PIPELINE CASING CONTROL AND MONITORING

Commission 2, Working Group G

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Foreword

Crossings of buried pipelines with roads and railways can be installed both with and without casings. The reasons for using casings are, among other things, pipeline protection, different materials and connection techniques for the pipelines and the resulting corrosion protection and operational aspects. In addition to the present technical considerations, regulations must be complied with.

A variety of technical solutions are applied where water, oil or gas transmission pipes cross under roads, rivers or railroads. In principle, there is a distinction between uncased and cased crossings. There are different types of casings and the annulus (the space between the carrier pipe and the casing pipe formed by the isolator centralizer) may be filled with different materials or left unfilled. Unless there is a local specific requirement or law, the decision for filling the casing is the responsibility of the pipeline operator (e.g., designer). Commonly used fills are conductive products such as sand, bentonite, or cement-based materials, or non-conductive products such as paraffin or similar waxes. Also, the use of inhibitors is possible depending on pipeline operator requirements[1].

Cased crossings reduce the risk of pipeline failures by mitigating some of the outside force threats, for example, in very congested areas where there are many underground utilities present. However, they can also increase the risk for corrosion threats to a carrier pipe. When a casing is shorted due to a metallic contact, corrosion can occur when a coating defect is present on the carrier pipe inside the casing, and cathodic protection (CP) may be shielded because of the configuration of the pipe within the casing. In this case, external corrosion cannot be avoided by regular means, and it is needed to carry out an action plan to solve the corrosion situation. It is noted that feedback has shown that a casing does not increase the risk of corrosion compared to the entire pipeline length.

[1] Angst, U., and Büchler, M.; Assessment of Cement-Based Fill Materials for the Annulus of Pipeline Casings; Swiss Society for Corrosion Protection (SGK), Zurich, Switzerland F. Moro, Holcim Technology, Ltd., Holderbank, Switzerland Material Performance, May 2014

1. Scope

The aim of this document is to describe fundamental recommendations and specifications to avoid corrosion of a cathodically protected carrier pipe inside a casing. Furthermore, this document describes methods to demonstrate that Cathodic Protection (CP) of the carrier pipe is effective inside the casing.

It is known that there are several integrity threats related to cased pipelines, for instance, poor construction techniques that may damage the pipeline coating, the lack of centralizers in older installations or misplaced or damaged centralisers. For the purpose of this document, protected structures are represented by buried or immersed steel pipes that are equipped with a CP system. The minimum requirements for CP for such structures are described in the EN and ISO standards referenced in the literature section of this document.

This document mainly addresses metallic casings, but recommendations may apply to concrete casings, steel reinforced concrete casings, plastic casings and coated metallic casings.

2. Definitions

Useful definitions are provided below. Some of the following definitions deviate from those in current standards and codes:

- **Carrier Pipe**: A pipe inside a casing, which carries a product such as a gas and/or a liquid.
- **Casing**: A pipe used to mechanically protect the carrier pipe. Also referred to as an encasement pipe or sleeve. Note that a casing can be made of a single continuous pipe or assembled pipes.
- **Coupon**: Metal sample of defined dimensions made of a metal of an equivalent specification to the metal of the carrier pipeline.
- **Direct contact**: Direct contact between the metallic carrier pipe and the casing.
- **Dogleg**: A term used to describe a vent pipe that is offset from the casing, which may cause the below-ground section to be shaped like the hind leg of a dog. The vent is offset as necessary to locate the above-ground section in a more acceptable location (e.g., to locate it off a right-of-way or to locate it where it is less susceptible to damage).
- **Electrode Potential:** Voltage measured in the external circuit between an electrode and a reference electrode in contact with the same electrolyte. A potential resulting from two or more electrochemical reactions occurring simultaneously on one electrode.
- **Electrolyte**: Medium in which an electrical current is transported by ions. A chemical substrate containing ions that migrate in an electric field and the medium in which electric current is transported by ions.
- **Electrolytic Couple or Contact**: Ionic contact between two metallic structures via an electrolyte. Electrolyte inside the casing that is also in contact with the carrier pipe is an example of electrolytic couple.
- **Electrical Circuit:** Complete circular path that electricity flows through. The corrosion of metals is an electrochemical process where the exchange of electrons is conducted by chemical reactions making a circuit.

- **End Seal**: A dielectric material to seal the end of a casing to assist in preventing water and soil ingress or filler egress. Device installed over or within the end of a casing to keep deleterious materials out of the casing or provide a water-tight seal between the casing and the carrier pipe
- **Filler**: A product placed in the annular space between the carrier pipe and the casing pipe to inhibit corrosion and assist in preventing the ingress of the external electrolyte.
- **Galvanic Corrosion:** Corrosion caused by electrical contact of two metals sharing the same electrolyte and having different electrochemical potentials
- **Holiday**: Unintentional discontinuity in a protective coating that exposes the steel surface to the environment.
- **Isolator or Spacer**: A dielectric device specifically designed to electrically isolate a carrier pipe from a casing and provide support for the carrier pipe.
- **Metallic Short or Metallic Contact**: Direct metallic contact between two metallic structures.
- **Probe**: Device incorporating a coupon that provides measurements of parameters used to assess the effectiveness of cathodic protection and/or corrosion risk.
- **Protection Potential:** Structure-to-electrolyte potential at which the metal corrosion rate is acceptable for the structure.
- **Reference Electrode**: Electrode having a stable and reproducible potential that is used as a reference in the measurement of electrode potentials.
- **Structure**: Coated metal structure surface consisting of more than one electrode.

3. Requirements of casings

Casings have historically been installed to provide additional protection for pipelines that cross traffic routes (including roads, railways, and water courses) or traverse areas with high population densities. Casings are constructed from steel, concrete or thermoplastics (PE/PVC)[2].

The use of cased carrier pipe for pipelines crossing under highways and railroads has been common practice in the industry. Up until around 1955, in many cases the emphasis was on the pipeline-related aspects of the problem when manufacturing casings. Today, the practices for installing casings have improved using heavy-wall casing pipe to cope with high external loads, installing isolating spacers to reduce the risk of possible electrical contact between the casing and the carrier pipe and end seals to keep the electrolyte (e.g., mud, water) out of the annular space between the carrier pipe and casing. Moreover, coatings with additional mechanical protection are used.

Casings can however, affect the cathodic protection of pipelines. Consequently, it is recommended in the case of pipelines that they are cathodically protected, where it is technically feasible, to limit the use of casings when possible and instead using other approved techniques by the pipeline operator (e.g., insert specially coated pipelines under roads and railways and / or increase the pipeline wall thickness).

[2] Sleeve Workshop Output – UKOPA

Casings are normally defined as a project requirement to avoid stresses on the pipeline during the construction phase. There are numerous accounts of different pipeline operator's experience in dealing with state and local officials with respect to the use of casings. Therefore, only if there are other engineering concerns, a casing design could simply be considered in order to withstand the loads of major or heavy traffic, unstable soils or as protection from third-party damage. There are other possible pipeline protection solutions, for example, the use of concrete slabs to protect the pipeline from external loads, but these alternatives are not covered in this document. Alternatively, protection of the carrier pipe from mechanical damage or additional loads at the crossing may be achieved simply by increasing the wall thickness of the pipe or by adding concrete coatings. Although some recommendations are pointed out for the design and construction of casings in this document, it is not the aim of it to define the best engineering solution.

4. Corrosion risk of carrier pipes inside casings

a. Types of casings

Following EN ISO 15589-1 [2], two kinds of casings must be considered: casings that shield cathodic protection current and casings that allow cathodic protection current to pass through. The first type includes synthetic materials (mainly plastic or polyethylene), coated concrete, low conductive concrete, and coated steel casings. Coatings are not perfect insulators and may not fully shield the CP current. The second type includes bare or poorly coated steel casings that has been damaged during installation, uncoated concrete casings that are sufficiently conductive and well-coated casings connected to a local earthing which will allow the cathodic protection current to flow.

The location of the casing should be considered be it either aboveground or underground. Regarding the possible interaction of the casing with the CP system, initially, only underground (buried or immersed) are considered. Nevertheless, in aboveground applications the design should follow the recommendations of this document to suspend or cradle support structures with isolators. Positioning the structure directly onto the ground surface must be avoided.

The best scenario is for there to be no casing at all, so there is not a best approach to select a type of casing or filler. Regardless, there are some requirements and conditions that must be considered according to the local regulations.

b. Electrical circuit

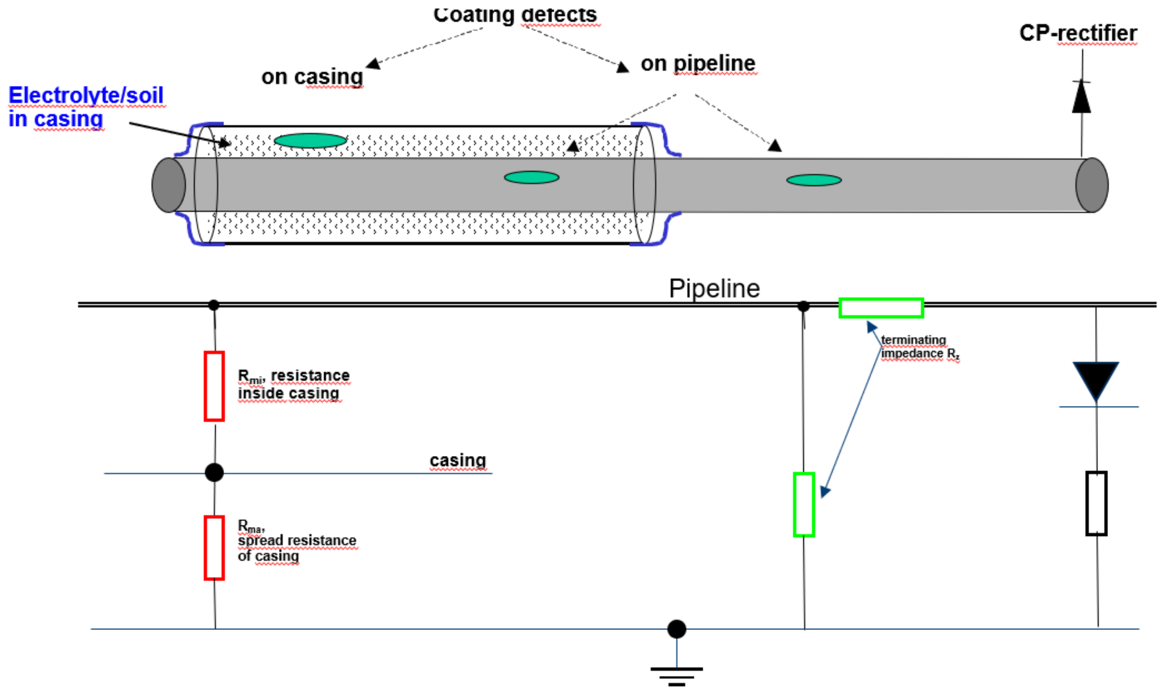


Figure 1: Simplified electrical circuit of CP protected pipeline in casing

It is generally not possible to determine the IR-free potential of a single coating fault on the carrier pipe in the casing. However, it is possible to estimate whether coating faults on the carrier pipe inside the casing are cathodically protected via a resistance comparison method. A minimum admissible spread resistance ($R_{a,min}$) of a coating defect on the pipeline inside the casing is calculated and compared to the determined resistance inside the casing (R_{mi}). According to DVGW GW 22 if $R_{mi} > R_{a,min}$ then CP is effective.

