

Corrosion Risk Assessment, Failure Analysis and Corrosion Mitigation for Aboveground Storage Tanks and Case Histories

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ABSTRACT

In this paper a general description of aboveground storage tank (AST) foundations and corrosion mitigation techniques to provide long term service is presented. Case studies involving earth foundation, soil corrosion, and double bottom tank are provided. The case studies apply standard electrochemical and failure analysis techniques to determine the primary causes and modes of failures. Soil chemistry, Microbiologically Induced Corrosion (MIC), pH and presence of chlorides in the soil will provide evidence for accelerated corrosion if there is deficiency in cathodic protection. Soil chemistry can be used to predict the penetration due to corrosion attack. If air traps or shielding is present, localized corrosion attack will take place in corrosive soil. Concrete foundations and corrosion inhibitors may be considered in corrosive conditions.

Keywords: Corrosion Protection, AST, Vapor Phase Corrosion Inhibitor (VCI), Failure Mechanism, Cathodic Protection, Concrete Foundations, Double Bottom Tanks.

INTRODUCTION

Unless protective measures are taken, ungrade steel storage tanks, piping, and other metallic components of fuel storage systems corrode and leak product into the environment. Corrosion can attack the metal either over the entire surface of the metal (general corrosion) or in a small, localized area, creating a hole. Localized corrosion can perforate an unprotected tank in little as a few years and is the most common form of corrosion.

Tank bottom corrosion from the soil could be prevented by using a concrete foundation but corrosion could still occur due to moisture accumulation between the tank bottom and the concrete pad due to condensation, blowing rain or snow, or flooding due to inadequate drainage and moisture entrapment. Proper measures should be taken for concrete foundation construction to eliminate the ingress of water and other corrosive contaminants between the tank bottom and the concrete pad.

A typical system for Monitoring and Mitigation of Corrosion in the Interstitial Space includes a) sealing any gaps between the tank floor and dead shell on double-bottom tanks, or gaps between the tank floor and concrete ring wall on single bottom tanks to prevent intrusion of fresh water and air into the interstitial spaces of these tank systems, b) engineered application of the Vapor Phase Corrosion Inhibitors (VCI) into the interstitial space in such a way that effective distribution of the chemistry is ensured and c) a corrosion rate monitoring system utilizing electrical resistance probe technology to measure the real-time rate of corrosion shoud be placed within the interstitial space and near the tank floor.

TYPES OF FOUNDATIONS FOR AST

EARTH FOUNDATION

Earth foundation is the most often applied foundation as it is easy to construct and also it is the cheapest compared to other foundations. However, the challenges with earth foundation are: 1) small leak moving out of the soil could lead to the destruction of the tank, 2) poor leveling or drainage of the bottom of the tank, 3) ineffective corrosion protection of the tank bottom due to voids and water pooling owing to uneven settlement of the foundation.

In practice, earth foundation will be used when the soil can withstand the pressure of the upper steel construction. Prior to earth foundation, determining the aggressive ions such as chlorides and sulfates along with measuring the pH and resistivity of the soil is very important as the soil analysis results will aid in designing the most practical corrosion prevention system for the tank bottom. In order to avoid corrosion of AST bottom due to corrosive soils, clean sand is used beneath the AST bottom.

EARTH FOUNDATION WITH A CONCRETE RING WALL

This particular foundation is most widely used for large diameter aboveground storage tanks because rigid reinforced concrete ring provides stability to the larger diameter tanks. It provides better leveling compared to earth foundation. However, the major drawback of this foundation is irregular settlement of the foundation/backfill that could lead to voids in the soil to steel interface.

Clean sand is the most common material used for backfill beneath the AST bottom. Clean sand minimum of 75 mm (3 in) thick is laid on top of the foundation. It is recommended to place 150 mm (6 in) thick of clean sand if cathodic protection is to be utilized. Bitumen-sand (cold patch asphalt) mix 50 mm (2 in) thick laid on top of the foundation under the tank steel bottom acts as a corrosion prevention layer. Bitumen-sand mix laid on top of concrete ring wall stops sand from eroding out from under the tank. This type of foundation allows for cathodic protection and leak detection materials/components to be placed in, or pass through, the sand pad for corrosion prevention and monitoring.

EARTH FOUNDATION WITH CRUSHED STONE RING WALL

This particular foundation is considered when high loads are imposed by a shell on the foundation. The advantages of this foundation is 1) good leveling, 2) preserves contour during construction and, 3) retains fill under the tank bottom. The drawback of this foundation is the difficulty of construction to close tolerances, selection of design and pitting corrosion of the AST bottom at contact areas between the large particles of the tank pad and the metal due to formation of differential aeration corrosion cells. In the event of water intrusion in to the tank bottom, the environment under the tank becomes alkaline, which may reduce corrosion. However, with time infiltrate the pad, corrosion may accelerate. Thus, the use of crushed limestone or clam shells does not clearly eliminate the need for cathodic protection.¹

This type of foundation allows for Cathodic protection and leak detection materials/components to be placed in, or pass through, the sand pad for corrosion prevention and monitoring. The use of cathodic protection on this type of foundation has produced mixed result.

With aging, there is a possibility that all the abovementioned foundations provide limited degree of protection due to ingress of corrosive ions from soil such as moisture, chlorides, and microorganisms. Many tanks are upgraded with double bottoms with interstitial space CP systems. However, designing and the maintenance/repair of CP system is problematic and considerations should be given to corrosion monitoring under the tank to monitor the effectiveness of corrosion mitigation.

