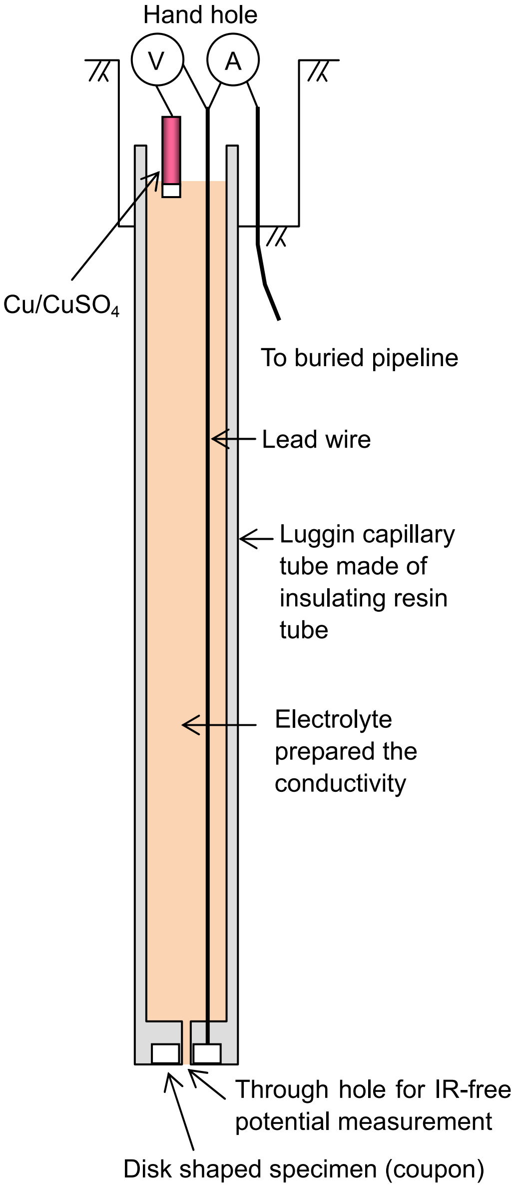


Fig. 1 Schematic vertical cross-section diagram of IR-free probe

(a) Type for installation with excavation

(b) Type for installation in an existing hand hole

(c) Type for entirely buried installation.

Fig. 2 External appearances of IR-free probe.