A more detailed depiction of the electrical circuit and the utilization of this circuit in the resistance comparison method is given in Annex A.

c. Integrity threats for the carrier pipe Corrosion process

The following integrity threats, either in isolation or in combination are observed:

- Insufficient cathodic protection of the pipeline in the annular space, or possibly outside the casing, due to a metallic contact.
- Corrosion due to MIC on the carrier pipe.
- Corrosion likelihood in presence of dc stray currents.
- AC corrosion on the pipeline in the annular space in presence of a low conductive electrolyte in the annular space, when the pipeline is subject to ac influences.
- Underground variable water level.

Additionally, the following corrosion effects could be observed with potential lower threats to the carrier pipeline:

- Casing corrosion.
- Atmospheric corrosion of the pipeline in the air-filled annular space.

Note that when there is no coating defect on the carrier pipe, the scenarios listed above are not a risk. A risk assessment analysis could be required to identify, assess and classify all of the potential risks and issues.

i. Metallic contact between casing and carrier pipe.

Cathodic Protection of a carrier pipe may be shielded by a direct metallic contact between a casing and a carrier pipe. This condition occurs when the metallic casing is in direct contact with the pipeline. This situation causes the CP current to be diverted from its intended path. With the short circuit in place, CP current collects on the outside of the casing and flows along the casing to the point of contact between the pipe and the casing. At the point of contact, the CP current flows to the carrier pipe through the metallic contact and then along the carrier pipe back to the rectifier. Under these conditions, essentially no CP current will flow through the casing wall to the pipe surface, leaving the pipe inside the casing free to corrode at coating defects even if the rest of the line is fully protected [20 or 21?].

Therefore, in the event of an electrical contact between an uncoated metallic casing and a coated pipeline, the casing acts as a very large coating defect at which sufficient protection current flow is not possible. Consequently, the pipeline is not sufficiently cathodically protected within the cased section. Furthermore, due to the large "coating defect" (casing), a high voltage drop could be created what could limit the protection of other sections of the pipeline outside the casing .

In addition, in the presence of dc stray currents, the metallic casing in contact with the pipeline acts like a large coating defect on the pipeline and may increase the dc stray currents flowing through the pipeline.

ii. Insufficient cathodic protection of the pipeline in the annular space

The cathodic protection of the carrier pipe in the annular space may be insufficient when the protection current flows from the casing to the carrier pipeline inside the casing, this is hindered by insulating layers such as inner coatings, outer coatings or casings made of plastic.

As specified in EN ISO 16440, plastic casings or coated casings are not recommended. When a plastic casing or a coated metallic casing is in place, a risk analysis can be carried out to define the appropriate solution to limit the corrosion risk on the carrier pipe section. Appropriate solutions can be:

- Filling the annular space,
- Installing a galvanic anode inside the annular space,
- Removing the casing,
- Or specific recommendation defined by the pipeline operator (e.g., risk assessment).

Sufficient cathodic protection in plastic casings as well as in coated casings can be achieved in new casings in the presence of infiltrated water or a filled electrolyte by the insertion of galvanic anodes in the annular space during the installation of the casing. Even though it is possible to protect the carrier pipe, it is very difficult to prove the performance of these systems.

iii. Casing corrosion due to the presence of unwanted electrolyte and insufficient CP current in the annular space

In the case where there is not a metallic contact between the pipe carrier and the metallic casing, carrier pipeline coating defects in contact with the electrolyte are very likely to be sufficiently cathodically protected provided the casing is made of a conductive material, such as steel or concrete, and if both inside and outside the casing there is no isolating coating present. The cathodic protection current flows from the ground onto the casing and then through the electrolyte to the defects in the coating of the pipeline. As a result, the casing is partly cathodically protected on the outside (current entry point). On the inside, this current leaves the uncoated casing in concentrated form near the coating defect on the pipeline As a result, over time the casing corrodes at this point. However, the corrosion rate could be very low as this current is usually spread across a large surface of the casing.

iv. Corrosion in presence of stray currents

DC stray current from third party sources can detrimentally impact the corrosion protection of the carrier pipe inside a casing in the same manner as it can at other locations on the pipeline. It is recommended to follow the guidance in standards (See EN 50162 or EN ISO 21857) and codes to monitor stray currents and apply remediation and mitigation systems to avoid external corrosion.

In the case that a metallic casing is in contact with the pipeline, it would act like a large pipeline coating defect, which can cause an increase of DC stray currents on the pipeline and so be a potential problem as described in the above mentioned standards.

v. AC corrosion in casing filled with conductive materials

AC corrosion can occur if there is sufficient AC influence [4] on the pipeline when an electrolyte or a conductive product with high conductivity is in contact with coating defects within the casing.

The flow of the protective current through conductive materials such as bentonite or through a cement-bonded mass to defects in the pipeline coating is possible as both have good electrolytic conductivity. However, this low conductive path also results in AC current flow and possible increased AC current densities in coating defects of the carrier pipe.
In the presence of a high conductivity and high pH electrolyte inside the annular space (e.g., bentonite), the corrosion likelihood may be high in presence of ac influences on the pipeline.

vi. Underground variable water level

When the end seals between the carrier pipe and the casing are not effective, electrolyte or water may move into the annular space. In this condition, if a coating defect is present within the casing, CP can function effectively against corrosion.

But when the electrolyte / water level varies with time, it means this coating defect is alternately cathodically protected and not protected. The defect surface will be covered with various forms of iron oxide. As a consequence, in presence of variable electrolyte or water level, the corrosion rate at coating defects on the carrier pipe inside the casing may increase, although some studies have confirmed this is not relevant risk parameter.

vii. Atmospheric corrosion in the annular space

Atmospheric corrosion in the carrier pipe within the casing has been observed at low levels. Atmospheric corrosion can occur in casings made of steel or plastic when the annular space is free of conductive/isolated product. This annular space is sealed from the soil and may be filled with humid air. Experience shows, seals can become permeable over time and water does enter into the annular space. When this water condenses on coating defects, an attack by atmospheric corrosion can then occur. This condensed water can bring oxygen on to the steel, causing corrosion. Subsequently, the oxygen in the annular space is consumed if it is not replenished. This leads to a reduction in pressure or a pressure differential between inside and outside, as a result of which air or water is drawn into the annular space.

The atmospheric corrosion is a relatively slow process. According to W. Vernon [18], corrosion rate with a relative humidity of 100% in pure air is 0.22 g / m^2 / day, which corresponds to a rate of 0.011 mm per year in most cases.

There are no reported incidents due to this corrosion threat.

5. Recommendation for protecting the carrier pipe

a. Casing shielding/not shielding the CP

An operator is required to protect the carrier pipe if the pipe casing is either electrolytically coupled or metallically shorted, which in both scenarios can be damaging to the carrier pipe where electrolyte is present.

Depending on the situation of the casing and the carrier pipe, it is necessary to determine three situations:

- If the casing is isolated from the carrier pipe and the operator wants to protect the carrier pipe where the casing is shielding cathodic protection current due to it is been coated, it may take into account that it could be achieved using galvanic anodes in the annular space provided there is a conductive electrolyte or filling in the annular space with appropriate material and with adequate long-term corrosion protection properties. If galvanic anodes are used, then there must be no contact between the casing (if metallic) and the galvanic anodes including any anode corrosion products that can potentially bridge the spacers.
- If the casing is passing cathodic protection current, the external cathodic protection of the carrier pipe can be effective in protecting the carrier pipe inside the sleeve provided there is no contact between the carrier pipe and the casing, and that there is enough electrolyte in the annular space.
- If the casing is in contact with carrier pipe, the carrier pipe will not receive sufficient Cathodic Protection inside the casing and probably in the surrounding area.

b. Spacers

Operators must identify the type and quantity of insulating spacers used in the annulus to electrically isolate the carrier pipe from its casing. Spacers consist of an electrically insulating skid strapped around the pipe through the casing at specific intervals. Spacers should be evenly spaced, following the recommendations of the manufacturer for the number and size of insulating spacers so that when the carrier pipeline is pulled into the casing, the end insulating spacers will be close to the casing end without any undesired gaps. This is a key requirement for installation, since stresses on the insulators during installation can be very large.

The insulators need to be effective in isolating the carrier pipe and the casing. There are two different types of spacers: synthetic spacers with metallic components and complete synthetic spacers.

Metallic components of synthetic spacers shall not have contact with the carrier pipe.

EN ISO 16440 states [4], the use of metallic components inside a spacer should be avoided, since ageing of spacers with metallic component always represents a higher risk of coating defects and in the worst-case provide electrical contact between the carrier pipe and the casing.

c. End seals

Isolating end seals are designed to be installed at both ends of a casing. End seals are used to keep electrolyte out of the annular space between the carrier pipe and casing. An end seal may be a pressure and watertight seal or a simple seal to prevent backfill from entering the annular space between the casing and carrier pipe.