SOIL CORROSION

Soil resistivity may provide valuable information about the corrosivity of the material used in the interstitial spaces, under and around a tank. A general resistivity classification is given in Table 1.

Table 1
Classification of Soil Corrosivity Based on Resistivity ²

Resistivity Range (ohm-cm)	Corrosivity
0 - 1000	Very severe
1,001 – 2,000	Severe
2,001 – 5,000	Moderate
5,001 – 10,000	Mild
>10,000	Very mild

There are several techniques for measuring soil resistivity. A common method is described in ASTM ⁽¹⁾ G57.³ It should be noted that soil resistivity alone should not be used to determine soil corrosivity. The

⁽¹⁾ ASTM International, 100 Barr Harbor Dr., West Conshohocken, PA

resistivity of the pad material may be higher than the existing surrounding soil. Corrosive soil beneath the higher resistivity pad material may contaminate the pad fill by capillary action and should be a consideration when determining sand pad thickness. Thus, resistivity of surrounding soil may be used to help determine the probability of corrosion on the tank bottom. The results of soil resistivity surveys should be considered and used to help determine the need for cathodic protection. However, other properties such as chlorides, sulfides and sulfates of the soil should also be considered. Example of analysis for sand in an AST application is shown in Table 2.

Table 2
Sand analysis results

Parameter & Method	Test Result	API ² 651 ⁴ Guideline Limit	Comments
Resistivity FM 5-551	57,400 ohm-cm (dry)	>30,000 ohm-cm	Pass
	18,240 ohm-cm (saturated)		Lower when wet due to chlorides (salt entrainment)
Water content ASTM D2216	5.9%	<5%	Marginal Fail – suggest scheduling use in dry season
pH FM 5-550	8.01	6.5 - 8.5	Pass
Chloride FM 5-552	15 mg/L	<300 mg/L	Pass
Sulphate FM 5-553	7 mg/L	<1000 mg/L	Pass

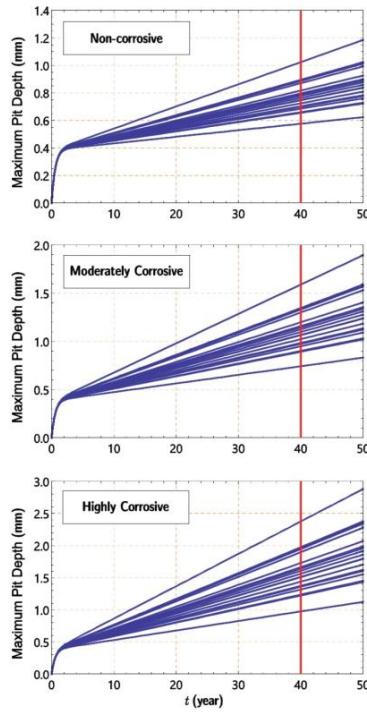


Figure 1: Photograph showing three different corrosivity rating and resulting penetration rates that can be used for remaining life determination.

⁽²⁾ American Petroleum Institute (API), 1220 L Street, NW, Washington, DC 20005-4070, USA

PREDICTIVE MODELING AND SOIL CORROSION DETERMINATION

A mathematical model to estimate the localized corrosion penetration and propagation in buried structures has been developed considering soil chemistry in the field (pH, resistivity, redox potential, and electrochemical potential at the soil–metallic structure interface) under the tank. According to many test results, this model provides an adequate description of thickness loss due to corrosion attack. This type of predictive modeling provides good damage prediction by using soil corrosivity parameters typically measurable in field. The plots (Figure 1) provide three different corrosivity rating and resulting penetration rates that can be used for remaining life determination.

FOUNDATION CORROSION CONTROL

For a better outcome, the following corrosion controls can be used a standalone or in combination.

CATHODIC PROTECTION

Cathodic protection to the tank bottom plates can be provided by either sacrificial galvanic anodes or by an impressed current cathodic protection (ICCP) system. Galvanic system is normally considered only for small diameter tanks (<20 feet (6.10 m)) or for the tanks with externally coated bottoms. Cathodic protection systems are designed and installed to prevent corrosion of a tank bottom by satisfying the requirements of one or more of the NACE criteria stated below.⁵

- A negative (cathodic) potential of at least 850 mV with the CP applied. This potential is measured with respect to a saturated copper/copper sulfate reference electrode contacting the electrolyte. Voltage drops other than those across the structure/electrolyte boundary must be considered for valid interpretation of this potential measurement.
- A negative polarized potential of at least 850 mV relative to a saturated copper/copper sulfate reference electrode, abbreviated as CSE).
- A minimum of 100 mV of cathodic polarization. The formation or decay of polarization may be used to satisfy this criterion.

In order to achieve the desired results, a cathodic protection system shall be properly designed. The cathodic protection system should be designed after a study of the following items:

- design and engineering specifications and practices
- operating procedures;
- safety, environmental, and hazardous area requirements;
- Field testing.

