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Investigations on Cathodic Protection Current Diversion to Carrier Pipe with VCI Gel Annulus Fill in Cased Pipelines

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ABSTRACT

Oil and gas transmission pipelines susceptible to corrosion are regulated by governing authorities all over the world. Cathodic Protection (CP) is the most common technique used to protect buried pipelines. When pipelines are installed inside casing pipe (casing) beneath roadways, railroads and other locations, the CP is ineffective for the cased section of carrier pipe. Furthermore, when the end seals on the casing are compromised, the corrosion threat is increased on the cased section of carrier pipe either due to metallic short or due to electrolytic coupling between the carrier pipe and casing. Pipeline operators in U.S. are mandated to comply with 49 CFR Part 192, Subpart O, to protect the cased carrier pipe from corrosion in High Consequence Areas (HCAs). One common approach used by pipeline operators is to fill the annulus space between casing and carrier pipe with a dielectric fill such as wax. It is assumed that wax fill process pushes out contaminated water, leaving annulus with the wax, however this is not always possible. During the wax fill process, contaminated water gets trapped in air pockets and around spacers, consequently increasing corrosion risk on the carrier pipe. Existing indirect assessment techniques, for pipeline integrity monitoring, cannot be applied to the wax filled casings due to shielding effects. NACE standard SP0200 recognizes multiphase vapor corrosion inhibitors as one of the viable options for corrosion mitigation of carrier pipes in the casing annulus space. Vapor Corrosion Inhibitors (VCIs) are water-based gel-like solutions that are injected in the casing annulus space. This paper explores effect of VCI gels in diverting the CP current to the holidays on the carrier pipe inside a casing and VCIs effect on indirect assessment techniques used for pipeline integrity of cased pipelines.

Key words: Vapor Corrosion Inhibitors, Cathodic Protection, Cased Pipelines, Pipeline Integrity

INTRODUCTION

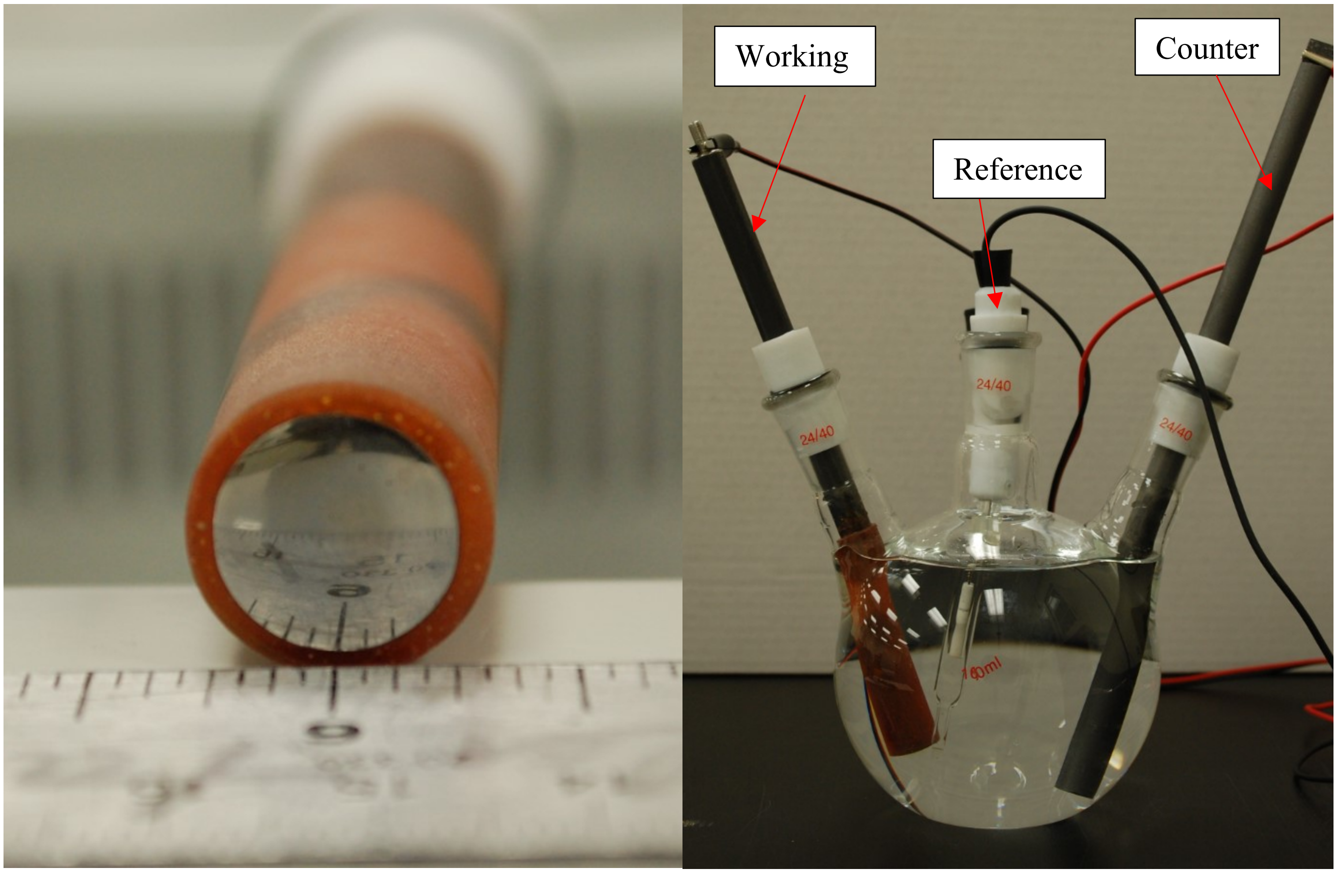
Oil and gas transmission pipelines susceptible to corrosion are regulated to protect the environment and ensure public safety. Cathodic Protection (CP) is the most common technique used to mitigate corrosion and is one of the regulatory requirements in the United States. When pipelines are installed beneath roadways, railroads and other locations, a larger pipe is used to encase the main pipe, i.e., carrier pipe. This arrangement is generally referred as casing. The two pipes in a casing are separated with airgap in-between and end seals are installed to prevent water/soil ingress into the annulus space. When the end seals on the casing are compromised, the threat of corrosion is increased on the cased section of carrier pipe due to ingress of contaminants; CP is ineffective for the cased section of carrier pipe either due to metallic short or due to electrolytic coupling between the carrier pipe and casing. Pipeline operators in the US are mandated to comply with 49 CFR Part 192, Subpart O, to protect the cased carrier pipe from corrosion in High Consequence Areas (HCAs). Specifically, the operators are required to assess the integrity of the carrier pipe using either recommended methods such as pressure testing, direct assessments, and inline inspection or a method acceptable to either state or federal regulators. Complying with the integrity assessment requirement inside a casing has proven challenging for operators, especially oil and gas distribution system operators that operate lines classified as transmission pipelines. In many cases, transmission pipelines were not designed to be "piggable." Pressure testing is generally not preferred because it disrupts service and introduces water. Direct assessment is problematic because the casing shields many of the indirect inspection techniques used to identify direct examination locations, and it is difficult to expose the carrier pipe for direct examination without excavating and removing the casing pipe.