During installation, prior to backfilling, casing end seals should be visually inspected to confirm their integrity and ability to contain the casing filler material (if requested by the design) during installation. If necessary, new casing end seals shall be installed prior to the filling operation.

d. Fillers

i. Parameters to consider for fillers

Prior to any filling, when required by the design, some basic information about the casing shall be considered:

- End seal condition and capacity (pressure, temperature, compatibility with selected filler).
- Casing integrity: Check, when possible, if there is any leak in the casing and what are the size of those leaks.
- Vents configuration (if any): where vents are connected to the casing (on top, at the bottom, etc.).
- Casing alignment (e.g., slope, bends).
- Air passage from one side of the casing to the other.
- Spacer type: shape (can it contain the filler), temperature resistance (in case of a hot applied filler).

End seal assessment is very important to ensure that the filler will not leak in the ground during or after filling, i.e., the end seal can withstand the filling pressure avoiding any potential leak.

Casing integrity shall be assessed to prevent any leak of the filler during or after filling. A leak during the filling leads to an incorrect filling ratio. Regardless of leaks, complete filling shall be ensured.

Cleaning the casing of water and debris prior the filling is required to avoid trapping water if the selected filler is not miscible with water or alternatively, mixing the product with ground water if the product is miscible with water. Some vent pipes may help to dry the casing during filling if the filler is not miscible with water. Cleaning can be a very difficult task and may have detrimental effects onto the coating, depending on water pressure by hydro-cleaning for example, so a detailed assessment must be done before starting.

The environmental impact of a filler must be assessed prior its consideration.

As casing annular space voids are different (thickness, length, etc.), the ability of the selected filler and application equipment to fill along all the annular space must be assessed with the manufacturer and the applicator.

ii. Empty Annular Spaces

Empty annular spaces may be vulnerable to atmospheric corrosion. However, the corrosion rate due to this mechanism is very low.
It shall be noticed that this practice has been using for many decades in Europe and it has never constituted to a major corrosion risk.

iii. Gas tight/Vacuum casings

Some operators use gas tight casings, which can be nitrogen filled or vacuum type, to fill the annular space to eliminate corrosive environments. When it can be shown that a positive nitrogen pressure can be maintained within the annulus for a minimum period of 12 months, then no further remedial action is required. Where a casing is incapable of maintaining positive nitrogen pressure, it is necessary to determine the cause and location(s) of the leak, implement repair solutions, and reinstate the nitrogen charge to a positive pressure.

Operational experience determined that the three most likely origins of nitrogen release are the nitrogen fill/test points, the high-pressure rubber connecting hoses and the sleeve end seals.
Advantages:

- Easy to achieve a complete fill

Disadvantages:

- Require a perfectly and permanent sealed annular space
- Require regular monitoring

e. Fillers

i. Conductive fillers:

Filling a bare metallic casing with electrolyte or conductive filler will make the carrier pipe behave as it would in soil. However, it could be very difficult to find and pin point coating holidays using DCVG or ACVG techniques.

The most used products by the operator are described below. It is possible to use others depending on documented CP compatibility studies.

<u>Cementitious materials:</u>
By means of cement-bonded (alkaline) mortar, the inner surfaces of the metallic casing and the metal at the defects in the coating of the pipeline are passivated, which provides corrosion protection.

Advantages

- High degree of filling.
- Eliminating the risk of metallic contact: The risk of establishing metallic contact between the carrier and casing pipes, particularly when compared with empty casings, sand fill (which tends to have a lower degree of filling), or bentonite fill (which has lower strength concrete but could be enough).
- Alkaline conditions: Cementitious fill materials have a higher pH than other fill materials. A pH level >12 is beneficial with respect to corrosion protection (except in presence of ac influences). Even in the absence of protective current from the CP system, steel corrosion will be negligible. More favourable to conditions where passivation could occur.
- High workability and possible long-term hydration reactions in comparison with the other materials.

Disadvantages

- When the pipeline is influenced with high AC values, an option to mitigate the AC risk may be to connect the carrier pipe to the uncoated casing by means of a decoupling device (capacitor). This will mean that the casing is then used as earthing to reduce the AC current. But this can increase the corrosion rate of the metallic casing. A better option may be to install an AC earthing system for the carrier pipe.

<u>Bentonite:</u>
Bentonite can be used to fill the annular space as it is a relatively easy solution for this application. Its high conductivity shall be taken into account, especially in the presence of ac currents on the carrier pipe as it may locally increase the corrosion risk.
Water used for the bentonite blend should be carefully inspected in order to avoid MIC.
Advantages:

- Relatively easy to apply.

Disadvantages:

- An increased risk of AC corrosion due to the low resistivity of bentonite compared to cementitious materials.

Sand

The corrosion rate of the carrier pipe in the annular space can be reduced considerably by low chloride content sand, as in this case there is no attack through atmospheric corrosion. Cathodic protection could be assured on metallic pipes without coating or internal coating on the metallic casing. Practically however, it is difficult to completely fill the annular space with sand. Sand has excellent capillary action capabilities, not just horizontally but also vertically. Most sand grain sizes will move water through the substrate, however, Cathodic Protection does not have an effect in voids regardless of the type of fill.

As in other cases, a complete filling is virtually impossible so void spaces will exist.

ii. Non-conductive fillers

Assuming that the annular space can be completely filled with a suitable polymer, such as wax, that offers durable resistance, i.e., that state when complete isolation of the electrolyte is achieved, and no corrosion can occur on the pipeline.

In the case of using fillers, carrier pipe and casing must be adequately supported in order to prevent movements that could cause a short-circuit after the filling process has been completed.

This technique requires to ensure:

- The annular space be clean (no water, no electrolyte, and no sediment). Most casings are easy to clean, but depending on the shape, it could be difficult to ensure on existing pipelines that the casing is completely empty. Some techniques (e.g., hydrocleaning) may affect the coating of the carrier pipe. Disbonded coating can shield the CP on the carrier pipe or can affect the filling operation (e.g., creation of empty local bubbles) when the annular space is filled with the chosen material. In addition, some coating residues can be blocked by the spacers.
- Wax is a coating with adhesion to steel and has a high dielectric strength, so it could act as a barrier protecting the carrier pipe at coating defects. In case of residual corrosion products and humidity in coating defects, it will, however, shield CP.

To obtain a completely filled environment inside a pipe casing is challenging, regardless of the size of the casing. Having wax pumped in until it comes out the opposite vent pipe, does not mean that the casing is completely filled as voids could appear between the wax and pipes, especially downstream of the spacers. Extreme caution is required during filling operations to minimise the creation of voids.

Advantages:

- Reduces the impact of AC current interference on the carrier pipe section by isolating potential coating defects on the carrier pipe section

Disadvantages:

- Requires a suitable vents and casing configuration for filling and drying
- Needs an experienced crew to dry and clean the annular space and fill it.

f. Inhibitors

An inhibitor is a substance that, when added in small concentrations, effectively decreases the corrosion rate. Depending on its mechanism and composition, there are four ways to categorize inhibitors: barrier layer formation, neutralizing, scavenging and environmental modification. The most commons ones are based on multiphase vapour or gel systems.

Inhibitors are normally used to protect low-flow areas, dead legs, the annular space in road casings and contingency equipment. Normally, inhibitors are mixed along with a coating (e.g., waxes) to provide a protective film over exposed surfaces.

The type and amount of inhibitor used depends on the amount of metal that it is protecting (length and diameter of the annular space), the working temperature range and the protection time desired.

Inhibitors are substances that, where corrosion occurs in moist environments, are added to the corrosive medium to lower the corrosion rate by retarding the anode process and/or the cathode process of a corrosion cell. Inhibitors are applied to provide protection either by continuous contact or by vapours. For a pipe-casing corrosion protection application, the amine-carboxylate based inhibitors are commonly used which act as multiphase inhibitors, i.e., provide protection by contact and in vapour space.

There are 3 ways to introduce an inhibitor into the annulus of a casing: As a dry powder, as a liquid slurry or as a gel. The gel system is injected as a low viscosity slurry which over a calculated timeframe sets up into a high viscosity gel. Any area of the steel that is not in direct contact with the gel is protected by the vapour molecules which emit from the gel. The molecules typically protect by forming a mono-molecular barrier layer or adjusting the pH (neutralizing)[3].

Advantages:

- Very low viscosity for the injection process

Disadvantages:

- Requires a complete and durably sealed casing to prevent inhibitor / water mix leakage from the casing
- Works only for a finite time i.e., is not a single application permanent solution

For protection of the carrier pipe inside the casing, corrosion inhibitor gel fillers can be used in the annular space between casing and carrier pipe. The corrosion inhibitor gel filler shall be specially formulated to mitigate corrosion on the external surface of the carrier pipe and the internal surface of the casing. The gel filler should be able to provide protection upon contact and in the vapor space of casing annulus.

The filler should have low viscosity when pumped into the casing, then transform into a higher viscosity gel after a short time and set inside the casing. The gel should stay in place in the

[3] NACE SP0200-2014. Steel-Cased Pipeline Practices – NACE

annular space and there should be prevention of the infiltration of water into the casing annulus and migration of the gel out of the annulus by end seals. The gel should also fill any small gaps in the casing pipe and end seals.

6. Inspection and maintenance

a. Assessment

The maintenance and assessment of cased crossings is necessary as the effectiveness of CP of the carrier pipe could be affected. To assess the CP efficiency where a carrier pipe is cased, pipe-to-soil potentials are recorded on the pipeline and on the metallic casing. When the casing is not metallic (e.g., concrete), measurements on the pipeline are recommended, but not mandatory. The CP measurements programme is under the guidance of a CP specialist.
The most common situations to remove a casing are because corrosion or other damage to the carrier pipe or casing pipe is indicated by inspection or a short-circuit between the carrier pipe and the casing has been detected. Some of the causes of metallic shorts are:

- Movement of the carrier pipe or the casing. Normally, it is due to external load and causes a metallic contact at some point. If the contact occurs at the ends of the casing, it could be resolved by adding a new spacer.
- Spacing materials or supports inside the casing have failed, allowing the casing to sag and come into metallic contact with the inner wall of the casing. The solution is more complex and sometimes, will require to remove the casing.