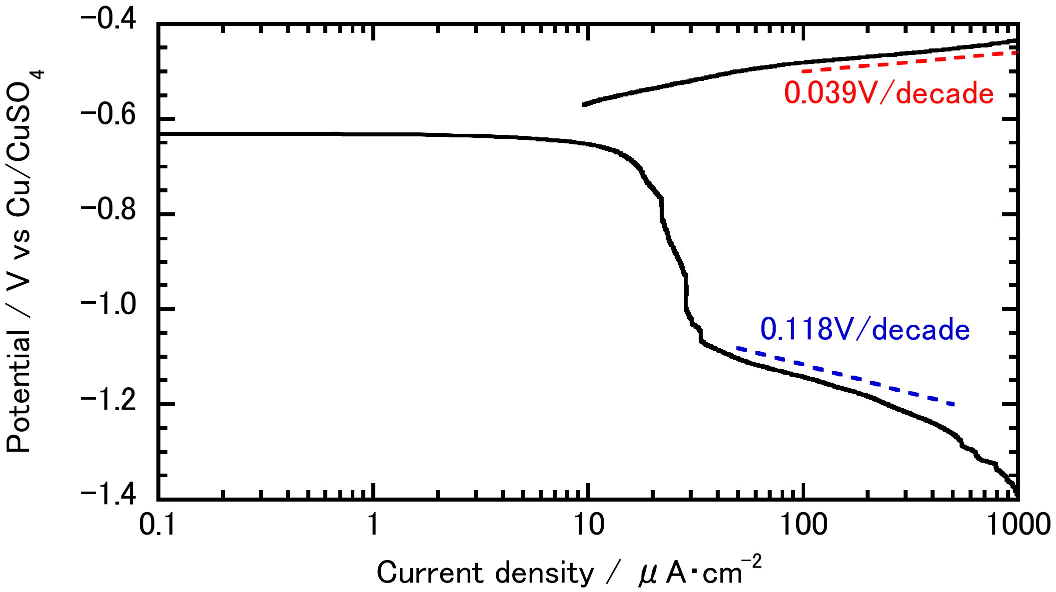
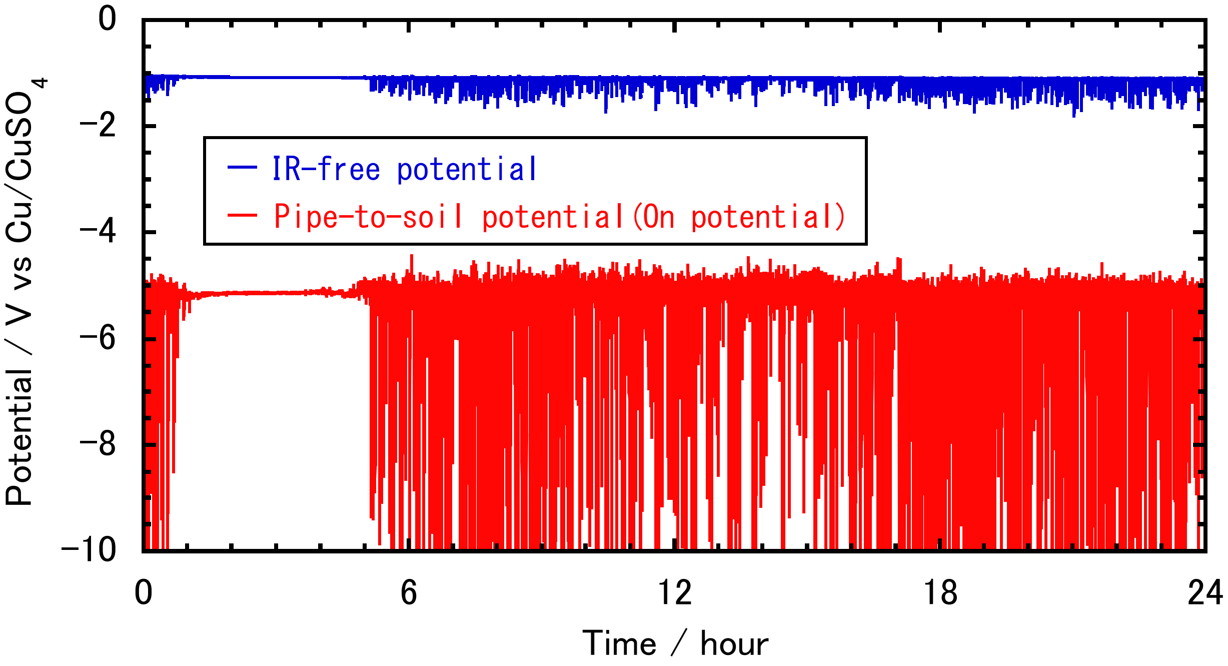


Fig. 3 Anodic and cathodic polarization curves in 20mS•m-1 purified water contained Na_2SO_4.

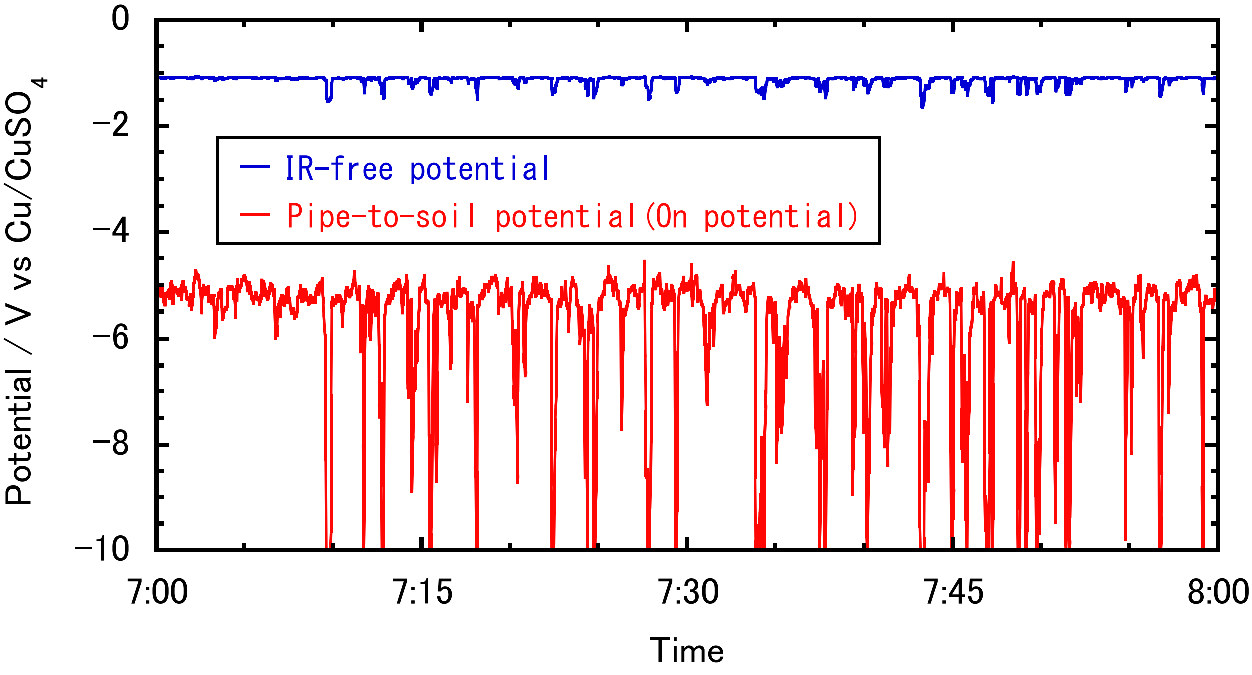
Table 1. Specifications of DC potential recorder

