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Evaluation of Cathodic Protection Effectiveness for Aboveground Storage Tanks

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ABSTRACT

Cathodic Protection (CP) is a mature technology and has been successfully used for decades to mitigate corrosion in a wide variety of applications within the oil & gas industry and beyond. CP has proven to be a long-term, robust tool for mitigation of Aboveground Storage Tank (AST) soil-side corrosion and its application has benefited from many AST specific improvements over time. However, the effectiveness of this technology is complicated by several factors; these include intermittent contact of floor plates with the tankpad; tankpad chemistry and moisture content; tankpad contamination during construction; in addition to the deficiencies in CP system designs specific to the tanks, installation, monitoring, evaluation, and maintenance. Further, it has been observed that AST CP systems' anode failures are not uncommon and are difficult to replace and supplement. A Pipeline Research Council International (PRCI)-sponsored study was conducted to quantify effectiveness of the CP systems for the AST application. CP data and floor inspection data were collected for several tanks with active CP systems. The American Petroleum Institute (API) 653 inspection reports were used to obtain tank bottoms wall-loss data and previous conditions, including new or replacement bottom timeline or the previous inspection result. This inspection data were used to estimate the soil-side corrosion rates of the tank bottoms. In addition, the CP data were used to determine the extent and duration of CP application to the tank bottom. The combined data, i.e., wall-loss from API 653 reports and CP data, were used to determine effectiveness of CP systems for AST application.

Key words: Cathodic Protection, Aboveground Storage Tank, Floor Inspection, API 653.

INTRODUCTION

The need to evaluate effectiveness of the CP systems for the tank bottom applications arose after completion of the PRCI-sponsored study[1] (published in 2018) focused on evaluating VCIs' performance for mitigating the soil-side corrosion of AST bottoms. The 2018 PRCI-study objectives included evaluating VCI effectiveness and comparing the VCI effectiveness data to active CP systems for ASTs that were achieving AMPP (NACE) cathodic protection criteria for corrosion control. In the 2018-PRCI study, the extensive amount of laboratory testing data and results indicated that VCIs are effective in mitigating corrosion; however, a historical comparison of CP system effectiveness with VCIs for ASTs could not be made due to a lack of documented CP effectiveness data. In addition, the CP performance criterion prescribed in the widely practiced standards NACE SP0193[2] and API 651[3] are non-specific, i.e., the CP effectiveness performance criterion is left to tank operators' judgement. In addition, the effectiveness of properly operating CP systems for tank bottoms is frequently complicated by the fact that soil-side corrosion control challenges are unique due to the variable corrosive characteristics of AST sand pads. Therefore, it was paramount to compile and review corrosion rate data for ASTs that had properly operating CP systems. Another PRCI-sponsored[4] (published in 2022) study was recently conducted to quantify effectiveness of the CP systems for a variety of AST applications. One of the objectives of the 2022-PRCI study[4] was to evaluate and document the effectiveness of working CP systems for a variety of field conditions by analyzing API 653[5] bottom plate inspection reports for a set of tanks with similar CP systems and tank foundation designs; this objective also included comparing CP systems testing and monitoring data to the to the localized corrosion rate data obtained from the API 653 floor inspections.

The following is also noted regarding comparison of industry CP performance criterion to developing industry criterion for VCI efficacy. One conclusion of the 2018-PRCI study[1] was that the VCIs mitigate soil-side corrosion of the tank bottom but not to extent mentioned in NACE SP0169.[6] SP0169 is specific to coated buried pipelines assets and is not applicable to the assets beyond the scope of that particular Standard Practice; this position is based on recent discussions with the SP0169 standard committee and authors' interpretation of the standard. In addition, one of the statements of NACE SP0169 Section 6.1.1 relates to the benchmarking of the effective corrosion control, more specifically, the statement specifies that a corrosion control measure is considered to be effective when corrosion rates are less than 1 mpy; the other statements in NACE SP0169 Section 6.1.1 state that a single criteria for evaluating the effectiveness of the CP systems might not be satisfactory for all conditions or for all locations across a structure. In addition, the statements include the following: use of any approach including a combination of methods or criteria to achieve adequate corrosion control is the responsibility of a user and should be based on the experience of the user and the unique corrosion conditions influencing the structure. Based on the data presented in the recent PRCI report (published in 2022),[4] it was determined that even the most effective CP systems seldom yield soil-side corrosion rates of 1 mpy or less over the entirety of a bare steel AST bottom. Overall, the benchmark set in NACE SP0169 Section 6.1.1 is not applicable to ASTs. Therefore, the conclusion derived in the 2018-PRCI report[1] that related the compared the VCIs' effectiveness with the SP0169 CP criterion is no longer applicable, and is being recanted.