There are three different conditions for assessment of steel casings:

- Direct metallic conducting contact between the carrier pipe and the casing with a difference of the metal electrolyte potential between pipeline and casing <10mV. In presence of metallic casing, no cathodic protection for the part of the pipeline inside the casing may be the principal risk.
- The casing shows simultaneous change of potentials and the difference of the metal electrolyte potential between pipeline and casing <100 mV. Efficiency of cathodic protection of the pipeline may be severely limited, close to a direct metallic contact.
- The casing shows simultaneous change of potentials and the difference of the metal-electrolyte potential between pipeline and casing >100 mV. Efficiency of cathodic protection of the pipeline may be limited.

Operators should assess the cathodic protection and the pipeline conditions to mitigate the corrosion risk considering technical and economic aspects.

b. Monitoring the corrosion risk of the casing

i. Key topics

Steel cased crossings may adversely affect the integrity of the carrier pipe by shielding the CP current to the pipe or reducing the CP effectiveness on the pipe inside and in the vicinity of the casing. The main reasons are electrolytic or direct metallic contact between the steel casing and carrier pipe. Hence, monitoring the CP is needed key to avoid external corrosion of the carrier pipeline. To monitor pipe-to-electrolyte potentials, currents and possible interferences, test stations should be installed in metallic and non-metallic casings, regardless of whether it is intended or not to protect the casing or the carrier pipeline. The purpose is to detect undesirable contacts between the casing and the carrier pipe and to assess the cathodic protection effectiveness. It is recommended to install within the test post a minimum of one cable from the pipeline and another one for the casing (when metallic).

Depending on the local regulations, it may be required to coat and/or protect the casing. In this case, the interaction with the pipeline CP system must be monitored regularly.

If CP has been applied inside the casing onto the carrier pipeline, it is necessary to monitor the CP levels by carrying out measurements. Monitoring the CP system can be a challenging problem as the accuracy of the probes, coupons or reference electrodes cannot be verified after having been installed inside the casing. The presence of fillers could influence the measurements depending on the type selected. These aspects need to be taken into account when determining the monitoring requirements for the effectiveness of CP inside casings.

The use of coupons is recommended to measure and calculate the AC current density and eliminate IR drops due to the presence of DC stray currents, equalizing currents and electrical interferences from cathodic protection systems of neighbouring structures. ER probes could be useful to evaluate corrosion rates of steel in the electrolyte.

Cathodic protection level shall be regularly assessed according to EN 12954 [1] / EN ISO 15589-1 [2] by measurements on different CP equipment such as test points, coupons, probes, and dc decoupling devices. These measurements will help to assess the CP effectiveness and to detect any deficiencies at casings. Casing vents could be used if there are no other points to measure the casing potential.

ii. Methods

Only competent CP personnel should carry out measurements. Conducting indirect surveys of casings during wet weather could help to identify possible issues. The main methods of testing are listed below. They can be combined to increase the relevance of the analyses:

- **Close Interval Potential Survey (CIPS)**: This method is the initial test conducted to identify a shorted steel casing:
    - Without interruption: Comparison of pipe-to-electrolyte and casing-to-electrolyte potentials.
    - With interruption: Compare pipe-to-electrolyte and casing-to-electrolyte potentials. Same direction and similar magnitude potentials suggest a metallic contact. Same direction but lower casing-to-electrolyte potential shift suggests electrolytic contact. A small casing–to-electrolyte shift or opposite indicates effective CP.
- **Internal Resistance**: This method indicates whether direct metal-to-metal contact exists between a carrier pipe and the steel casing pipe by measuring electrical resistance. A low resistance value indicates a need to take remedial action. A high resistance value indicates an isolated casing; however, the resistance of the test lead wire and vent pipe must be considered for valid interpretation.

- **Four-Wire IR Drop**: This method may indicate the existence and location of a short. A four-pin resistance meter to determine the as-found resistance between the carrier pipe and casing may also be used as part of this test.
- **Cycling Rectifier**: Cycling the CP rectifier is a method used to evaluate the electrical isolation between carrier pipe and casing. If the pipe-to-electrolyte potentials taken on the pipe and the casing are identical during both the rectifier on and off cycles (with the reference electrode at the same position), a shorted steel casing is indicated.
- **Casing Polarization/Depolarization:** This technique verifies isolation status by discharging a direct current (DC) to/from the casing. A significant potential difference occurs between the casing and carrier pipe if the two structures are not in metallic contact.
- **Direct Resistance Measurement**: This technique uses an earth resistance meter to determine the as-found resistance between the carrier pipe and casing. This method works better with the four-wire method. This resistance value is useful to be compared with the sum of the resistances to remote earth of casing and carrier pipe respectively[4].
- **Pipe/Cable Locator**: The presence and location of a pipe-to-casing metallic contact may also be approximated by following a low-power audio or radio signal set between the carrier pipe and the casing. The signal returns at the point of metallic contact, which should be verified from the opposite end.
- **Direct Current Voltage Gradient (DCVG):** Coating holiday indication near the end of the casings denotes a possible metallic or electrolytic path between the casing and the carrier pipe.
- **Alternating Current (AC) Current Attenuation**: Compares current flow at each end of casing. Measurement in mA or dBmA/m (dBmA/ft) when the signal in injected from the other end.
- **A-Frame AC Voltage Gradient:** Measure dBµA signal strength and direction at each end of the casing when the signal is injected from the other end.
- **Temporary Intentional Short:** Compare pipe-to-electrolyte and casing-to-electrolyte potential or shift with temporary short between pipe and casing in place and then removed. No change indicates contact of similar resistance exists.
- **Polarization coupon connected to the casing and to the carrier pipeline:** Annex B details this technique from CEFRACOR Recommendation PCRA n°010.
- **Current density consideration.** Annex A details this technique from AfK 1. This procedure allows for demonstration of effectiveness of CP on the carrier pipe inside metallic casings that may also be coated.

c. Other means of detection

The most common problems regarding steel casings are:

- The casing is in electrical metallic contact with (shorted to) the carrier pipe.
- Coating defects form on the carrier pipe within the casing
- The casing becomes filled or partially filled with an electrolyte and an electrolytic path may exist between the casing and the carrier pipe in presence of coating defects.

[4] Kioupis, N.; Cathodic protection testing of onshore gas pipelines insulating joints and similar piping accessories; CEOCOR congress, June 2013.

Apart from the related methods in the previous paragraph, there are different techniques to check if these situations are happening or have occurred in the past. Guided Wave Ultrasonic Technique or In-Line Inspection (ILI) procedures are applied for cased pipe segments based on their interpretation of the current requirements. If feasible and practical, in-line inspection of a pipeline can help to detect the presence of external corrosion on the carrier pipe. This would mean that there has been a lack of cathodic protection since the last ILI run. It is important to highlight that in-line inspection techniques are only capable of detecting corrosion damage within a threshold and cannot identify the electrochemical processes taking place at the surface. ILI may detect metal-to-metal contact between the casing and carrier pipe, but not all of the tools are able to identify this particular case. Furthermore, those methods used to assess casings are not always possible to achieve due to constraints in the line i.e., unpiggable lines, operational issues or costs.

The use of other techniques such as the External Corrosion Direct Assessment may be more practicable and useful for early detection. A risk-based approach for casings is the risk represented by the cased pipeline along with the probability of having a problem. A risk-based approach is particularly relevant for non-piggable pipelines where only above ground measurements allow the pipeline integrity assessment. Such an approach can focus the monitoring requirements on the most critical casings.

The operator should monitor the CP following ISO and EN standards and confirm the status of the carrier pipe with different approaches.

d. Remote monitoring of casings based on a corrosion risk approach

In the presence of a remote monitoring system, frequencies for field measurements defined in EN 12954 and EN ISO 15589-1 do not apply. Consequently, the pipeline operator can define their own policy to assess the corrosion risk of casings. An approach based on corrosion risk will determine the most relevant maintenance to be carried out on each type of casing including the types and frequencies of measurements.

For instance, this approach may be based on different parameters of corrosion risk, such as:

- Presence/absence of dc/ac stray currents.
- Un-piggable / piggable pipeline.
- Length or diameter of casing.
- Type of casing.
- Lack of CP at the casing.
- Type of crossing (road, water, rail, etc.).

The most critical casings identified by a risk assessment could be remotely assessed to detect any malfunction of the CP system.

e. How to solve potential problems

The purpose of the resolving issues is to eliminate the recognised risk to the safe and trouble-free operation of the pipeline or to reduce it to reasonably applicable proportions. The choice of the repair measures and an optimised cost-benefit ratio must be taken into account.

Each case must be assessed on its own merits. Consequently, a catch-all solution cannot be given.

The most common repair methods are described below along with advantages and disadvantages. Combinations of the different methods may also be effective:

i. Removal of the electrolyte from the annular spaces

If electrolyte is found inside the casing, it is advisable to remove the electrolyte when possible. Depending on the shape and length of the casing this solution may not be possible. In some casings, it is possible to remove the electrolyte using the vent pipes. If not, it may be necessary to excavate and then replace the end seals though rarely, to change the spacers at the end. The casing integrity should be checked. It is very common to see new casing with water leaks even new casing projects can have serious issues due to welding (steel casing) or joint problems (concrete casings).

Advantages:

- Depending on the casing location, shape and length, it could be a cost-effective solution.

Disadvantages:

- Not always possible to do.
- Potential on-field problems need to be overcome.
- New end seals may not be effective for as long as expected.
- Relies on the quality of the end seal and spacers used.

ii. Excavate the pipeline

The pipeline is excavated in the vicinity of the casing and the casing is moved so that there is no longer a metallic contact with the casing. The pipeline can be fixed in this position by means of a suitable substructure such as anchor block or pipe support.

Advantages:

- Almost always possible.

Disadvantages:

- Only possible with contacts at the end of the casing or short casings (typically) less than 12 m long.
- Problematic in the case of adverse ground conditions.
- Cost in case of large or deep excavation.

iii. Filling of the annular space

With a filled annulus, the stability of the casing is increased, meaning higher loads may be accommodated and the likelihood for metallic contact between carrier and casing pipe is smaller.