Indirect assessment methods associated with the on- and off-potential measurements are widely used to assess integrity of the carrier pipe. One complication in applying the indirect assessment methods is shielding of the carrier pipe in a casing either because of airgap between the carrier and casing or a dielectric fill material such as wax.[1] Pipeline operators have been using petroleum-based wax to fill the annulus space between the casing and carrier pipe with the assumption that the wax fill process pushes out all contaminated water from casing annulus, and ensuing interaction between the carrier pipe and wax will be non-corrosive, and thus provide corrosion protection to the carrier pipe. However, contaminated water gets trapped in void spaces and air pockets and around spacers during the wax fill process, consequently increasing corrosion risk on the carrier pipe, and making the carrier pipe even more inaccessible to indirect assessment. NACE standard SP0200[2] recognizes multiphase vapor corrosion inhibitors as one of the viable options for corrosion mitigation of carrier pipes in the casing annulus space. Vapor Corrosion Inhibitors (VCIs) are water-based corrosion inhibitors that are injected in gel form in the casing annulus space and several studies have been conducted on feasibility of using VCIs in cased crossings.[3,4,5,6] Being water based, VCIs not only provide corrosion protection but also creates electrolytic coupling between the carrier and casing pipes. The VCI-based electrolytic coupling is different from the electrolytic coupling established due to intrusion of ground water in the annular space in following manners: (i) VCIs provide corrosion protection to any holiday on the carrier pipe inside the casing, (ii) VCIs-based electrolytic coupling creates a consistent and homogeneous ionic path between a holiday and anode for CP current to be delivered to the holiday inside, and (iii) a consistent electrolytic coupling between the two pipes provide means to inspect the cased section through indirect inspections. This paper explores the use of VCI gels in diverting the CP current to the holidays on the carrier pipe inside a casing. The paper also explores feasibility of applying the indirect assessment techniques for pipeline integrity assessment in VCI-filled casings.

