PARSC 019 – Potential Impacts of Abandoned Anode Beds – Engineering Study

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ABBREVIATIONS

CCME	Canadian Council of Minister of the Environment
CP	Cathodic Protection
EPA	Environmental Protection Agency
HSCI	High Silicon Cast Iron
IC	Impressed Current
Mg	Magnesium
MMO	Mixed Metal Oxide
PARSC	Pipeline Abandonment Research Steering Committee
PTAC	Petroleum Technology Alliance Canada
Zn	Zinc

1 INTRODUCTION

The Petroleum Technology Alliance Canada (PTAC), through the Pipeline Abandonment Research Steering Committee (PARSC), has commissioned various research topics covering different facets related to abandonment of pipelines. PARSC 019 was commissioned to develop a best practice surrounding the abandonment of cathodic protection anode beds. The main activities involved with this proposal will be based on completing a review of available information about the topic and formulating first steps at approaching the topic of anode bed abandonment.

2 BACKGROUND

To assist in the prevention of corrosion to exposed steel on below grade pipelines, cathodic protection (CP) systems are installed. CP systems can be split into two (2) categories: including impressed current cathodic protection (ICCP), or galvanic (sometimes referred to as sacrificial systems). ICCP system require an external current source to function while galvanic systems do not.

ICCP systems will typically include a current source such as a rectifier or DC controller which is connected to both the structure to be protected and the installed anode beds via cabling. The external power source is used to impress driving voltage between the structure and the anodes which subsequently results in DC current flow, the magnitude of which is determined by the overall system circuit resistance. Galvanic CP systems, function by directly or indirectly connecting active anode material metals via cabling to the structure to be protected. For buried pipeline applications the galvanic anode material utilized is often zinc or magnesium. Where an ICCP system functions by impressing a DC driving voltage, galvanic systems function because of the natural DC voltage differences found between dissimilar metals. In the case of both ICCP and galvanic systems, the respective components create a system whereby the anodes are sacrificed and the target structure to be protected has its lifespan extended. It should be noted that on a case by case basis, various other components may be installed as part of an overall ICCP or galvanic system. These supplementary components may include but not be limited to electrical isolation devices, junction boxes, test posts, miscellaneous monitoring provisions, and remote monitoring units.

There are various methods of installing anode beds to provide the required cathodic protection. The two main methods for pipeline applications are, first, a horizontal configuration where the ground is excavated near the pipeline and the anodes are laid in the ditch just below the frost line. The second configuration is a vertical well where wells of various depths are drilled based on design requirements. The anodes are lowered into the wells and connected to the CP system. Anodes as part of an ICCP system are almost exclusively installed remotely from a pipeline, whether in a horizontal or vertical configuration. For galvanic systems the horizontal anodes may be installed remotely from the pipeline or within a shared trench line with the pipeline dependent on various factors. The choice of configuration depends on various factors including the land requirements, piping configuration, and ground conditions, among others.

ICCP anodes are often in a tubular or stick form, and are surrounded with a calcined carbon cokebreeze backfill material which reduces the electrical resistance at the interface between the anode and the surrounding soil. Certain other types of ICCP anode material such mixed metal oxide ribbon (MMO) is often installed without the surrounding calcined carbon cokebreeze. Zinc and magnesium galvanic anodes are generally installed in the form of a ribbon, or more typically as a block within prepackaged cardboard tubes or cloth bags. The galvanic anodes are surrounded by a gypsum bentonite material which helps reduce undesirable polarization of the anodes themselves as CP is applied.

Typical CP systems are designed to last for many years, up to decades. However, depending on the lifetime of the pipeline beyond the lifetime of the CP system, anode beds may require replacement. It is generally a common practice during the replacement of anodes to abandon the initial anodes in place and install new anodes nearby. The abandonment process is often as simple as cutting the old anode header cable thereby electrically isolating the old anodes from the remainder of the system and updating as-built records accordingly. The new anodes are then installed and connected into the remainder of the pre-existing CP system. Pipelines are also eventually abandoned when no longer required, and as part of abandonment activities CP systems are often abandoned, unless specified within landowner agreements or regulatory conditions. Both anode replacement and pipeline abandonment require the abandonment of anodes. Options for anode bed abandonment are mainly abandonment in place or full removal of the components.

Typical activities associated with the abandonment of anode beds include removal of any surface facilities, such as rectifiers, vent piping, junction boxes, and test stations, along with disconnecting of header cables from anodes to any power source, and sealing of vertical wells [1]. Anode beds are normally left in place due to the challenging nature of attempting to remediate the areas which the anode beds are installed, both for horizontal and vertical installations.