One method consists of filling the casing annulus, after a cased segment has been assessed and the integrity of the carrier pipe has been confirmed. If it is assumed that the filling was done properly and the threat of corrosion has been reduced to acceptable levels, the operator could determine that the pipe segment no longer needs to be assessed and check the cathodic protection as usual. The operator must, however, perform calculations based upon the information collected during the casing installation to determine the amount of filler needed. For existing pipelines where information about the casing is unavailable, an operator shall determine through investigation and/or excavation, the size, condition, and type of casing, carrier pipe, annulus volume considering the size and quantity of the spacers and casing end seals used. The fill must be performed in favourable conditions. The procedures must be reviewed, and recommendations agreed with the vendor/fill contractor prior to fill application. Vents must not be blocked and leaking end seals or casings replaced or repaired. The ambient temperature [12] shall be recorded depending on the type of product to be installed inside the casing, a[5] can significantly affect the performance properties of the filling material. Careful consideration must be given to the duration of the filling procedure.

<u>Filling with conductive material</u>
The annular space between the pipeline and the casing is filled with sand, cement mortar or a similar product. This can be carried out through the casing ends or through aeration pipes.
Advantages:

- Relatively simple and cheap.
- Long term proven experience (available in many operator studies)

Disadvantages:

- Success of complete filling may be doubtful.
- Risk of macro-cell formation with anodic zones in regions of the pipe, which is not a problem in presence of effective CP.
- isk of ac corrosion in the presence of ac influences on the pipeline.

<u>Filling with electrically isolating material</u>
The annular space is filled with wax-based products.
Advantages:

- Relatively easy to apply.
- Flows into the annular space without pressure.
- Long term proven experience (available in many operator studies)

Disadvantages:

- Difficulties to obtain a clean annular space (no water, no electrolyte, no sediment, and no waste) depending on the shape of the casing.
- Depending on the filler, difficulties to ensure the annular space is always properly filled.
- Expensive solution.

iv. Cathodic protection within the casing

By installing magnesium or zinc ribbon anodes in the annular space of the casing, the pipeline can be cathodically protected within a casing. This method is only recommended for new pipelines with the following advvantages and disadvantages:

[5] PHMS; Guidelines for Integrity Assessment of Cased Pipe for Gas Transmission Pipelines in HCAs (2010).

Advantages:

- Relatively cost-effective for a new pipeline as it is included in the design and installation, but not for existing pipelines.
- Additional monitoring equipment can be installed at the same time.

Disadvantages:

- Difficulties to monitor the true situation inside the casing.
- Virtually only possible on newly laid casings.
- Permanent presence of electrolyte in annular space necessary.
- Results of measurements difficult to gather and analyse.
- Questionable for DC/AC mitigation.
- Necessary to have no contact between anode and casing (when metallic).
- Need to insure before installation there is sufficient space inside the annulus whilst considering the the presence of spacers.
- Expensive to install.
- Damage to CP system can more readily occur especially in existing casings

v. Mechanical solutions

Facilitate current access to the carrier pipe

In the case of coated casings, current access can be facilitated by peeling or earthing the casing.

Removal of the casing

The casing is dug up and cut into pieces using special cutting tools. Subsequently, the coating of the pipeline is checked and if necessary repaired, perhaps even renewed.

Advantages:

- Technically the best solution as there is no longer a casing.

Disadvantages:

- Digging up a casing is not always possible (motorway, railway, etc.).
- Complicated and relatively expensive, but less expensive than removal and installation of a new thicker walled pipeline.
- Risk to the integrity of the pipeline when casing removed.

Shortening of the casing

When there is a contact between the pipeline and the casing at one the end of the casing, it can be excavated, and the piece of the casing in contact with the carrier pipe is cut off and the contact is thereby removed.

Advantages:

- Almost always possible.
- Relatively cost-effective.

Disadvantages:

- Contact can once again occur in adverse soil conditions.
- Only possible when contacts are at the end of the casing.

Replacement of the pipeline within the casing

The pipeline is replaced within the casing and tied into the existing pipeline.

Advantages:

- Technically good solution.

Disadvantages:

- Very expensive.
- The pipeline must be taken out of operation (except with a bypass).
-

Installation of new crossings

Next to the defective casing crossing, a new one is laid and connected inside the existing network.

Advantages:

- Technically clean solution

Disadvantages:

- Very expensive
- Pipeline must be taken out of operation (unless a bypass is used)

vi. Management of contact between the pipeline and a metallic casing

Considerations	Possible solution or investigation	Recommended time frame	Comment
Possible contact between pipe and metallic casing (e. g., E_{casing} < -800 mV_{SCE})	Additional measurements to confirm the type of contact	High priority	Additional measurements to carry out quickly to confirm the contact.
Direct contact between pipeline and metallic casing	Risk assessment approach	High priority	CP is not possible inside the casing, any defect in the coating could lead to corrosion on the carrier pipeline
	Mechanical work	High priority	
Electrolytic/resistive contact with delta $\Delta E_{pipe\text{-}casing}$ < 100 mV	Remove the electrolyte (if any and when economically and technically possible)	Medium priority	The smaller is $\Delta E_{pipe\text{-}casing}$, the higher is the risk in the carrier pipeline
	Compensatory disposals (e.g., additional measurements to be carried out, risk assessment approach,…)	Medium priority	
	Filling the annular space (when economically and technically possible)		
	Mechanical works		
	Compensatory disposals (e.g.,	Low priority	The smaller is $\Delta E_{pipe\text{-}casing}$, the higher is the

Electrolytic/resistive contact with $\Delta E_{pipe\text{-}casing}$ > 100 mV	additional measurements to be carried out, risk assessment approach, RMS, …)		risk in the carrier pipeline
	Filling the annular space (when economically and technically possible)		
	Mechanical works		

vii. Pipeline management inside isolating casings

Considerations	**Possible solution or investigation**	**Recommended time frame**
Casing length less than 10 m	Not required	/
Casing length between 10 and 20 m	Risk assessment approach	Medium priority
Casing length more than 20 m	Mechanical work, peeling or earthing for coated steel casing, etc.	High priority

7. Design and construction

a. Introduction

Casings may have an impact on pipeline corrosion risk when the CP maintenance program is not performed strictly according to standard requirements. Consequently, it is suggested where technically feasible in the case of pipelines to be cathodically protected, to limit the use of casings and instead to install thicker walled, specially coated pipelines at crossings such as roads, railways, etc. There are no regulations requiring pipelines to be cased; therefore, only if there are engineering concerns regarding protection of a pipeline should a casing design be considered.

The design of casings is critical to ensure suitable mechanical integrity and optimize construction costs. The design step is fundamental for the lifetime of the pipeline. A reliable design will include the maximum allowable loads to the pipeline operators and will avoid any connection or metallic contacts between the carrier pipe and the metallic casing at installation and in the future. The following summarises some casing design and cathodic protection recommendations to be considered in the selection, construction and installation of casings. Additional recommendations are described in the Specification for Casing and Tubing by API Spec 5CT, EN ISO 15589-1 and in EN ISO 16440.

b. Design

The design will be performed by a competent pipeline designer. The main conditions to be taken into account are:

- The carrier pipe shall be effectively coated with a high-quality coating for protection against corrosion, whether or not the casing is installed.
- The carrier pipe shall be properly supported inside and outside the casing to prevent contact between the casing and the carrier pipe.
- Cement based casings are to be preferred to metallic casings
- If it is possible, metallic casings should not be coated in order to avoid any shielding or interaction with the carrier pipe.

If the casing is not filled, it is recommended to have a sufficient annular space with adequate support strength to prevent metallic contact between the carrier pipe and the casing. To achieve this, the casing should be kept as short in length as possible.
Casing isolators shall be carefully selected to ensure they have the mechanical strength required to withstand the actual installation and casing end seals shall be designed to prevent ingress of water or debris. Vent pipes (if designed) must be located at both ends of the casing in order to detect a leak of transported product and must be designed to prevent intrusion of water and debris. If required, vents can be used to monitor releases, be test points for the cathodic protection monitoring and testing provided they are connected to the casing. However, a vent pipe should not be considered of equivalent integrity as a cable, but valid information can be obtained from it.

c. Installation and Construction

There are different ways to install a casing (jacking, boring, directional drilling, tunnelling, or open cutting), but in all of them it is essential to minimize coating damage of the carrier pipeline in order to avoid initiating the corrosion process. The carrier pipe coating must be electrically inspected for holidays by a competent person using an approved electrical holiday detector before the installation of isolating spacers. The casing must be visually inspected and be clean and free of any undesired material.

The quantity, design and spacing of the casing isolators must follow the manufacturer's instructions and the design engineer's advice. During the installation operation, it must be ensured that there is no displacement or damage to the carrier pipe coating, isolators or spacers. After installing the carrier pipe into the casing, it must be tested so that the casing (if metallic) and carrier pipe are not electrically shorted.

Isolating casing end seals must be installed at both ends of the casing to prevent displacement or ingress of electrolyte.

d. Enlarging casings

Enlarging existing casings or construction of new casings on existing pipelines must fulfil specific requirements to avoid future bending of casings as well as damage to the carrier pipelines. Extensions should be avoided as much as possible for integrity reasons.

The existing casing ends shall be prepared for welding in accordance with approved specifications by coded welders, using a new pipeline compatible with the existing casing. In addition, the carrier pipe coating shall be inspected and repaired before enlarging the casing.

Taking advantage of the excavation, by removing old test posts and installing new ones with advanced test equipment should be considered. It is also recommended to check the integrity of the carrier pipeline (coating, external corrosion presence, cathodic protection values, etc.).

8. Cathodic Protection considerations

The effectiveness of the CP must be assessed by potential measurement along with other data. Depending on the CP system installed on the carrier pipe and the casing, different measurements and inspections can be carried out. In the simplest scenario, the operator should ensure that the pipeline is protected and electrically isolated from the casing. If casing isolation is not achieved, the operator shall ensure that the carrier pipe is cathodically protected, or negligible corrosion is present.

Evaluating the corrosiveness in the annular spaces in cased pipeline systems may not be easy. The corrosiveness within the annular space may be evaluated by inserting coupons, electrical resistance probes, or other monitoring devices into the annulus. If the probe is not installed during construction, an excavation will be needed or remote monitoring of the delta E between the pipe and the metallic casing when there is an electrolytic or resistive contact between the pipe and the metallic casing.