EXPERIMENTAL

The investigations are divided into two stages: (i) the effectiveness of VCI in providing carrier pipe corrosion protection was evaluated in the liquid form and in the gel form, and (ii) the pipe-casing scenario was evaluated for CP current diversion to carrier pipe with VCI fill in annulus space. An amine carboxylate based VCI was used for testing purposes. The VCI had an added soluble corrosion inhibitor (SCI) in its formulation, the pH of VCI was in the range of 9 to 10.

In the first stage, Electrochemical Impedance Spectroscopy (EIS) experiments were conducted using a three-electrode configuration setup: carbon steel (working electrode), graphite rod (counter electrodes) and saturated calomel electrode (reference electrode). A 1-L 4-neck flask was used for the test setup shown in Figure 1. The liquid and gel form VCI were prepared at 5% and 20% concentrations. VCI solutions were prepared by mixing the VCI powders with potable water so that the net volume was 1000 ml. For gel phases, 60 g of gelling material was added to the potable water with 5% and 20% concentrations of VCI powder so that the net volume was 1000 ml, adequate time was allowed for gelling material to swell and form a uniform VCI gel solution. Potentiostat was used for conducting EIS experiments on liquid phase and gel phase VCIs, the experiment was repeated with 3 runs for each liquid and gel test.



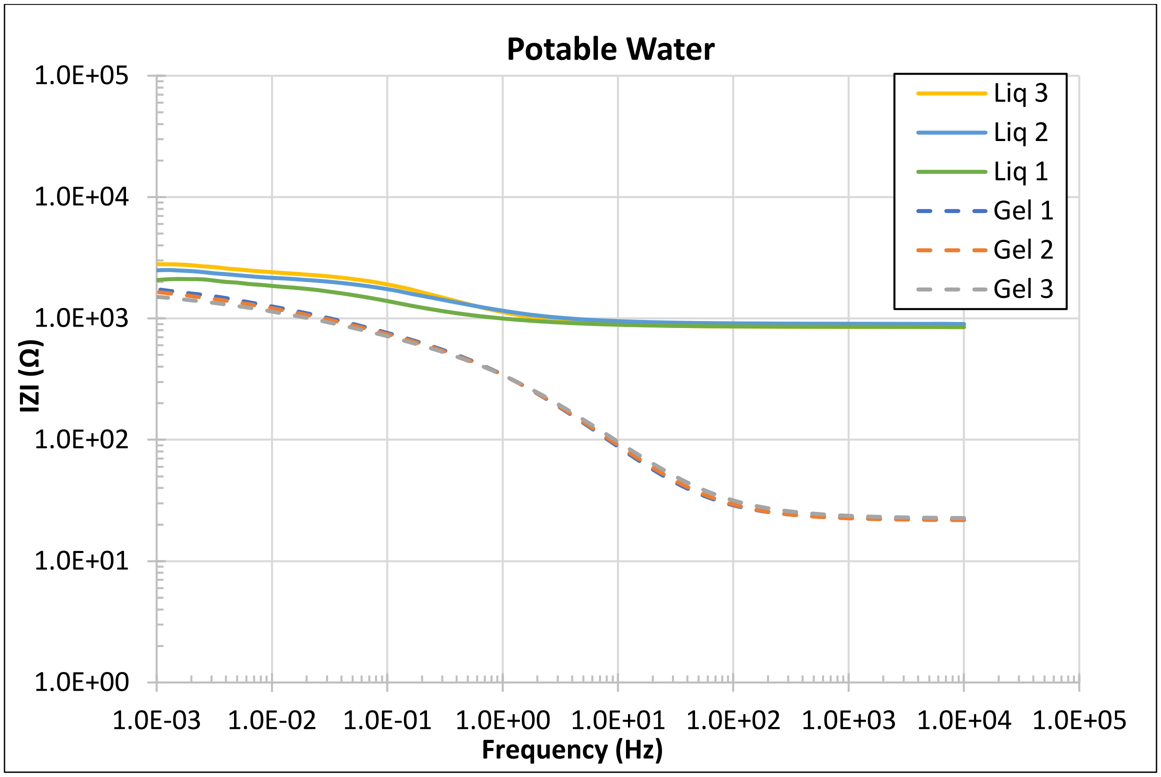
(a) Polished working electrode **(b) 3-electrode configuration**