Cathodic protection is achieved by directing the flow of current from an anode to a cathode, resulting in protection of the cathode. Anything that acts as a barrier or shield to the flow of current will prevent the application of cathodic protection. In 2012, a survey carried out at an oil and gas facility in the Arabian Peninsula on randomly selected tanks showed that soil-side corrosion was present on all CP protected and non-CP protected tanks.⁶ Voids or air gaps formed between the tank bottom plates and the tank foundation due to filling and refilling of the storage tanks and weld overlaps also prevent the CP current from reaching to the bottom plates at these areas.

COATING

To avoid soil-side corrosion of the tank bottoms, coatings may be considered in conjunction with cathodic protection. However, mechanical damages during installation, pin holes, blisters and delamination in the coatings are real challenges. Damaged coating substantially reduce CP current requirement and enhance CP current distribution unless shielding conditions exists for CP at the coating defect/crevice.

VAPOR PHASE INHIBITOR (VCI)

VCI is a chemical substance when injected into the interstitial spaces between the foundation and the tank bottom adsorbs onto surfaces in the space and prevents or decreases the reaction of the tank bottom with the environment. VCI chemistry is also available as a thin liquid solution that can be delivered into the interstitial spaces under the tank floor through injection pipes placed in the sand layer while the tank is in service.⁷

Research and fieldwork show that some vapor phase corrosion inhibitors (VCI) by themselves or in combination with cathodic protection can be used for the protection of the bottoms of the above ground storage tanks. ^{8,9,10}

CORROSION MONITORING

Monitoring the corrosive environment of the tank bottom is important in determining predictive maintenance plans to increase the service life of the tank. Tank-to-soil potential measurement is the standard method of determining the effectiveness of cathodic protection at the tank bottom. These measurements are performed using a high-impedance voltmeter and a reference electrode contacting the electrolyte (sand in between both tank bottoms) in the dual bottom storage tanks.

Another good resource in determining the corrosion rate of the underside of the tank is electrical resistance (ER) probes. ER probe measures electrical resistance of a steel element in the probe face over a period of time. The increase in electrical resistance compared to initial reads is an indication of accumulated corrosion in the exposure period. ER probes can be used in a wide range of environments and can be considered for low conductivity and nonaqueous conditions, where electrochemical techniques are generally unsuitable. ER corrosion sensors have been likened to "intelligent" coupons, facilitating a simple corrosion measurement without the need to remove the coupon from service.

LEAK DETECTION

Leak detection is an effective way to minimize environmental damage and limiting the cost for cleanup. There are few different methods for leak detection but the most common are:

1. Secondary containment with interstitial monitoring: Secondary containment uses a barrier or a liner around the tank. The product leaked from the tank is directed towards an interstitial monitor located between the tank and the outer barrier. Interstitial monitoring methods include the use of an automated vapor or liquid sensor permanently installed in the system to monitor interstitial spaces.
2. Automatic tank gauging system: In this system the probe installed in the tank is connected to a monitor to provide information on product level and temperature. The system automatically calculates the change in product volume that can indicate a leaking tank.

3. Vapor monitoring: Product fumes in the soil around the tank or special tracer chemicals added to the tank which escape in order to check for a leak can be measured by vapor monitoring. This method requires installation monitoring wells at strategic locations. Vapor monitoring should be performed periodically using permanently installed equipment.
4. Groundwater monitoring: Liquid floating on the ground water can be sensed by groundwater monitoring. In this monitoring method, monitoring wells will be installed in the ground near the tank and along the piping. The wells should be checked periodically with permanently installed equipment to discover if leaked product has reached groundwater. It is recommended that this method should not be used at the site locations where groundwater is more than 20 feet (6.10 m) below the surface.

This systems are best when used in conjunction with one another with a proper maintainance schedule. Electrochemical measurements and installing test copuns are necessary to determine that corrosion protection has been established. Conditions that affect protection are subject to change with time, this requires periodic measurements and inspections to determine that corrosion protection is still being achieved.

CASE HISTORY 1

This section describes the investigation of a corrosion failure and perforation of the bottom plate on an aboveground diesel fuel storage tank in an island environment. 60 feet (18.29 m) diameter tank was constructed on concrete ringwall in 2004. The nominal bottom plate thickness is 0.312 inch (0.12 cm).

As part of the investigation an (1) on-site inspection, (2) cathodic protection system evaluation, (3) soil corrosivity study and metallurgical failure analysis was performed. These efforts are described in the following sections. Seven (7) of these areas were through-thickness holes initiating from soil side. 160 areas were exhibiting accelerated thickness loss on the soil side.

The onsite investigation consisted of internal inspection, visual examination of bottom plate, electrochemical potential and rectifier readings and samples were identified for subsequent laboratory testing.

Tank considered for inspection is shown in Figure 2. Tank internal photographs are shown in Figures 3 and 4. There is extensive thickness loss and perforation observed on bottom plate.

ON-SITE CATHODIC PROTECTION EVALUATION

The cathodic protection system was installed during construction of the tank. The cathodic protection system consists of an impressed current cathodic protection (ICCP) system with a rectifier and four mixed metal oxide (MMO) anode hoops placed under the bottom plate. Commissioning of the cathodic protection system was performed on August 1, 2005.

A measurement of 1.8 Amps was obtained across the shunts in the junction box at the time of the investigation. The potentials collected at the junction box between the cables from tank and permanenet reference electrodes are in the range $-419\text{mV}_{\text{CSE}}$ to $-437\text{mV}_{\text{CSE}}$ which indicates less than adequate protection. 100mV shift criteria is also not satisfied. The presence of extensive loss in thickness, perforation and review of historic data also indicates a lack of corrosion control for the bottom plate.