The following considerations may be taken into account:

Considerations	Potential Solutions or Investigations	Recommended Time Frame	Comments
Possible contact between pipe and metallic casing	**Additional measurements to be carried out and risk approach study**	**High priority**	**A survey should be done to define whether there is a possible metallic /electronic or electrolytic /resistive contact**
	Detection/investigation of contact	**High priority**	
Direct Contact between metallic /electronic casing and pipe	**Additional measurements to be carried out and a risk approach study**	**High priority**	**CP is not possible inside the casing, any defect in the coating could lead to**

			corrosion of the carrier pipeline
	Mechanical works	**Low priority**	
Electrolytic / resistive contact	**Remove the electrolyte (if any)**	**Medium priority**	**The larger the shift the bigger risk you could have to the carrier pipeline**
	Additional measurements to be carried out and risk approach study	**Low priority**	
	Filling the annual space	**Medium priority**	
	Mechanical works	**Low priority**	

It is up to each pipeline operator to set the frequencies to check these items taking into account other available testing techniques.

Therefore, it is recommended to install suitable devices during construction to monitor the cathodic protection of the structures and check frequently the performance of the system.

Annex A

This annex details the technique of current density consideration covered in the standard AfK-1 / DVGW GW 20.

Electrical circuit

A simplified electrical circuit of the casing/pipeline construction is considered to be as follows.

cp-rectifier

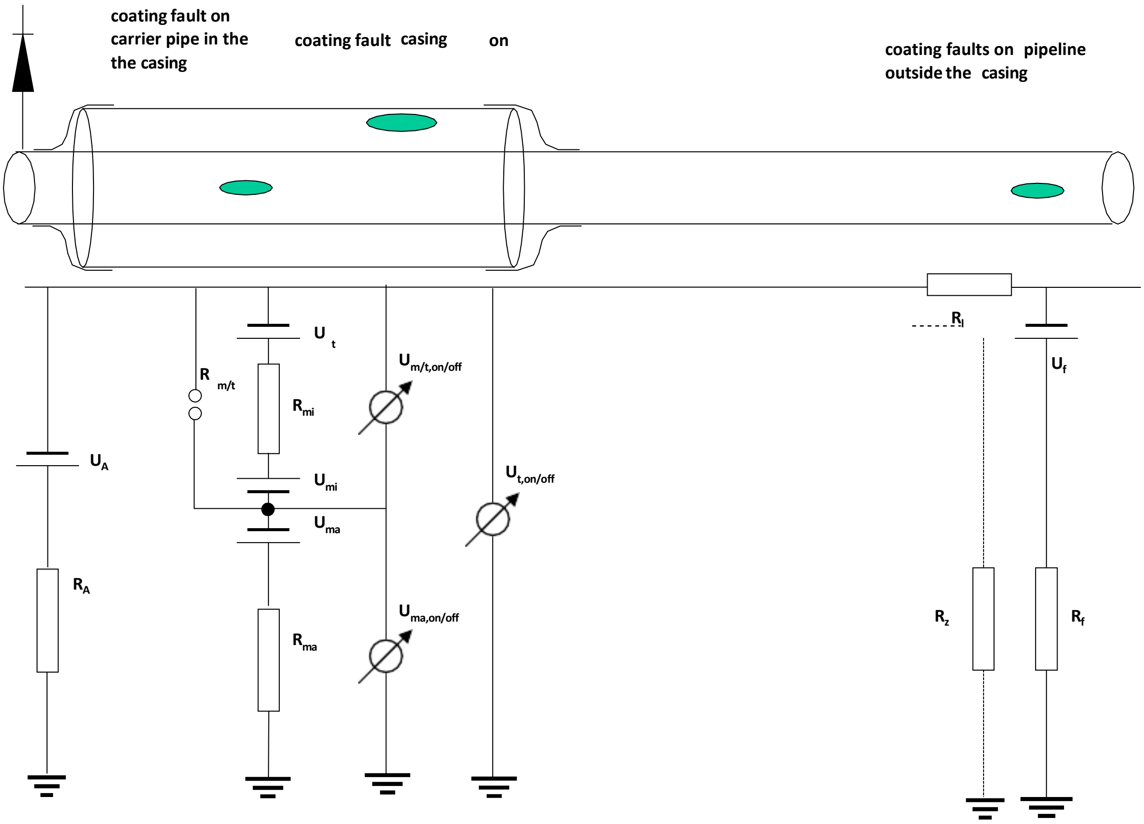


Figure 1: Simplified electrical circuit of a casing/pipeline construction

It is assumed that the annular space is electrically isolated from the surrounding environment, e.g., by end seals. Each indicated coating fault, i.e., on the carrier pipe within the casing, on the casing and on the pipeline outside the casing, represents the mean electrical characteristics of all coating faults present on the pipe section respectively, i.e.: The spread resistance R_f of the coating fault on the pipeline outside the casing is considered to represent the resulting resistance from the parallel arrangement of spread resistances from the entirety of coating faults on this pipeline section. The combination with the longitudinal resistance, R_f, of the pipeline yields the terminating impedance R_z. In an analogue way the potential U_f is considered to be the average value from the IR-free potential of all coating faults on this pipeline section. In practise U_f can be measured as the pipeline off-potential $U_{t,off}$ if $R_z << R_{mi} + R_{ma}$.

Very similar considerations are applied to the coating faults on the casing in order to define U_{ma} and R_{ma}.

U_t is defined as average value from the IR-free potential at all coating faults on the steel pipeline within the casing while R_{mi} (defined as coating resistance of the carrier pipe in the casing) is a part of the spread resistance resulting from the parallel arrangement of these coating faults.

Pipeline outside casing

To evaluate the terminating impedance, R_z, the characteristic impedance Z of the pipeline (with infinite length) outside the casing is considered. Z is given by:

$$Z = \sqrt{\frac{R'}{G'}} \quad (1)$$

Where $R' = \frac{4\rho_{steel}}{\pi(d_2^2 - d_1^2)}$ is the longitudinal resistance load (ρsteel-resistivity of pipeline steel, d1 and d2 inner and outer diameter of steel pipeline respectively) and $G' = \frac{\pi d_2}{r_u}$ is the leakage load of the pipeline (r_u-average coating resistance of the pipeline). As a first approximation it may be assumed that a pipeline is terminated with its characteristic impedance, i.e., R_z=Z, if the length exceeds the characteristic length l_k:

$$l_k = \frac{1}{\sqrt{R'G'}} \quad (2)$$

In case that the pipeline exceeds its characteristic length on both sides of the casing the terminating impedance R_z is calculated to be half of the characteristic impedance Z, i.e., R_z=Z/2.

As an example, Fig. 2a draws the characteristic impedance Z (equation (1)) as a function of the average coating resistance r_u for pipelines of different diameter, d_2 and different wall thickness s=d_2-d_1 Figure 2b shows the characteristic length l_k (equation (2)) for the same set of pipelines.

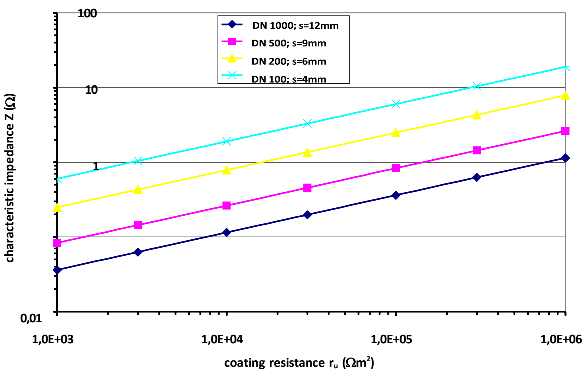


Figure 2a: Characteristic impedance Z of pipelines with different coating resistances (calculated from equation (1))

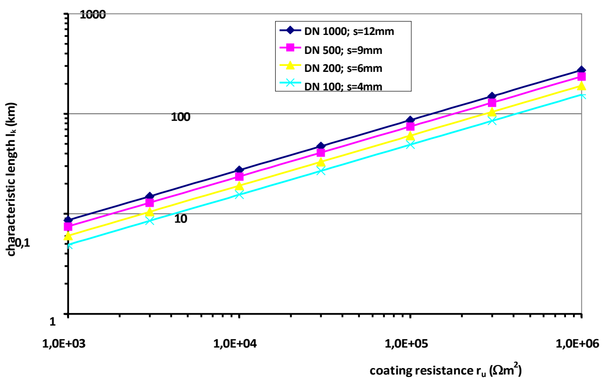


Fig 2b: Characteristic length l_k of pipelines with different coating resistances (calculated from equation (2))

In a case that the length L of the pipeline at one side of the casing is shorter than the characteristic length l_k, the terminating resistance $R_{z,L}$ of this pipeline section is estimated according to equation (3):

$$R_{z,L} = Z \cdot \coth\left(\frac{L}{l_k}\right) = Z \cdot \frac{1}{\tanh}\left(\frac{L}{l_k}\right) \quad (3)$$

Casing and carrier pipe in the casing

The following Cathodic Protection data can be readily obtained (see figure 1):

- $U_{t,on}$ on-potential of pipeline, measured against remote earth
- $U_{t,off}$ off-potential of pipeline, measured against remote earth
- $U_{ma,on}$ on-potential of casing, measured against remote earth
- $U_{ma,off}$ off-potential of casing, measured against remote earth
- $U_{m/t,on}$ voltage measured between casing and pipeline (cp-rectifier switched on)
- $U_{m/t,off}$ voltage measured between casing and pipeline (cp-rectifier switched off)
- $R_{m/t}$ resistance measured between pipeline and casing.

The measurement techniques used should consider:

- Potentials and voltages measured during the on-phase and during the off-phase of cp-rectifiers are to be taken simultaneously if the pipeline is interfered by d.c. - stray currents. The magnitude of stray current interference should be constant while on/off-potentials/voltages are measured.
- The resistance $R_{m/t}$ between pipeline and casing may be measured using a handheld ohmmeter; more accurate results, however, are obtained if $R_{m/t}$ is calculated from the voltage drop $\Delta U_{m/t}$ across pipeline and casing while injecting a galvanostatically controlled d.c. current pulse ΔI: $R_{m/t}=\Delta U_{m/t}/\Delta I$ (d.c. current injection test). For both measurement techniques separate electrical circuits are required for current- and voltage-measurements
- Potentials must be measured against remote earth; this should be considered if coating faults on pipeline and/or casing cause extended potential gradients in the soil.