Figure 1: Test setup for EIS experiment with VCI electrolyte

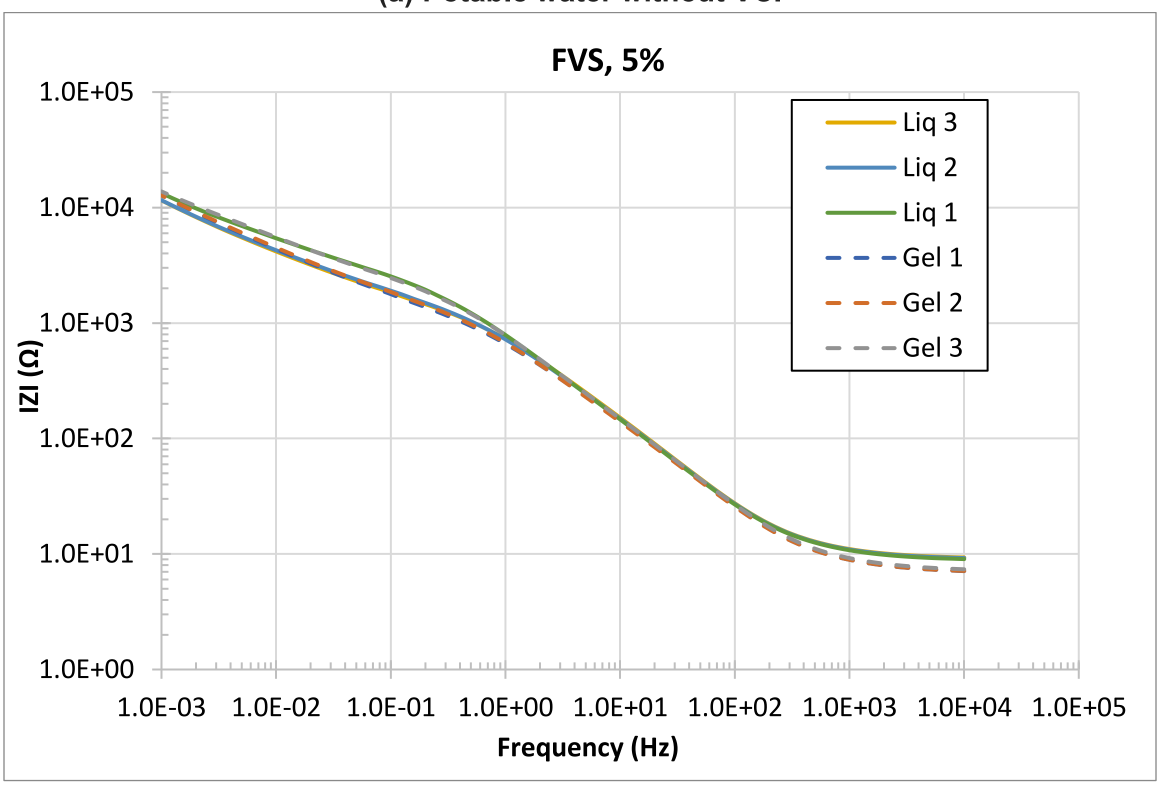
RESULTS AND DISCUSSION

Electrochemical Impedance Spectroscopy

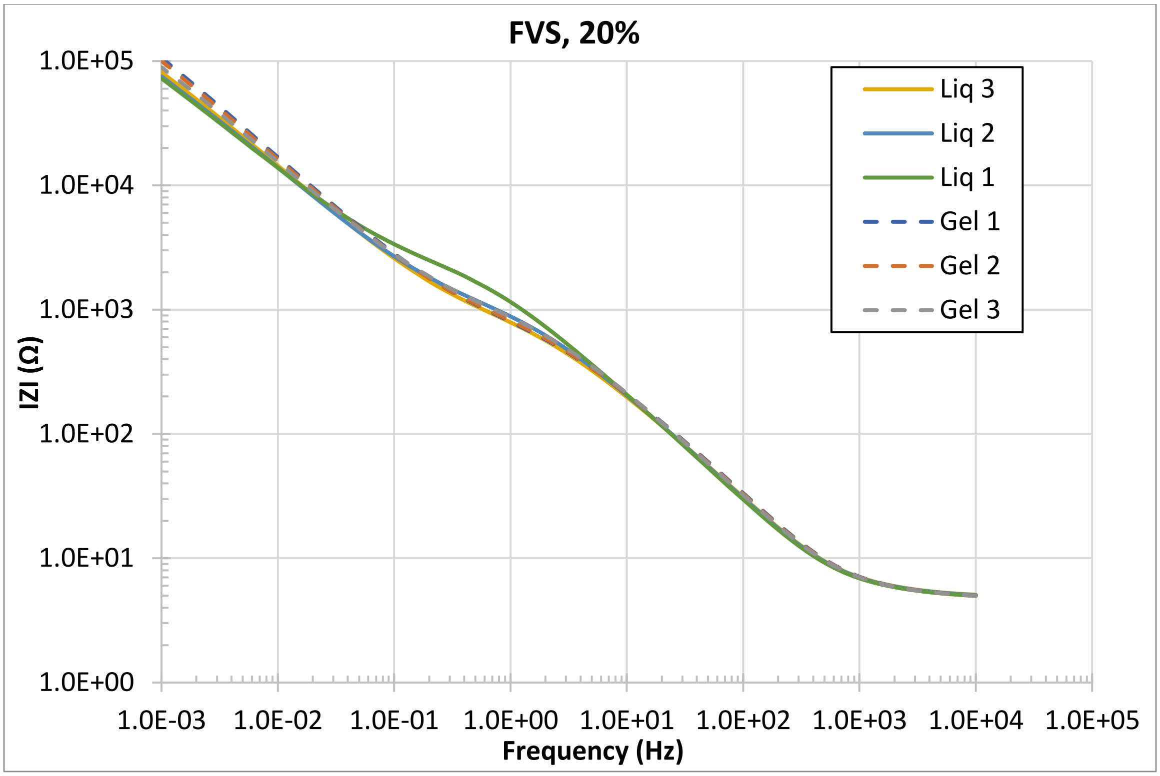
The corrosion potentials of the working electrodes were allowed to stabilize and reach steady-state in each corrosion cell test setup. Electrochemical impedance spectroscopy (EIS) was used to measure several impedance spectra of the working electrode in liquid from and gel from VCIs, three repetitions were conducted for each test setup. EIS technique was chosen for this application because it allows measurement of sub-mil corrosion rates. EIS measurements were conducted at the open circuit potential of the working electrodes and the impedance data was analyzed using a constant phase element (CPE) type electrical circuit to obtain the polarization resistances (Rp) as described in Shukla et al.[5] The impedance of VCIs at different frequency is plotted as bode plots shown in Figure 2 (a)-(c). Table 1 shows the corrosion rates calculated from the Rp values which served as a basis for evaluation of VCI corrosion protection effectiveness.



(a) Potable water without VCI



(b) VCI at 5% concentration



(c) VCI at 20% concentration

Figure 2: Bode Plots from EIS testing for different VCI concentrations

Table 1
Polarization resistance values estimated from the circuit model fit to the impedance data and calculated corrosion rate of the electrode

Electrolyte	Impedance Spectrum Runs	Resistance Polarization "Rp" (Ohms)	Corrosion Rates (mpy)	Average Corrosion Rates (mpy)
Potable Water	Liq1	1382	18.79	16.14
	Liq2	1620	16.03	
	Liq3	1910	13.60	
	Gel1	1257	20.66	19.47
	Gel2	1348	19.27	
	Gel3	1405	18.48	
VCI- 5 %	Liq1	7584	3.42	3.64
	Liq2	6900	3.76	
	Liq3	6962	3.73	
	Gel1	8454	3.07	2.73
	Gel2	9764	2.66	
	Gel3	10610	2.45	
VCI - 20 %	Liq1	6474000000	8.69×10^{-6}	5.16×10^{-6}
	Liq2	5434000000	4.78×10^{-6}	
	Liq3	12900000000	2.01×10^{-6}	
	Gel1	11580000000	2.24×10^{-6}	1.77×10^{-6}
	Gel2	12990000000	2.00×10^{-6}	
	Gel3	24250000000	1.07×10^{-6}	

The data in Table 1 for 20% VCI concentration is consistent with the values reported in Shukla et al.[5]

CP Current Diversion to Carrier Pipe