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LABORATORY INVESTIGATION

A laboratory investigation was performed that consisted of a soil corrosivity study and metallurgical failure analysis of the corroded section of the tank.

SOIL CORROSION STUDY

Analysis of soil sample collected from the perforated area revealed that the soil resistivity was 1300 ohm-cm. This indicates a conductive soil which is considered corrosive in direct exposure to steel with mill scale. Corrosion rate data was measured using Linear Polarization Resistance (LPR). Corrosion rate of 3.8 mpy was measured for water saturated soil sample collected from project site. Soil chemistry indicated the presence of calcium carbonate, iron corrosion products and silicates.

FAILURE ANALYSIS

VISUAL EXAMINATION

The underside of the sample taken from tank bottom plate is shown in Figure 5. Note that the second, circular hole in the center of the sample diameter is a drilled hole needed for sample removal. Thick corrosion products and deposits were observed on one area of the bottom plate underside. Loss of plate thickness due to corrosion was also observed in some areas including around the hole. Figure 6 shows the locations of maximum corrosion product thickness, and loss of thickness due to corrosion with respect to the hole. The line in Figure 5 shows the plane of cutting and cross section examination. The hole in the tank bottom as viewed from the outside of the tank is shown in Figure 7. The hole in the tank bottom as viewed from the inside of the tank is shown in Figures 8. No appreciable corrosion was observed on the inside surface of the tank bottom plate.

The corrosion products on the underside of the tank bottom plate were examined at moderate magnifications using an optical stereomicroscope. The corrosion products are shown in Figures 9 - 10.

SEM/EDS ANALYSIS

Qualitative analysis of the corrosion products on the underside of the tank bottom plate was determined using a scanning electron microscope (SEM) equipped with an energy dispersive x-ray spectrometer (EDS). A spectrum of the bright orange corrosion products is shown in Figure 11 and consisted primarily of iron (Fe) and oxygen (O) plus lesser amounts of carbon and chlorine (Cl). A spectrum of the black corrosion products is shown in Figure 12 and consisted primarily of iron (Fe) and oxygen (O) plus lesser amounts of aluminum (Al), silicon (Si), sulfur (S), chlorine (Cl), calcium (Ca), chromium (Cr), manganese (Mn) and copper (Cu).

METALLOGRAPHIC EXAMINATION

Transverse cross sections through an area of minimal plate thickness loss, maximum plate thickness loss, and maximum corrosion product thickness were prepared for subsequent metallographic examination. In the as polished condition the corrosion in a lightly corroded area of the tank bottom underside is shown in Figures 13 and 14. A layer of mill scale was observed within the corrosion products that had been lifted by corrosion occurring underneath the mill scale layer (Figure 15). The thick corrosion product layer is shown in Figure 16.

SUMMARY OF FINDINGS

Tank failed due to accelerated corrosion of the bottom plate side exposed to the soil. Extensive thickness loss and 7 perforated holes were observed during the inspection of the tank. The existing cathodic protection system did not protect these areas. The presence of extensive thickness loss at the bottom plate, perforation, through thickness holes due to corrosion attack and review of historic data indicates the CP system was not adequate and failed to provide corrosion protection and extend the life of the tank adequately.

CASE HISTORY 2

This section describes the corrosion risk assessment of a double bottom aboveground storage tank. As part of the investigation an (1) on-site inspection, (2) cathodic protection system evaluation, (3) soil corrosivity study and metallurgical failure analysis was performed. These efforts are described in the following sections. 50 feet (15.24m) diameter tank was constructed on concrete ringwall in 1957. New second bottom was put in 1993. The nominal bottom plate thickness is 0.250 inch (0.1 cm). Galvanic anode cathodic protection system was installed during construction of the tank.

ON-SITE TESTING

POTENTIAL MEASUREMENT

In-situ potential measurements was performed by placing a copper/copper sulphate (CuSO_4) reference electrode in the electrolyte (sand between tank bottoms) and electrically connecting a high impedance potential measuring instrument, high impedance voltmeter, between the reference electrode and the top tank bottom (Figure 17). Potential measurements revealed that at least -850 mV instant OFF and 100 mV shift NACE CP criteria are not satisfied which indicates that there is no cathodic protection for the tanks.

CURRENT REQUIREMENT TEST

Current requirement test was performed to identify the number of anodes to be placed between the tank bottoms in order to establish cathodic protection of the tank bottoms. During this test, 15 feet (4.57 m) long randomly perforated PVC pipe was inserted in between the tank bottoms and then 15 feet (4.57 m) long carbon steel rod was inserted inside the PVC pipe. PVC pipe was used to avoid the contact between carbon steel rod and the tank bottoms. In this case, carbon steel rod is the auxiliary electrode (Figure 18).

External power source is connected to the auxiliary electrode and the current is increased in steps up to 10 amperes. Reference electrode is placed in other ports for the potential measurements. Even with increase in current settings to the maximum in the external power source unit, there was no increase in potential reads (Figure 19) which indicates low conductivity of the electrolyte and that large amount of current is required to achieve -850mV minimum NACE CP criteria.