During operation of the CP system chemical reactions are occurring at the anodes, and these reactions produce ions and compounds that propagate into the surrounding environment. These ions and compounds have the ability to mobilize based on the ground conditions in which the anodes were installed and can move through the surrounding environment potentially impacting environmental features such as aquifers, wetlands and watercourses. Horizontal anode beds also have the potential to impact surface water along with the introduction of various ions and compounds in the vicinity surrounding the anodes. These items among others will be reviewed further to determine potential impacts and to begin formulating a best practice surrounding the abandonment of these installed anode beds.

3 LITERATURE REVIEW

In order to determine the potential impacts of disturbing abandoning anode beds, a literature review was completed to identify documentation within industry applicable to the topic of anode bed abandonment. Based on the currently available material a literature review was completed on the following topics to determine potential impacts:

- Anode Types
- Backfill Material Composition
- Anode Installation Configurations

These items appear to have a significant impact on anode bed operation and resulting condition of the anode bed and surrounding area as it reaches a state where abandonment is contemplated.

3.1 Anode Materials

Depending on the specific CP system design, a variety of different types of anodes can be installed to achieve the intended results [2]. For the purposes of this report the most commonly installed CP systems and the associated anodes will be reviewed, which are galvanic (sacrificial) systems and ICCP systems [2].

3.1.1 Galvanic (Sacrificial) Anodes

In a galvanic anode configuration, the anodes are installed and connected to the pipeline without a current source, with the anodes being manufactured with a metal that is more active, and thus more easily corroded, than the steel pipe [2]. In this configuration the anode is effectively "sacrificed" and corroded thereby reducing the corrosion rate of the pipeline metal. Based on the design requirements there are two typical galvanic anodes used for buried pipeline applications, magnesium (Mg) or zinc anodes (Zn) [3] [4]. Each anode type will react in the CP system and produce either Mg or Zn ions along with hydrogen gas as the anode is slowly sacrificed over the lifetime of the system. The hydrogen gas will escape to atmosphere slowly, however the ions will remain and mobilize into the surrounding environment as the anode slowly reacts. These ions have the ability to alter the pH level of the material surrounding the anodes and impact water quality if significant quantities of ions build up in water volumes. While these ions are known to enter the surrounding environment during system operation, the nature of the penetration into the earth of the ions is not fully understood. A further study to assess the relative penetration of these ions into the surrounding area around the anodes could be undertaken to collect additional information regarding the behavior of these galvanic anodes. The results of these field studies should be taken into consideration when determining abandonment activities to appropriately assess the long-term impacts of the installed anodes and the scope of work to abandon the anodes given their installation configuration.

3.1.2 Impressed Current Cathodic Protection (ICCP) Anodes

In an ICCP configuration different anode compositions are used, typically a High Silicon Cast Iron (HSCI) anode or a mixed metal oxide (MMO) anode [2]. Graphite anodes are also occasionally used for pipeline applications however in more recent years they are specified far less commonly than the other two (2) anode compositions noted. These anodes can be installed in both horizontal and vertical configurations to accommodate both types of ICCP designs. The HSCI, and MMO anodes are typically comprised of:

- HSCI – Silicon rich cast iron, often including galvanized chromium, typically surrounded with calcined carbon cokebreeze backfill material during installation
- MMO – Rare earth metals galvanized to titanium or niobium base

The installed anodes in an ICCP system are inert unless the power source is active. While the system is functioning chemical reactions are occurring, producing various ions and compounds dependent on which type of anode has been selected. Ions and compounds are produced, migrating to either the cathode or anode based on their ion charge [5]. The ions and compounds produced include, but are not limited to:

- Fe^{3+}
- Cr^{6+}
- Cl_2
- Ni^{2+}
- Cu^{2+}

Other ions may also be produced based on the composition of the anodes [5]. As the ions and compounds are migrating between the anode and cathode they are moving through the area surrounding the anode. Due to the solubility and absorptive nature of these ions and compounds they will eventually affix themselves to nearby compounds within the ground [5]. Field studies have shown that levels of various ions are present above the Canadian Council of Ministers of the Environment (CCME) guidelines for drinking water in the ground surrounding the anodes [5]. Table 1 below details some results of lab sampling compared to CCME guidelines for water quality at the time of testing. These levels tend to dissipate quickly away from the installed anodes and levels of ions have generally dissipated to near zero levels within metres from the anode [5].