The ability of CP current to reach the carrier pipe inside the casing mainly depends on the carrier pipe electrical isolation with the casing, and environment inside the casing, i.e., either dry or wet or combination of two. For a newly installed casing with end seals, there is expectation of complete electrical isolation between the carrier pipe and the casing and the environment is relatively dry. Consequently, CP current is not expected to reach the carrier pipe inside the casing, also with a dry environment inside the casing, no accelerated corrosion is expected on the carrier pipe other than the atmospheric corrosion at coating anomalies.

When the end seals are compromised, ground water mixed with soil gets inside the casing and fills up the annulus space. This is especially the case when ground water tables rise and reach close to the grade. Intrusion of ground water mixed with soil is termed as "electrolytic couple" between the casing and the carrier pipe, with the casing being electrically isolated from the carrier pipe. The water plus soil mixture inside the casing will act as an electrolyte to the carrier pipe and becomes a path for CP current to reach the carrier pipe. However, due to variations in annulus fill levels and their resistivity of the resulting electrolyte, the magnitude of CP current and its uniform distribution along the length of the carrier pipe is difficult to determine. Risk of the carrier pipe corrosion at coating anomalies is likely with the contaminated water present in the annulus. The risk is mitigated when a coating anomaly is in complete contact with the electrolyte which is a conductive medium between the carrier and casing pipes. CP current will flow through the electrolyte and enter the pipe at coating anomaly locations; the casing pipe simply acts as an ion transport medium, like the soil outside the casing. Even though the CP current reaches the carrier pipe inside the casing, the existing NACE CP criteria *"-850 mV_{CSE} instant-off potential"* may not be achieved. Risk of corrosion is high when there is either partial or incomplete contact between coating and water plus soil electrolyte. Such situation will result in formation of concentration cell, and thereby causing accelerated corrosion on the carrier pipe at coating anomalies.