The findings of the site visit are as follows:

1. During CP assessment, it was noticed that at most of the locations the sand was not in contact with the top bottom plate. At the time of testing, tank was full. It should be noted that CP will be

ineffective at the locations where the sand is not in contact with the bottom plate and accelerated corrosion could take place at these locations.

- From the CP survey, it was observed that a large bare surface has to be protected. So, large amount of current is required to protect the large bare surface of the tank bottom.
- As the area around the tank is lined, the anodes should be placed in between the two bottom plates.
- Since a large amount of current is required to protect the large bare surface of the tank bottom, several anodes have to be installed in between the two bottom plates. Careful attention has to be paid to avoid placing of the anodes too close to each other and to the tank bottoms. If the anodes are in close proximity to one another, there is a possible threat of hydrogen generation when CP is in place which could result in unacceptable risk of hydrogen gas ignitions. Hydrogen generation depends on pH, oxygen concentration and presence of magnetite on the bottom surface. Hydrogen generation should be considered and is considered a risk at less noble potentials in this application.

SOIL RESISTIVITY MEASUREMENT

Field measurements involved the use of four metallic pins driven into the ground outside the containment dike. The instrument supplies a current to the soil through two outer pin electrodes and the voltage difference is read between the two inner pin electrodes. To measure the soil resistivity at different depths, measurements were performed with different spacing (10, 15 and 20 feet) between the pins at the surface. Test results indicate that the soil is non-corrosive.

Table 3
Soil Resistivity Test results

Depth, ft	Resistance, ohms	Resistivity, ohms-cm
10	5.4	10341
15	3.5	10054
20	2.1	8043

LIQUID ANALYSIS

During site visit, liquid samples were collected (Figure 20) from the interstitial space between two tank bottoms of the storage tank. The collected samples were analyzed in the lab. The test results do not show any abnormality.

Table 4
Liquid Analysis results

Liquid sample No.	Conductivity μS	LPR mpy	Sulfates ppm	Chlorides Ppm	pH	Sulfides mg/L
1	176	2.56	42	3.37	6.54	<0.04
2	411	3.24	34	6.53	7.75	<0.04
3	187	2.4	112	3.25	7.33	<0.04

Electrochemical evaluation using Gamry potentiostat/Galvanostat 3000 unit was performed using the liquid as an electrolyte, saturated calomel electrode as the reference electrode, graphite as the auxiliary electrode and CS 1010 as the working electrode. During potentiostatic scan (Figure 21), a cathodic

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potential of $-1.022V_{CSE}$ was applied to the working electrode and the current corresponding to this potential was measured as 160 microamps for the exposed working electrode area of 8.3 cm^2 (1.29 inch^2).

ANALYSIS OF SAND

During site visit, sand sample was also collected from the interstitial space between two tank bottoms of the storage tank. The collected sand sample was analyzed in the lab. The test results are shown in Table 5. Moreover, corrosion rate was also predicted (Figure 22).

Table 5
Sand Analysis results

As Received Resistivity $\Omega\text{-cm}$	LPR mpy	Sulfates ppm	Chlorides ppm	pH	Moisture %	Redox mV	Sulfides mg/L
1,394	2.79	10	2.01	8.64	20	291.9	<0.04

SUMMARY OF FINDINGS

Considering the challenges with installation of anodes in between the tank bottoms, consideration of the injection of VCI/contact inhibitor between the tank bottom plates is recommended. A promising industrial practice is to introduce VCI materials under tank bottoms to either supplement existing CP systems or provide protection in its absence.

RECOMMENDATIONS

Different types of foundations are considered for aboveground storage tanks based on the surface, subsurface, and climatic conditions. The pad material, air gap and voids under the tank has a significant influence on the soil-side corrosion of the tank bottom and can influence the effectiveness and applicability of external cathodic protection. Moisture and presence of salty environments (C5) should be considered in corrosion mitigation strategy.

Reference electrodes and ER probes should be installed at various locations under the tank for monitoring the corrosion rate to determine the remaining life of the VCI.

- Reference cells should be installed under the tank. The investment is worth as we can achieve accurate potential readings by installing reference electrodes under the tank.
- ER probes need to be monitored on a monthly basis to ensure corrosion protection.
- The chim of the tank should be sealed to prevent intrusion of moisture.

For optimal corrosion protection utilizing the ring wall foundation, cathodic protection should be used. An impressed grid system utilizing mixed metal oxide ribbon anodes (MMO) coke breeze and VCI should be installed under the tank with an HDPE liner as a bearer in case of leaks and to prevent shallow ground water from migrating to the sand causing a highly corrosive environment.

- Cathodic protection should be designed for the life of the tank bottom.
- Reference cells should be placed under the tank.

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- VCI in conjunction with cathodic protection can last up to 15 years depending on the corrosiveness of the environment.¹¹
- ER probes need to be monitored on a yearly basis to ensure corrosion protection.
- Cathodic protection needs to be monitored on a yearly basis to ensure that criteria is met.
- The rectifier needs to be monitored on a bi-monthly basis.
- The chim of the tank should be sealed to prevent intrusion of moisture.

Corrosion protection can be achieved, provided care is taken in monitoring and quantifying the corrosion risk.

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Figure 2: Photograph showing Fuel storage tanks.



Figure 3: Photograph exhibiting perforated areas due to external corrosion. Perforated areas are randomly distributed.