TABLE 3. INTERIM CANADIAN ENVIRONMENT QUALITY CRITERIA FOR CONTAMINATED SITES, REMEDIATION CRITERIA (μg/L) FOR WATER

	Irrigation	Livestock Watering	Drinking Water	Maximum Found in Laboratory Model
Arsenic	100	500 – 5 000	25	<40
Barium			1 000	<311
Boron (Total)	500 – 6 000	5 000	5 000	10 000
Cadmium			5	<3.8
Chromium (total)	100	1 000	50	80 000*
Cobalt	50	1 000		300*
Copper	200 – 1 000	500 – 5 000	<1 000	4 00*
Iron	5 000	--	<300	400 000
Lead	200	100	10	300
Manganese	200		<50	4 500
Molybdenum	10 – 50	500		400*
Nickel	200	1 000	---	30 000*
Selenium	20 – 50	50	10	100
Vanadium	100	100		250
Zinc (Total)	1 000 – 5 000	50 000	<5 000	300
PCDDs, PCDFs	----	---	----	

Based on reference (2).

* Concentrations of these metals are a function of current flux through the anode system

Table 1. CCME Guidelines in Comparison to Lab Results for Various Compounds in ICCP Operation [5]

3.2 Backfill Materials

To ensure stability of the vertical well, lowering of the resistance to earth of a horizontal or vertical system, and to provide the primary reactive surface for the anode, a carbon based backfill material is typically filled around the anodes as they are installed [1]. Based on the type of CP system which is installed there are different kinds of backfill materials used to increase the effectiveness of the anodes.

3.2.1 Carbon Backfill Material

Carbon backfill material is typically selected for installation in an ICCP system inclusive of HSCI anodes. There are a number of different carbon backfills available to suit different anode installation configurations and ground conditions [6]. The main component of the carbon backfill is carbon, with some backfills having over 99% fixed carbon content [6]. Other components of the carbon backfill are ash and specific volatile compounds, produced in insignificant quantities, a result of the carbon coking process which heats the carbon backfill to extremely high temperatures [6]. The overall component makeup of the carbon backfills pass Environmental Protection Agency (EPA) guidelines for buried products [6]. While carbon backfills meet EPA guidelines for buried products, they don’t typically provide an effective seal where vertical wells are installed through aquifers. In vertical wells that pass through aquifers, conductive concrete mixtures can be used in lieu of carbon backfills. These conductive concrete mixtures have a similar effect in lowering the resistance to earth between the anodes and ground, but also provide sealing abilities to limit any movement of ions and compounds into the surrounding aquifer formations.

Oxidation reactions at the anode have shown to produce compounds such as polychlorinated dibenzo-p-dioxins and dibenzofurans [5]. These hydrocarbons are likely produced along with nickel and vanadium ions as part of the reactions occurring with the carbon backfill material that was installed around the anodes [5]. Concentrations of these hydrocarbons were shown to have levels in excess of CCME guidelines for concentrations in soil for agricultural use at proximities close to the anodes [5]. However, concentrations of these hydrocarbons appear to decrease to relatively no contamination within approximately one metre from the installed anodes [5].

3.2.2 Galvanic Anode Backfill Material

Backfill material used in sacrificial anode configurations typically is a combination of gypsum, bentonite clay, and sodium sulfate [7]. This backfill material offers uniform contact between the anodes and the surrounding ground, lowers the resistance between the anodes and the earth, and prevents anode polarization [7]. The components of this backfill material are non-toxic and inert, so installation of galvanic anode backfill material should not adversely affects ground conditions and cause a contamination risk.

3.3 Anode Installation Configuration

The two main installation configurations and types of CP systems can have a significant bearing on the long-term impacts of the installed anodes along with the resulting impacts to complete identified abandonment activities.

In a horizontal anode bed configuration, the anodes are much closer to the ground surface, so any impacts to the surrounding ground resultant from operation of the CP system have a higher probability of impacting items such as topsoil and surficial water. Removal of horizontal anode beds involves excavating down to the anodes, removing the anodes and associated backfill material, completing in-situ tests to determine contamination, removing all contaminated material, and backfilling with approved backfill material. Depending on the number of anode beds which require removal this could be a significant effort to complete removal for all anode beds identified during a pipeline abandonment. Furthermore, the added environmental impact to complete an excavation of this nature may offset any benefit of completing a removal and thus should be considered.