When the casing is electrically shorted to the carrier pipe, the CP current will collect on the casing and flow directly back to the carrier pipe at the point of the electrical short. In situations where casings are electrically shorted along with electrolytic couple, the risk of corrosion at coating anomalies is higher compared to the case of only electrolytic couple: CP current will flow through the electrical contact (metallic short) between the two pipes, leaving no protection current for the coating anomalies. There are possibilities when a near short scenario also exists, i.e., higher resistance is in the metallic short path between the two pipes. In such cases, the CP current will get distributed between the metallic path and coating anomalies. Shukla et al.[7] developed a model to estimate CP current distribution inside a casing when there is either electrolytic coupling or metallic short or combination of the two. The holidays on the carrier pipe inside the casing will receive most of the CP current in case of only electrolytic coupling. Shukla et al.[8] computed the extent of CP current diversion in case of electrolytic coupling with VCIs. CP current density for a 10 cm^2 holiday ranged between 10 to 15 A/m^2. An analysis was conducted to estimate distribution of CP current between the metallic path and coating anomaly in a VCI-gel filled casing. Math et al.[6] calculated the resistivity of VCI electrolyte at different concentrations and reported the VCI electrolyte resistivities range between 15 to 50 Ω-cm; a nominal value of 30 Ω-cm was used in this analysis. Effective radius of a 10 cm^2 holiday is 1.8 cm. Resistance to charge flow to the holiday is calculated by following equation:

$$R_h = \rho /(4r_0) \qquad (1)$$

where,

R_h	—	Resistance to charge flow through electrolyte in a holiday (Ω)
ρ	—	electrolyte resistivity (Ω-cm)
r_0	—	equivalent radius of holiday (cm)

Assuming pipe potential is invariant between coating anomaly and at the point of electrical short, the fraction of CP current entering the casing is given by

$$I_h/I = R_E/(R_E+R_h) \tag{2}$$

where

R_E	—	Resistance to current through the metallic short (Ω)
I_h	—	CP current at holiday (A)
I	—	Total CP current diverted to casing (A)

Figure 3 shows fraction of CP current diversion to a 10 cm^2 holiday in a 30 Ω-cm VCI gel fill casing as a function of R_E. As seen in the figure, CP current to the holiday increases with increasing R_E. The CP current fraction is above 0.9 when metallic short resistance is 40 Ω or more, and fraction is above 0.5 when R_E exceeds 4.5 Ω. This analysis indicates that in case of a high resistance short or complete electrical isolation scenario, VCI gel would provide conductive enough path for the CP current to reach the holiday inside a casing. When a 100% metallic short exists, fraction of CP current reaching the holiday on the carrier pipe is zero or negligible: in such cases corrosion on the carrier pipe is mitigated by the VCI gel, the corrosion growth rate of a holiday with 20% VCI gel concentration is illustrated experimentally as listed in Table 1.