The following approach was used to analyze for industry criterion on acceptable rates of AST soil-side corrosion. PRCI members provided operations data in the form of API 653 inspection reports and concurrent CP potential measurements and CP system output data for numerous ASTs. The floor inspection reports were used to identify the soil-side corrosion indications and remaining wall thicknesses at the time of inspection; these data, along with tank bottom installation dates, were used to estimate the ranges of mils-per-year (mpy) average rates of soil-side corrosion. The CP data included instant-off and polarized potentials, which were aligned with the tank operational periods. The perimeter and undertank instant-off and polarized potentials along with tank bottom CP current densities were also available for a few tanks. The CP data was then compared with the corrosion rates of soil-side corrosion indications. The review of more than hundred API 653 inspection reports indicated a consistent minimum remaining floor thickness criteria was used by industry. This remaining floor thickness criterion varied somewhat based upon the intended time of inspection interval, but most often equated to 5 mpy. Therefore, tanks with active CP and a large fraction of the soil-side corrosion indication corrosion rates greater than 5 mpy were considered to have CP systems with questionable effectiveness. A more detailed analysis was conducted for six tanks to identify a possible correlation between distributions of the indications and instant-off and polarized potential distributions.

FIELD DATA AND ANALYSIS

PRCI members provided API 653 inspection and CP reports for more than hundred tanks. Of these, data for 113 tanks were used to assess effectiveness of the CP systems for those tanks. The API 653 reports provide tank bottom inspection data and information on the tank bottom age such as the date of tank construction and dates of tank bottom replacement if applicable. Specifically, the reports contain tank bottom wall-loss data at the time of inspection. This information was used to estimate the soil-side corrosion rate of the tank bottom indications. In addition, the CP data was used to determine the extent and duration of CP application to the tank bottom. The combined data, i.e., API 653 report and CP data, were used to determine effectiveness of CP systems for field application. Detailed data for each tank are provided in the PRCI report.[4] The tank CP systems were evaluated based on several parameters described in Table 1. These parameters included tank dimensions, soil-side indications in latest API 653 inspection report, highest corrosion rate, assessment of the CP data with the -0.850 V off and 100-mV polarized potential criteria, and tank bottom CP current density.

Table 1
Description of Various Parameters Used for Analysis of Tank Inspection Data

Parameter	Description
Tank dimensions	Bottom diameter and height are reported for each tank.
Soil-side indications	Number of soil-side indications listed in the API-653 report are listed. The number of indications is reported when remaining wall thickness was below the reporting threshold.
Highest corrosion rate	Whenever available, the corrosion rate of the deepest soil-side indication is reported. The corrosion rate at the indications were calculated using the API 653 inspection year and the bottom installation year. The highest corrosion rate value is reported even when there was no recorded soil-side remaining wall thickness below the reporting threshold.
CP Criterion assessment	Annual CP system data surveys were performed for the tanks. CP systems on- and off-potential measurements were available for most of the tanks. In addition, polarized potentials were also available for some tanks. Instant off potentials and polarized potentials were assessed for their compliance with the -850 mV and 100 mV criteria. The following assessment notes were made: • Off yes: all measured instant-off potentials met -850 mV criterion. • Off mostly yes: if approximately 10% or less potentials did not meet the criterion, but remaining measurements met the criterion, it was noted that instant-off potentials mostly met the criterion. • Off sometimes yes: if less than 50% but more than 10% off the instant-off potentials met the criterion, it was noted that off-potentials sometimes met the criterion. • Off no: all measured instant-off potentials did not meet -850 mV criterion. • Off mostly no: if approximately 10% or less potentials met the criterion, but remaining measurements did not meet the criterion, it was noted that instant-off potentials mostly met the criterion. • Off sometimes no: if less than 50% but more than 10% off the instant-off potentials did not meet the criterion, it was noted that off-potentials sometimes did not meet the criterion. • 100 mV yes: all polarized potentials met the 100-mV criterion. • 100 mV mostly yes: if approximately 10% or less polarized potentials did not meet the criterion, but remaining measurements met the criterion, it was noted that polarized potentials mostly met the criterion. • 100 mV sometimes yes: if less than 50% but more than 10% off the polarized potentials met the criterion, it was noted that off-potentials sometimes met the criterion. • 100 mV mostly no: if approximately 10% or less polarized potentials met the criterion, but remaining measurements did not meet the criterion, it was noted that polarized potentials mostly not met the criterion.