Figure 4: Close up of a perforated area



Figure 5: Photograph showing the hole in the tank bottom as viewed from the outside of the tank. Note-circular hole in center is a drilled hole.



Figure 6: Photograph shows the locations of maximum corrosion product thickness and loss of thickness due to corrosion.



Figure 7: Photograph showing the hole in the tank bottom as viewed from the outside of the tank.



Figure 8: Photograph showing the hole in the tank bottom as viewed from the inside of the tank. Note-circular hole in center is a drilled hole.



Figure 9: Photograph at 7x showing the corrosion products on the underside of the tank bottom.

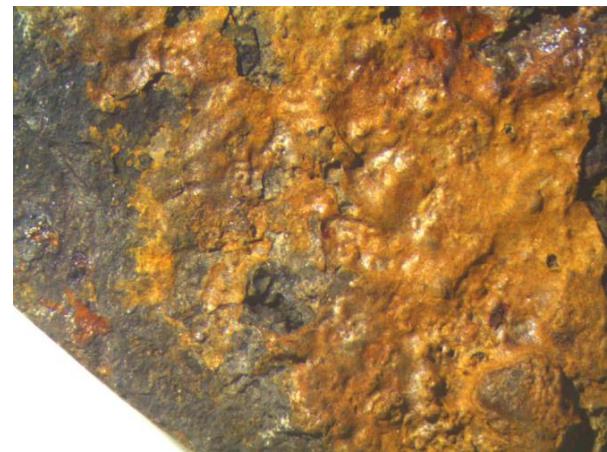


Figure 10: Photograph at 7x showing the corrosion products on the underside of the tank bottom.

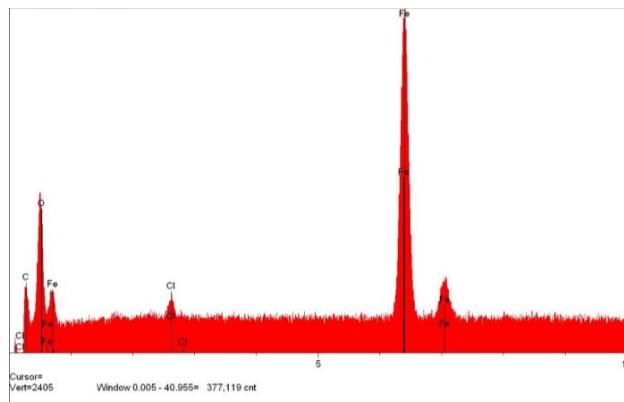


Figure 11: EDS spectrum of the bright orange corrosion products.

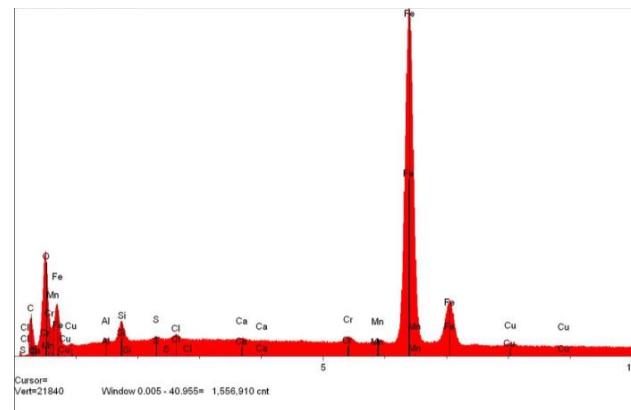


Figure 12: EDS spectrum of the black corrosion products.

Note the presence of chlorides and sulfur containing compounds.

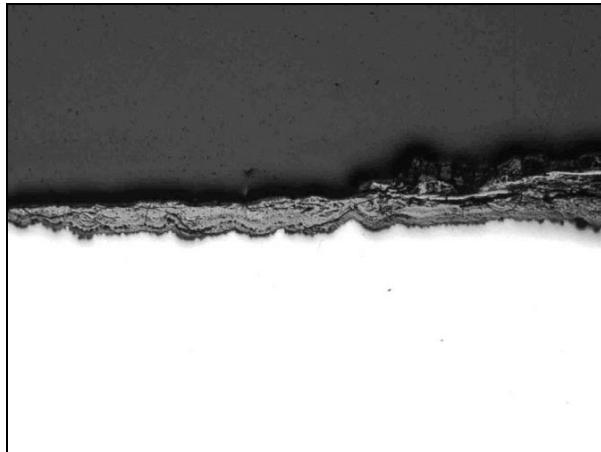


Figure 13: Photograph at 50x showing corrosion of the underside of the tank bottom in an area of minimal corrosion. As polished.

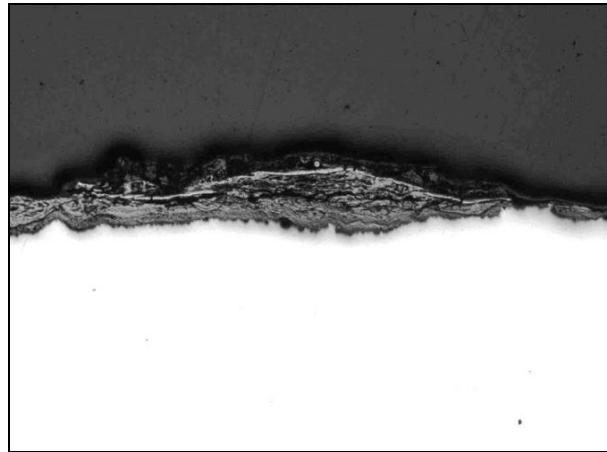


Figure 14: Photograph at 50x showing corrosion of the underside of the tank bottom in an area of minimal corrosion. As polished.