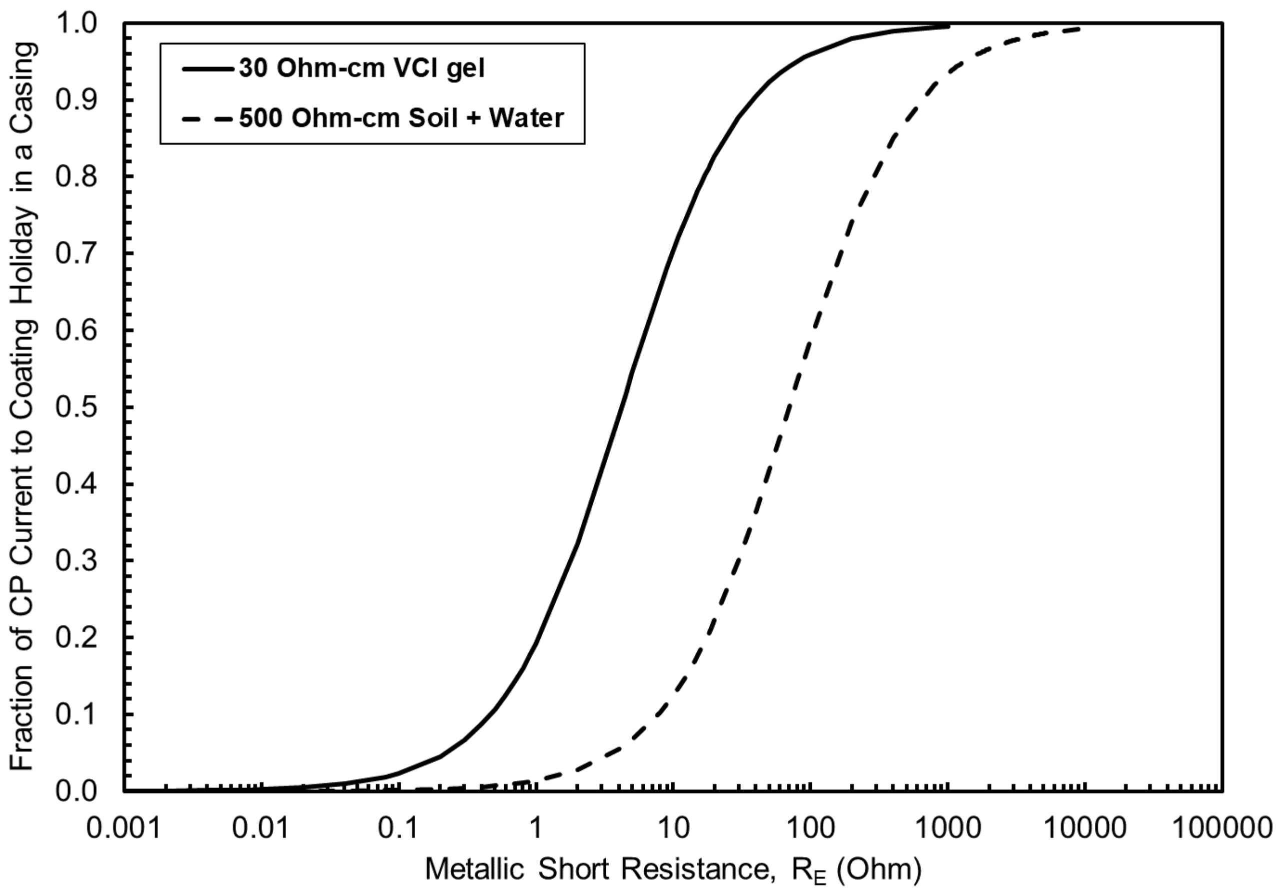


Figure 3. Fraction of CP current to a 10 cm^2 holiday in casing as a function of metallic short resistance. The casing is assumed to be filled with 30 Ω-cm VCI gel. Dash line is for 500 Ω-cm soil plus water mixture.

A summary table is developed based on the analysis in this section. The summary table highlights potential benefits of using VCI gels in casings with electrolytic couple and metallic short scenarios and are listed in Table 2.

Table 2. Comparison between without and with VCI gel in casings under different conditions

<table>
<tr><th rowspan="2">Condition</th><th colspan="2">Diversion of CP Current</th></tr>
<tr><th>Without VCI</th><th>With VCI</th></tr>
<tr><td>No electrolytic coupling or metallic short</td><td>Atmospheric corrosion at coating anomalies</td><td rowspan="2">VCI gel solutions provide a conductive path for CP current to the holidays. Inhibitor action of the VCIs provide background corrosion inhibition. Corrosion inhibition is augmented by CP current at the coating anomalies.</td></tr>
<tr><td>Electrolytic coupling between carrier and casing pipe, complete electrical isolation.</td><td>Diversion of CP current will be dependent on level of fill, and resistivity of the soil plus water mixture in the casing. Partial or incomplete contact between the water plus soil mixture and pipe could cause formation of concentration cells, leading to aggressive corrosion at coating anomalies</td></tr>
<tr><td>Electrolytic coupling plus metallic short</td><td>Soil plus water mixture will create corrosive condition at the coating anomalies. Distribution of CP current will depend on contact resistance of the metallic short, and resistance to charge flow at the holiday. Exact extent of CP current distribution cannot be predicted.</td><td>VCI gel solutions provide background corrosion inhibition and a conductive path for CP current to the holidays. VCI gels resistivity range between 15-50 Ω-cm. A prediction on extent of CP current distribution between the metallic short and coating anomalies can be made for a VCI gel filled casing.</td></tr>
</table>

VCI gels could be used to engineer the electrolytic coupling between casing and carrier pipes. The engineered coupling provides a predictable path for CP current distribution between coating anomalies and metallic short.