Semi-deep or deep well anodes installations are installed significantly below the ground surface, so contamination of surficial areas such as topsoil is not likely, however the potential exists to release contaminants into features such as aquifers if not properly sealed. Removal of a vertical anode bed will be a significant undertaking. Vertical anode bed removal will involve bringing in a hydrovac truck or drilling rig based on the depth of the well to remove the material surrounding the anodes prior to removing the anodes from the vertical well. With consideration to the depths of some of these system configurations, it may prove impossible or certainly impractical to complete a removal of a vertically configured anode bed. Dealing with the potential contamination will also be an issue as it will be difficult and costly to complete in-situ tests any radial distance away from the borehole, and potential remediation options are likely limited to in-situ decontamination methods.

4 ABANDONMENT CONSIDERATIONS

In determining the next steps regarding the abandonment of anode beds, there are a number of elements which should be considered when determining abandonment activities. Depending on the location, configuration, and materials selection of the CP system, these items influence the potential impacts that anode beds can have to the public and the environment. These above elements should be evaluated against potential impacts to future land use, public safety, environmental impacts, and existing assets in operation to determine the appropriate abandonment activities to be completed specific to each anode bed.

Determining the required abandonment activities can be achieved by completing a site specific assessment for each anode bed during abandonment planning, taking into account the above mentioned elements. These assessments should make use of available information for the site along with engaging in discussions with various impacted stakeholders, such as landowners and regulatory authorities, to ensure due diligence has been completed in determining the appropriate abandonment activities.

4.1 Current and Future Land Use

Prior to completing any remediation activities, a review of the current and future land use should be completed. Depending on the land use type at the anode bed location, it may be prudent to remove the anode bed or leave in place. For locations where the current land use is sensitive to disturbance it's possible leaving locations undisturbed will be more beneficial to completing field activities to remove anode beds [8]. In looking at future land use, it would be beneficial to review available information to determine if there is any planned future use for which that anode bed could become an obstruction or hindrance to future works [8].

4.2 Public Safety

As cathodic protection assets are abandoned, attention should be paid to addressing specific items which could cause issues for the public [8]. Of note are potential issues such as:

- Ground Subsidence
- Induced Voltages
- Above ground appurtenances such as rectifiers, junction boxes, test posts, etc.
- Subsurface Apparatus

4.2.1 Ground Subsidence

With both horizontal and vertical configurations, the majority of the backfilled material will either be native backfill material or galvanic or carbon backfill material as required to improve the anode efficiency. These backfill materials will consolidate over time to return to similar to in-situ conditions, and while the reactions in the anodes and cokebreeze will consume some of the material and produce gas which will be vented to atmosphere, these reactions will not produce significant voids in the backfill material. As such it can be expected that if proper backfilling procedures are completed during installation there should be no significant subsidence issues at both horizontal and vertical anode installations.

4.2.2 Induced Voltages

Anode beds left in place during CP system abandonment will be disconnected from the pipeline and the remaining CP system by cutting the header cable connecting the anodes to the rectifier or pipeline. In this scenario there will be small lengths of wire left in the ground connected to the anodes. With no power source connected to the wires this typically will not create a hazardous scenario. However, in a power line fault scenario, while being rare, could create a potentially hazardous condition. If the power line fault is near the anode bed, depending on the magnitude of the fault, there is a possibility an arc could be generated between the faulted structure and the nearby anode bed. A review of the anode bed locations should be taken into consideration during abandonment planning to assess the proximity to any structures or systems which could create an electrical hazard.

4.2.3 Above Ground Appurtenances

During operation of the CP system, various above ground appurtenances are installed such as rectifiers, junction boxes, and test stations, to ensure continued operation of the CP system along with monitoring capabilities. Previous discussions and papers related to pipeline abandonment have indicated that these above ground appurtenances should be removed during abandonment of the CP system [8]. This is considered to be an appropriate activity since these items will be no longer required once the anodes are abandoned, either in place or through anode removal. Removal of these items will ensure that there is no hindrance to the public where those facilities were installed during CP operation.

4.2.4 Subsurface Apparatus

Previous papers have indicated that along with removal of surface facilities associated with pipelines, subsurface facilities to a depth of one metre should also be removed [8]. In regards to CP systems, horizontal and vertical anode beds typically are installed below a depth of one metre in order to ensure the anodes are installed below the frost line. The main facilities associated with CP systems below grade to a metre will typically be header cables connecting the anodes to the rectifier or pipeline. As these header cables don't present a significant safety risk it would be beneficial to conduct a review prior to completing any below grade activities to determine if removal of header cables is beneficial or if abandoning in place without disturbance is a more effective option.