For further calculations, the ratio $A=R_{ma}/R_{mi}$, i.e., the ratio from spread resistance of the casing R_{ma} and the resistance within the annular space of the casing R_{mi} (see figure 1), will be defined. According to figure 1 the variable A may be evaluated from the voltage drops $U_{ma,on}$-$U_{ma,off}$ and $U_{m/t,on}$-$U_{m/t,off}$ across R_{ma} and R_{mi} respectively:

$$A = \frac{R_{ma}}{R_{mi}} = \frac{(U_{t,on}-U_{m/t,on})-(U_{t,off}-U_{m/t,off})}{U_{m/t,on}-U_{m/t,off}} = \frac{U_{ma}-U_{ma,off}}{(U_{t,on}-U_{ma,on})-(U_{t,off}-U_{ma,off})} \quad (4)$$

According to figure 1 the resistance $R_{m/t}$ measured between pipeline and casing is:

$$R_{m/t} = \frac{R_{mi}(R_{ma}+R_z)}{R_{mi}+R_{ma}+R_z} \quad (5)$$

Combined with equation (4) gives for R_{mi}:

$$R_{mi} = \frac{R_{m/t}(1+A)-R_z}{2A} + \sqrt{\frac{R_{m/t}(1+A)-R_z}{2A} + \frac{R_{m/t}R_z}{A}} \quad (6)$$

In the case where R_z can be ignored compared to R_{ma}, i.e., $R_z << R_{ma}$ (see equation (5)), which is generally fulfilled for long bituminous coated pipelines reaching the characteristic length l_k (equation (2)), a simple expression is obtained for R_{mi}:

$$R_{mi} = R_{m/t}\frac{1+A}{A} \quad (7)$$

In regard to the explanations given for figure 1, R_{mi} will be interpreted as part of the accumulated spread resistance of coating faults on the carrier pipe in the casing.

The spread resistance of the casing, R_{ma}, can be calculated from equation (4). Taking into account the geometry (length, diameter) of the casing, a conclusion can be drawn concerning the quality of the coating. In the case that casings are used to reduce the level of any induced ac-voltage, e.g., by establishing an electric connection between pipeline and casing via a capacitor, R_{ma} is the grounding resistance that has to considered, e.g., by calculation of inductive interference.

A more accurate value for R_{ma}, R_{mi} and R_z will be obtained if $R_{m/t}$ is calculated from the results of a d.c. current injection test (see previous). Simultaneously, the variation of $U_{ma,on}$ and $U_{t,on}$ due to the current pulse ΔI, i.e., $\Delta U_{ma,on}$ and $\Delta U_{t,on}$ respectively. According to figure 1, a ratio $B=R_z/R_{ma}$ is evaluated from the voltage drops $\Delta U_{t,on}$ and $\Delta U_{ma,on}$ across R_z and R_{ma} respectively:

$$B = \frac{R_z}{R_{ma}} = \frac{\Delta U_{t,on}}{\Delta U_{ma,on}} \text{ (8)}$$

Combination with $A = \frac{R_{ma}}{R_{mi}}$ (see equotion 4) and $R_{m/t} = \frac{R_{mi}(R_{ma}+R_z)}{R_{mi}+R_{ma}+R_z}$ (equotion 5) yields:

$$R_{mi} = R_{m/t} \cdot (1 + \frac{1}{A\cdot(1+B)}) \text{ (9)}$$

R_{ma} and R_z can be obtained from the definitions of A and B.

Resistance comparison method

This method first comprises the estimation of the minimum spread resistance, $R_{a,min}$, of a single circular coating fault on the carrier pipe in the casing that can be cathodically protected with the cathodic protection system of the pipeline and by taking into account the electrical characteristics of the casing construction. The comparison of $R_{a,min}$ with R_{mi} allows us to conclude the effectiveness of cathodic protection. Similar procedures have been described to assess the effectiveness of cathodic protection for long electrically isolated pipeline sections, e.g., HDD-pipeline sections and for cathodic protection remote control of well-coated pipelines.

Considering a circular geometry, diameter d_{max}, of a coating fault, the spread resistance $R_{a,min}$ is given by (Both pore-and polarization resistance are neglected):

$$R_{a,mi} = R_{m/t} \frac{\rho}{2d_{max}} \text{ (10)}$$

and

$$R_{a,mi} = \frac{4|U_d|}{|J_s|\pi d^2{}_{max}} \text{ (11)}$$

Hence, U_d is the driving voltage and J_s is the current density for cathodic protection of this coating fault needed to achieve the protection potential U_s, e.g., according to EN 12954 [1].

Substituting d_{max} by combining equation (10) and (11) gives:

$$R_{a,mi} = \frac{|J_s|\pi\rho^2}{16|J_s|} \text{ (12)}$$

$R_{a,min}$ can be estimated as follows:

- If not directly measured cathodic protection current density J_s=0.1A/m2 may be assumed as a reasonable default value for cp-current density under stagnant groundwater conditions as present in the annular space of casings.

- If not directly measured ρ=30Ωm may be assumed as a reasonable default value for the resistivity of the medium in the annular space of casings.
- To estimate Ud for a coating fault on the carrier pipe within the casing it has to be taken into account that a part $\frac{R_{ma}}{R_{mi}+R_{ma}}$ of the voltage $U_{t,on}$ - U_s (which is the maximum driving voltage for cathodic protection at a given adjustment of cp rectifiers) appears as voltage drop across R_{ma} (figure 1), i.e., $U_d = \frac{R_{ma}}{R_{mi}+R_{ma}} \cdot (U_{t,on} - U_s)$ Combination with equation (4) yields:

$$U_d = \frac{1}{A+1} \cdot (U_{t,on} - U_s) (13)$$

Note: These considerations imply that polarization of the steel surface within coating faults on the casing is negligible, i.e., $U_{ma} \approx U_{mi}$. In the case that polarization has to be considered $|U_{t,on}$-$U_s|$. (according equation (13)) must be reduced by $|U_{ma}$-$U_{mi}|$.

Figure 3 draws the minimum spread resistance $R_{a,min}$ for different parameter values J_s, ρ and $|U_d|$ according to equation (12).

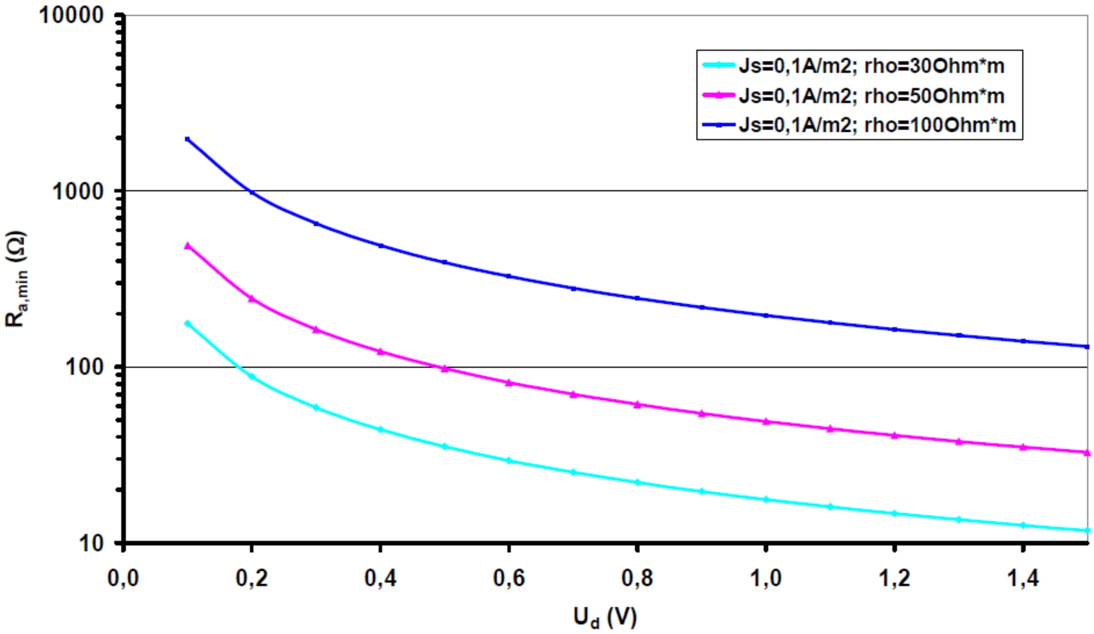


Figure 3. Minimum spread resistance in order to achieve effective cathodic protection of a circular coating fault at various conditions characterized by driving cp-voltage $|U_d|$, cp-current density J_s and soil resistivity ρ (equation (12)).

The comparison of $R_{a,min}$ with R_{mi} (from equation (6) or (7)) may give:

- $R_{mi} > R_{a,min}$
- This result indicates effective cathodic protection for coating faults on the pipeline within the casing, provided $R_{a,min}$ had been estimated using reasonable values for the resistivity ρ of the medium in the annular space of the casing and the current density J_s that is required to achieve effective cathodic protection.
- $R_{mi} < R_{a,min}$
- In this case cathodic protection for coating faults on the carrier pipe within the casing should be considered to be questionable because it cannot be excluded that there is a

single circular coating fault with a spread resistance smaller than $R_{a,min}$ that cannot be cathodically protected.

The following hints should help to interpret this situation in more detail:

- It may be assumed that R_{mi} results not only from one individual coating fault but from a number of differently sized coating faults. If mutual interference of neighbouring coating faults can be neglected (i.e., potential gradients do not significantly overlap) effective cathodic protection will be achieved if the spread resistance of each individual coating fault is smaller compared to $R_{a,min}$.
- In the case that the distance between casing and pipeline is small, e.g., 100mm or smaller, it can be assumed that the resistance between casing and pipeline that has to be attributed to an individual coating fault on the carrier pipe within the casing is considerably smaller than calculated according to equation (10). Consequently cp-current density J_s (e.g., 0.1A/m^2) will be achieved on larger coating faults, showing lower $R_{a,min}$* compared to $R_{a,min}$ as calculated from equation (12), (see also [3]).
- It is frequently found that $U_{ma,on}$ significantly differs from $U_{ma,off}$ thus indicating a possible polarization of the casing which reduces the driving voltage $|U_d|$ for cathodic protection (see equation (13)).