Indirect Assessment of Carrier Pipe Inside Casing

Inline inspection tools aid in determining corrosion on the carrier pipe for pipelines that are piggable. For unpiggable pipelines, the operators must depend on indirect assessment techniques in determining corrosion on the carrier pipe inside the casing. High risk of corrosion exits in presence of a metallic short between the carrier pipe and casing, and the annulus is filled with groundwater water mixed with soil and contaminants. The regulations require the pipeline operator to address the metallic shorts immediately. As per NACE SP0200 Exhibit B1.3.2, a metallic shorted casing may exist if the potential difference between the carrier pipe and the casing is less than 100 mV, additional tests are recommended to verify existence of the short.

An analysis is conducted to determine if VCI gel filled casing will interfere with the 100-mV criterion used to detect the metallic short. Three resistances are considered: (i) resistance to charge flow through VCI gel electrolyte, (ii) interfacial resistance at coating holiday and VCI gel, and (iii) interfacial resistance at casing pipe and gel. Regarding (i), resistance is approximately 4.2 Ω for a 10 cm^2 holiday in 30 Ω-cm

VCI gel. Additional parameters such as polarization resistance at the casing gel interface, and holiday and gel interface are needed to estimate items (ii) and (iii). The two polarization resistances are provided in Shukla et al.[8], and are listed in Table 3.

Table 3. Parameters used to estimate potential drop between carrier and casing pipes

Parameter	Value
Polarization resistance at casing and VCI gel interface	400 Ω–m^2
Polarization resistance at holiday and VCI gel interface	0.3 Ω-m^2
Casing length	30 m
Casing pipe inner diameter	26 inches

The sum of interfacial resistance between casing pipe and holiday is approximately 310 Ω. Correspondingly, the potential drop between the carrier and casing pipes is 3.1 V, much above 100 mV threshold. This analysis indicates that VCI gel filled casing will not interfere with detection of metallic short.

The potential of the carrier pipe inside the casing depends on the current pick up at the external surfaces of the coating holidays on the carrier pipe. The current pickup can be estimated by the various resistance paths that exist between the remote earth and the carrier pipe. With CP, one of the protection criteria is to achieve -850 mV_{CSE} instant-off potential for the entire length of the carrier pipe to be compliant with the regulations. The cased section of the carrier pipe is shielded by the casing and hence the above ground surface potential measurements cannot measure the potential of the carrier pipe inside the casing. Pipeline operators are always faced with this difficult scenario and carry the burden to prove that the carrier pipe inside the casing is protected and meets regulatory compliance. The approach that the pipeline operators adopt is to use indirect assessment techniques to identify the short scenarios. In case of the metallic short, the common practice is to fill the annulus space between the carrier pipe and the casing with dielectric wax. This is not a permanent solution, as the regulations require periodic reassessments and monitoring of the corrosion rate on the carrier pipe inside casing. The indirect assessment techniques such as Guided Wave Ultrasonic Testing (GWUT) cannot cover the entire length of carrier pipe with dielectric wax fill. If the pipeline operator cannot prove the integrity of carrier pipe during periodic reassessments, then the regulatory requirements are not fulfilled. The cased section is considered at high risk and would need to be excavated, the dielectric wax fills needs to be removed and the carrier pipe must be directly examined for any corrosion activities.

On the contrary, the use of VCI gel in the annulus provides corrosion protection of the carrier pipe holidays, illustrated by experiment data listed in Table 1 where the data show reduced corrosion rates with increased VCI concentrations. Use of VCI gel also eases application of indirect assessment techniques required during periodic reassessments, since the VCI gel is highly conductive, it allows AC/DC electrical signals to get through the annulus space during assessments.

SUMMARY

1. EIS experiments indicate significant reduction in corrosion rates of steel sample in contact with VCI electrolytes as compared to potable water electrolyte. There was no significant difference between the VCI electrolyte in liquid form vs. gel form.

2. For electrolytic couple scenarios, VCI gel solutions provide a conductive path for CP current to the holidays. Inhibitor action of the VCIs provide background corrosion inhibition. The corrosion inhibition is augmented by CP current at the coating anomalies.

3. For metallic short scenarios, VCI gel solutions provide background corrosion inhibition and a conductive path for CP current to the holidays. VCI gels resistivity ranges between 15-50 Ω-cm. For high resistance metallic shorts, a prediction on the extent of CP current distribution between the metallic short and coating anomalies can be made for a VCI gel filled casing.

4. The use of VCI gel in the annulus space eases the use of indirect assessment techniques required during periodic reassessments, since the VCI gel is highly conductive it allows AC/DC electrical signals to get through the annulus space.

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