4.3 Environmental Impacts

During abandonment planning, various environmental factors should be reviewed to determine the scope of abandonment activities. Specific to vertical well systems, the vertical well should be field inspected to determine if there is any potential for creating a conduit for surficial water to travel down the well and potentially enter an underground aquifer [1]. A review of available downhole documentation should also be completed to determine if any below grade aquifers were identified during installation and isolation measures were implemented. If the aquifers were adequately isolated there should be limited risk to further aquifer contamination, if any, as anode reactions will stop once the CP systems are abandoned.

As indicated in the above sections, reactions occur within the anodes and backfill material during operation of the CP systems reactions. These reactions produce various metal ions and other compounds which then integrate into the surrounding area. The effect of these reactions can create an localized environment of specific ion and compound concentrations above environmental guidelines for drinking water or agricultural use. It has also been shown that due to the solubility and absorptive nature of the ions and compounds migration away from the anodes is not significant, typically stopping within a metre or two from the anode location [5]. The effect of a localized contamination should not create a consequential risk if such items as topsoil or other sensitive environmental features are not in close proximity to the anodes. These factors should be taken into consideration if the anode beds to be abandoned are located in areas planned for future use as agricultural or if they are in close proximity to drinking water sources to determine if removal and remediation is a prudent choice.

The propagation of ions and compounds in the ground surrounding the anodes should also be considered when reviewing the location of anode beds in proximity to surficial wetlands and watercourses. A review of anode beds in close proximity to these features should be completed to determine the potential environmental effects of either removing the anodes or abandoning them in place.

4.4 Existing Operating Assets

Another consideration to be taken into account during abandonment planning will be the effect of abandoned CP components on existing assets. For galvanic type anodes, if the anodes are fully consumed during operation only a steel core will remain in place. If the steel cores are not disconnected from existing assets in operation, these cores will draw current as they will appear as a coating holiday to any existing CP systems in the area. If there are other pipeline assets near these abandoned anodes could potentially draw current and subsequent protection from the operating assets , reducing the effectiveness of the CP system in operation on those operating assets. Careful review of as-builts should be undertaken during abandonment planning to identify any locations where assets to be abandoned may be bonded to operating assets to ensure there is proper isolation of CP and pipeline assets to avoid unintentionally drawing protection away from those operating assets.

5 RECOMMENDATIONS

Abandonment planning for aging pipeline assets must include associated systems such as cathodic protection systems. Much the same as abandonment of other pipeline assets, a number of different elements need to be considered when considering the abandonment of cathodic protection assets. The design, installation, and operation of cathodic protection systems is well-understood, however, a formalized best practice for the abandonment of these systems has not been fully developed to date.

This literature review identified a wealth of existing knowledge on the properties of the components of the anode bed, mainly the types of anodes and their composition, along with the various components which make up the various types of backfill material. While literatures exists which contains information detailing field studies of various vintages of anode beds in operation [5], further investigation is recommended to determine the effects of the surrounding ground conditions around the anode during system operation. Identifying anode bed candidates in various types of ground conditions and different land use types would enable information to be gathered relating to impacts of both ground types and land use types on potential ion and compound movement during CP system operation. The results of these field studies will provide additional information to companies on the profile and migration of certain ions and elements which could be contamination threats. This information would enable companies to better determine if those ion and element concentration profiles and migrations create a contamination risk threat that is above the company risk profile and require mitigation, or if the threat is within acceptable thresholds given the ability to determine that there is an acceptable risk to the public and the environment. As indicated previously, this recommendation should be undertaken for both galvanic and ICCP systems to further understand the behavior of the produced ions and compounds in both systems.

Further investigating the effect of power line faults on anode beds abandoned in place is also recommended. While field investigations of these scenarios will likely prove difficult to impossible, modelling software can be employed to study various scenarios as it relates to power line configuration and voltages, combining pipeline and anode bed installation locations, to determine the effect of anode beds on resulting power line faults. This modelling information could be further used to identify safe separation distances when reviewing whether to abandon in place or remove taking into account the risks involved in both options.

These recommendations, along with a recommendation for continued industry participation and adoption of appropriate abandonment activities into company specifications, will be a positive start to determining an effective starting point at determining best practices for the abandonment of anode beds and supporting CP infrastructure.

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