Target of measurement	Pipe-to-soil potential, IR-free potential	Probe current*
Range of recording voltage	±20 V	±100 mV
Accuracy	±1 mV	±10 μV
Power supply	Rechargeable AA battery ×4	
Sampling rate	1 Hz (One data recording per a second)	
Temperature in use	-10 ～ +50 degree	
Input impedance	≧ 10 MΩ	
Continuous recording time	≧ 30 days	
Waterproof property	Commercially available waterproof container storage	

*At the time of the probe current measurement, the voltage is measured between both ends of a shunt connected in series between the probe and the pipeline.



(a) 24 hour measurement data



(b) (a)'s data expanded from 7:00 to 8:00

Fig. 4 Relationship between the IR-free potential and the pipe-to-soil potential under CP affected by DC interference.

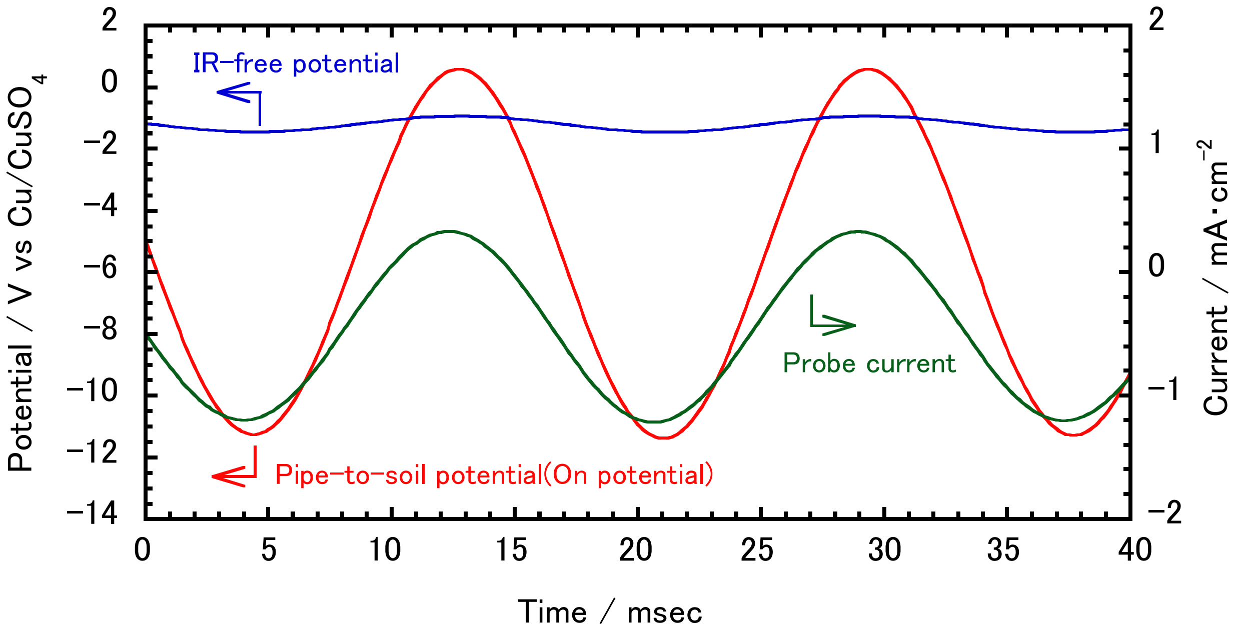


Fig. 5 Waveform of the IR-free potential, the pipe-to-soil potential and the coupon current under CP affected by AC interference.