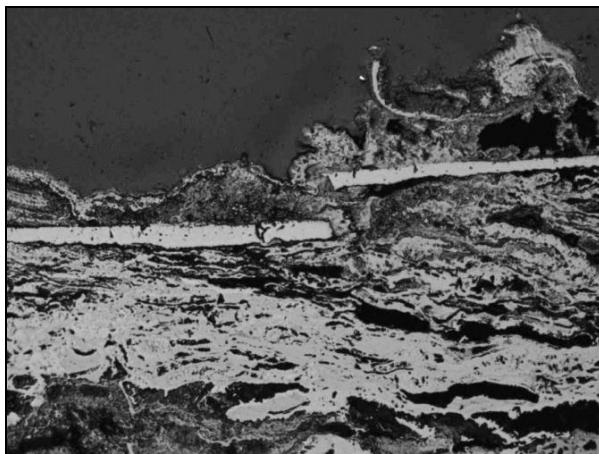


Figure 15: Photograph at 200x showing mill scale within the corrosion products. As polished.

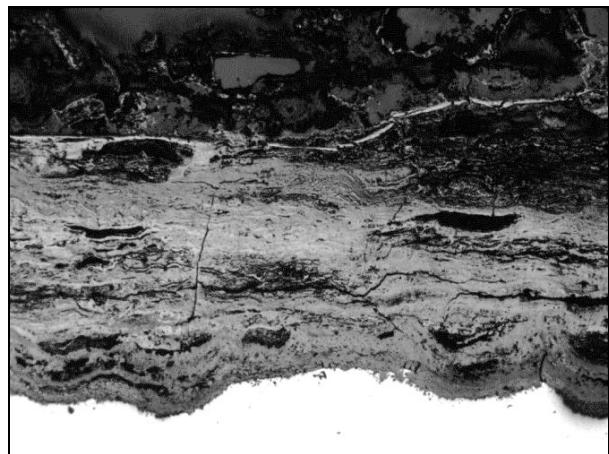


Figure 16: Photograph at 50x showing the thick corrosion products on the underside of the tank bottom. As polished.

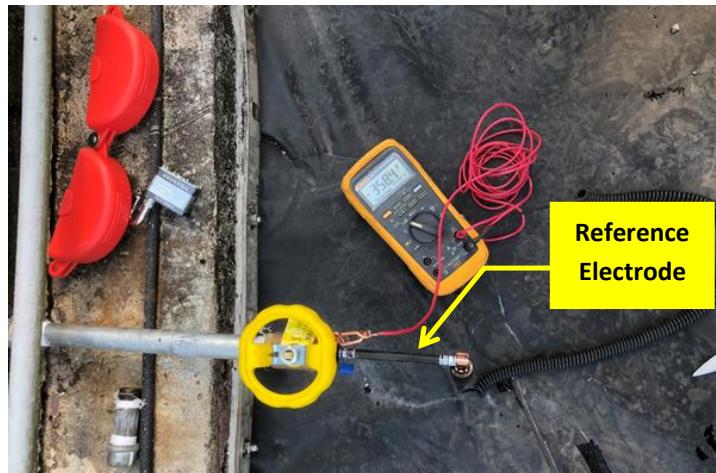


Figure 17: Photograph showing that reference electrode is pushed into the sand from the slot available between both tank bottoms and the tank bottom – to – sand potential was measured.



Figure 18: Photograph showing placing of auxiliary electrode in between the tank bottoms.