Table 1 summarizes results from measurements at six casing construction on a DN 400 pipeline constructed in 1962.

Data sheet to assess cathodic protectection in casings

Assessment of cathodic protection of carrier pipe within a casing by comparing R_{mi} with $R_{a,min}$.

$R_{mi} \geq R_{a,min}$ **cp o.k.**

$R_{mi} < R_{a,min}$ **cp questionable**

input data

ρ - medium resistivity in annular space	30	Ωm
J_s - cp-current density:	0,1	A/m^2
U_s - protection potential:	-850	mV
r_u - coating resistivity of pipeline	2	kΩm^2 => Rz= 0,06 Ω (L>L_k)
d - outer diameter	500	mm
s - wall thickness	9	mm

test post no.	comment	pipeline $U_{t,on}$ mV	pipeline $U_{t,off}$ mV	casing $U_{ma,on}$ mV	casing $U_{ma,off}$ mV	$R_{m/t}$ Ω	A	U_d mv	$R_{a,min}$ Ω	R_{mi} Ω	cp
1		-1490	-1190	-1100	-990	2,1	0,58	-405	44	6	questionable
2		-1490	-1170	-550	-540	14,4	0,03	-620	28	457	o.k.
15		-2030	-1240	-730	-520	4,9	0,36	-866	20	18	questionable
17/18		-2020	-1180	-1820	-1170	3,9	3,42	-265	67	5	questionable
28/29		-1920	-1210	-1000	-890	4,1	0,18	-904	20	26	o.k.

Table 1: Results from measurements at several casing constructions on a DN 400 pipeline constructed 1962

Data have been evaluated to determine the ratio A (equation (4)), the driving voltage U_d (equation (13)), $R_{a,min}$ (equation (12)) and R_{mi} (equation (6)). Effectiveness of cathodic protection is assessed by comparing R_{mi} with $R_{a,min}$

Cathodic protection is clearly effective inside the casing at test post no. 2 where R_{mi}=457Ω indicates a good coating quality of the carrier pipe. In case of casing at test post no. 28/29 corrosion likelihood should be low but a possible polarisation of the casing should be taken into account (See comment to equation (13)). In accordance with these assessments results from an intelligent pig run did not indicate external metal loss on the carrier pipe in these casings.

There is a minor problem with the casing at test post no. 15 where R_{mi} is slightly smaller compared to $R_{a,min}$. The problem could be overcome by constructing an additional ground electrode (spread resistance e.g., 6Ω or less) and electrically connect it with the casing. Results from an intelligent pig run, however, did not indicate external metal loss on the carrier pipe within the casing.

Effectiveness of cathodic protection is clearly questionable in casings at test post no. 1. Results from intelligent pigging did not however indicate external metal loss on the carrier pipe in these casings. Possible reasons might be an arrangement of distributed small coating faults on the carrier pipe rather than one large coating fault and/or a small distance between carrier pipe and casing, e.g., at the bottom where distance is approx. 5 cm due to the size of spacers.

Effectiveness of cathodic protection is also questionable inside casing at test post no. 17/18.

Annex B

This annex details the technique covered in CEFRACOR Recommendation PCRA n°010.

i. Method explanation

This method consists of comparing coupon On/Off measurements when a coupon is connected to the cathodically protected carrier pipe to the one when it is connected to the metallic casing.

ii. Equipment required

- Temporary coupon (rod, plate, …),
- Data logger recording On/Off potential measurements and current measurements through the coupon,
- $Cu/CuSO_4$ reference electrode,
- Cable connections.

iii. Symbols

- E_{on} : coupon-to-soil potential when connected to the carrier pipe
- E_{off} : coupon-to-soil potential when disconnected from the carrier pipe,
- I_T : current through the coupon when connected to the carrier pipe (warning: in this Annex, cathodic current is negative [**negative terminal** of the ammeter connected to the coupon]).

Note: potentials are measured with a $Cu/CuSO_4$ reference electrode.

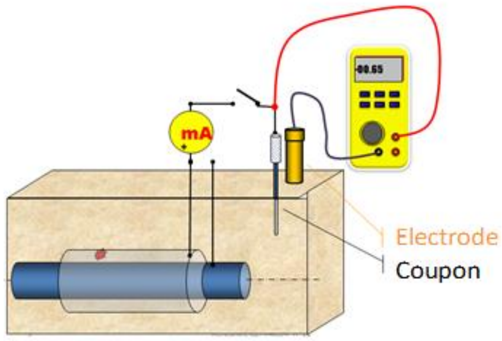
iv. Methodology

Schemes below describe how to implement the method in the field. The data logger is symbolised by in interrupter.

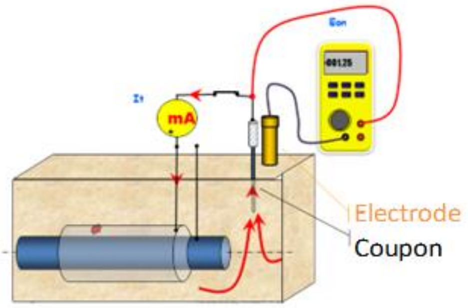
Coupon and reference electrode are placed on the soil next to the carrier pipe to be assessed and they shall be kept in the same place during all the measurements.

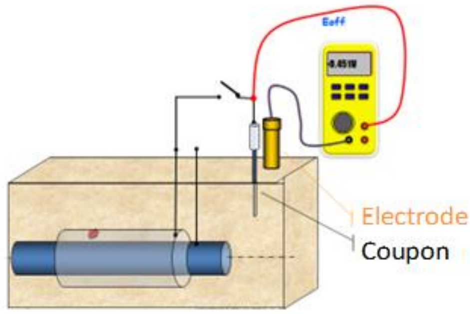
- Connect the coupon, the reference electrode to the data logger. The cable for the carrier pipe or the casing shall not yet be connected to the pipe.
- Read measurements to validate all connections made: E_{off} and E_{on} shall be equivalent and shall correspond to the free corrosion potential of the coupon in soil. No current shall be measured through the coupon: $I_T = 0$.

The procedure shall start by first connecting the free cable from the data logger to the casing to avoid any polarisation of the coupon (mainly when the carrier pipe is well cathodically protected).

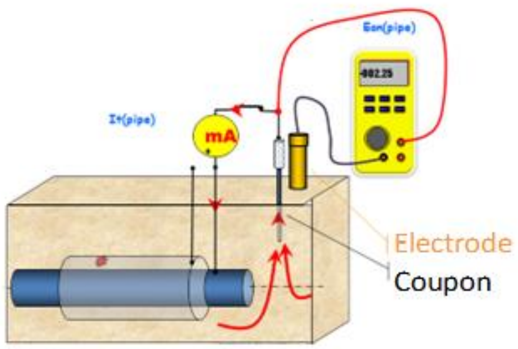


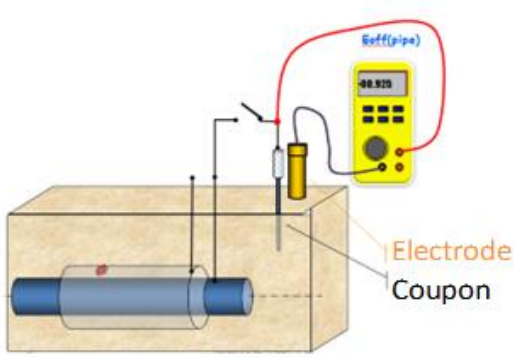
- Connect the free cable from the data logger to the casing.
- Record measurements on the coupon for 15 minutes : E_{off}, E_{on} and I_T. The last measurements are kept for comparison with the ones obtained at the next step.



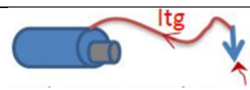
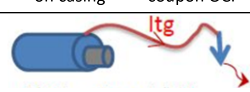


- Connect the free cable from the data logger to the cathodically protected carrier pipe.
- Record measurements on the coupon for 15 minutes: E_{off}, E_{on} and I_T. The last measurements are kept for comparison with the ones obtained at the previous step.





Procedure to analyse measurements results

	Comparison of measurement results			Conclusion
Situation 1	$E_{on\ pipe} = E_{on\ casing}$	$E_{off\ pipe} = E_{off\ casing}$	$I_{T\ pipe} = I_{T\ casing}$	Direct metallic contact
Example	$E_{on\ pipe}$ = -2,5 V $E_{on\ casing}$ = -2,5 V	$E_{off\ pipe}$ = -1,0 V $E_{off\ casing}$ = -1,0 V	$I_{T\ pipe}$ = -1,0 mA $I_{T\ casing}$ = -1,0 mA	
Situation 2	$E_{on\ pipe}$ » $E_{on\ casing}$	$E_{off\ pipe}$ » $E_{off\ casing}$	$I_{T\ pipe}$ » $I_{T\ casing}$	Electrolytic contact
Example	$E_{on\ pipe}$ = -2,5 V $E_{on\ casing}$ = -2,0 V	$E_{off\ pipe}$ = -1,0 V $E_{off\ casing}$ = -0,7 V	$I_{T\ pipe}$ = -1,0 mA $I_{T\ casing}$ = -0,2 mA	
Situation 3	$E_{on\ pipe} < E_{on\ casing}$	$E_{off\ pipe} << E_{off\ casing}$	$I_{T\ pipe} << I_{T\ casing}$ And $I_{T\ casing}$ » 0	Absence of contact
Example 1	$E_{on\ pipe}$ = -2,5 V $E_{on\ casing}$ = -1,0 V	$E_{off\ pipe}$ = -1,0 V $E_{off\ casing}$ = -0,5 V	$I_{T\ pipe}$ = -1,0 mA $I_{T\ casing}$ = -0,1 mA	 $E_{on\ casing} < E_{coupon\ OCP}$
Example 2	$E_{on\ pipe}$ = -2,5 V $E_{on\ casing}$ = -0,6 V	$E_{off\ pipe}$ = -1,0 V $E_{off\ casing}$ = -0,3 V	$I_{T\ pipe}$ = -1,0 mA $I_{T\ casing}$ = +0,1 mA	 $E_{on\ casing} > E_{coupon\ OCP}$

Symbols:

-  : carrier pipe + casing,
-  : coupon,
-  : connection between the coupon and the casing,
- OCP : Open Circuit Potential.

Note: cathodic current through the coupon is negative.

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