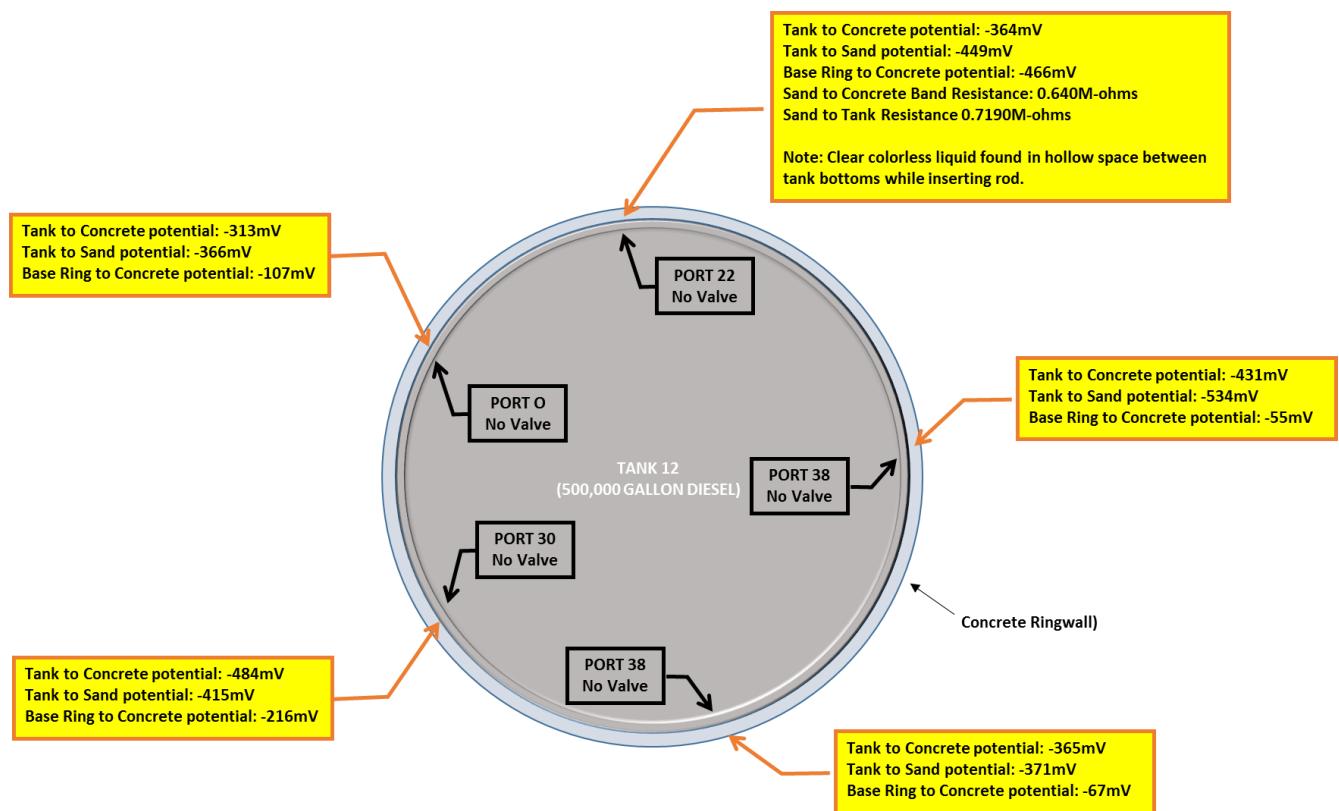


Figure 19: Photograph showing that at least -850 mV with the CP applied criteria is not satisfied which indicates that there is no cathodic protection for the tanks. Reference electrode is pushed into the sand from the slot available between both tank bottoms



Figure 20: Photograph showing collection of liquid samples from the space between the tank bottoms of the storage tank.

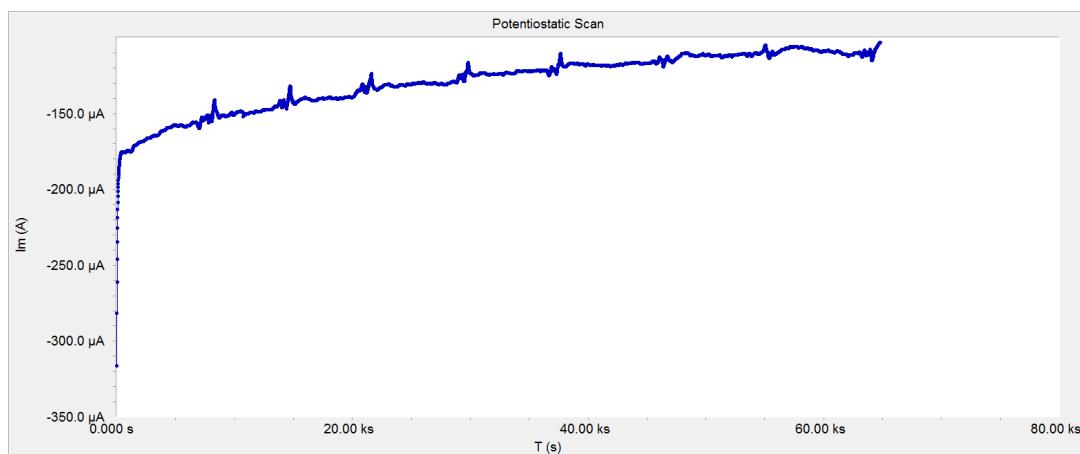


Figure 21: Photograph showing potentiostatic scan plot

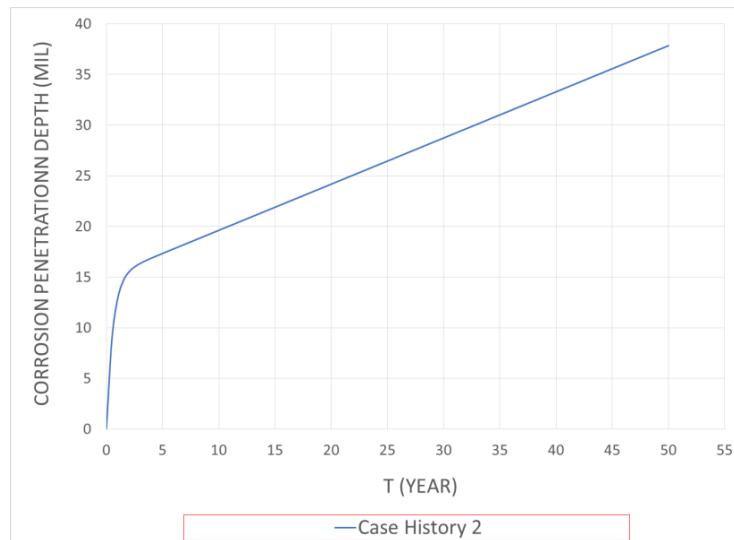


Figure 22: Photograph showing resulting penetration rates that can be used for remaining life determination.