Table 1
Description of Various Parameters Used for Analysis of Tank Inspection Data

Parameter	Description
	• Not enough data: if the number of data points was less than five, it was judged that amount of data were insufficient.
Current density	Whenever available, the current density at the tank bottom, generated by the CP system, was calculated and reported.
Cathodic Protection Effectiveness	It was common practice in the floor inspection data analysis that the remaining wall thickness (RWT) threshold criterion equals a corrosion rate of 3-5 mpy over a multi-year inspection interval. The RWT number is typically selected as the threshold to initiate repairs on all floor plates where corrosion indications indicate metal loss equal to, or in excess, of the RWT. This indicated CP was not as effective as desired within those repair areas and led to the use of 5-mpy as the threshold for questionable CP effectiveness in this research. Thousands of corrosion indications, in excess of 5-mpy, were discovered in this group of data for cathodically protected ASTs. Yes: whenever tank bottom was completely inspected and soil-side indication corrosion rates were less than 5 mpy, the CP was stated to be effective. If a few (less than 10) soil-side corrosion rates were between 5-10 mpy, but most of the indications were below 5 mpy, CP was also judged to be effective. Questionable: If large fraction of soil-side indications corrosion rates were greater than 5 mpy, then the tank CP system's effectiveness was judged to be questionable. In some cases, only small fractions of the tank bottoms were inspected, and tank operator decided to end the inspections and replace the bottoms; in such cases, it was judged that CP systems' effectiveness were questionable.

The following points are noted regarding the CP potentials data that was available for analysis:

- Most of the potential data available for this work were the perimeter potentials. In some cases, the undertank data collected using the profile tubes were also provided.

- The polarized potential data was obtained by calculating the difference between the instant-off potentials and native potential. A common practice used widely and employed is to deactivate all rectifiers at a terminal and perform a depolarized survey at all test points. These static or native-state potentials are recorded and used as the baseline potentials for all the polarized potential evaluation and comparison with the 100-mV criterion.

- Regarding the undertank CP potentials, there are a variety of processes used by CP technicians when measuring potentials through profile tubes. Some Operators dictate the procedures to be utilized. The procedures used for collection of this data was not provided by the tank operators supplying the data.

- No potential data provided by the tank operators were listed as measured with respect to the undertank stationary reference electrodes.

- Finally, based on the analysis of the instant-off potentials, it was determined that there was sufficient contact between the tank bottoms and tanks pads, otherwise, the tank potentials would have spiked values due to concentration of the CP current in the in-contact areas only; such spiked instant-off potentials values were not observed. It is also noted that potential spikes also occur when a potential is measured above a close-coupled anode.

The tank inspection report data and CP effectiveness assessments for each tank are provided in the recent PRCI report.[4] In total, one hundred thirteen (113) tanks were evaluated. Of these, CP systems were found to have effectively mitigated soil-side corrosion on sixty-seven (67) tanks. The soil-side corrosion was judged to be not effectively mitigated in forty-four (44) tanks even with functional CP systems. Data for two (2) tanks were insufficient to make any informed judgement. A detailed data analysis of a sample tank is presented next.

Sample Tank Data Analysis

A new bottom was installed for the sample tank in 2012. The API 653 inspection was conducted in 2021. The MFL scan detected 3,347 soil-side corrosion indications with corrosion rates of 5 mpy or greater. A summary of the available CP data during 2018-2021 is listed in Table 2. The CP current density at the tank bottom ranged between 1.2-1.6 mA/ft^2. The tank CP system has 19 looped anodes located approximately 1-foot below the tank bottom; of these, twelve anode loops produced no current output during the 2020 CP survey, and thirteen anode loops had no current output during the 2021 CP survey.

Table 2
Sample Tank CP Data Summary

CP Data Year	Rectifier Data		GB Resistance	Current Density (mA/ft2)	Anodes less than 0.1 A	# IRF Potentials ≥ -0.850	Potential Profile Graph Description	Perimeter Potentials OFF ≥ -0.850	Perimeter Potentials OFF ≥ 100mV shift
	V	A							
2018	9.1	44.9	0.2	1.4	no data	no data	no data	1 of 8	2 of 8
2019	11.7	39.9	0.3	1.2	no data	no data	no data	6 of 8	7 of 8
2020	8.7	51.3	0.2	1.6	12 of 19	10 of 37 39 of 43 33 of 36	#1 is not good; #2&3 are fine	7 of 8	7 of 8
2021	14.9	43.2	0.3	1.3	13 of 19	no data	no data	0 of 8 LOTO	1 of 8 LOTO

Notes:
- Current density is adequate but current distribution was likely limited by the failed anodes.
- Thirteen of nineteen anodes are inactive.
- The potentials under the tank met the criterion.
- Most perimeter potentials met both criteria for the last 3-years, but floor scan shows significant corrosion within 20 ft of the shell.

Regarding the tank's instant-off potentials, the potentials were measured through the three under tank profile tubes, running from east to west. The potential data were available for the 2020 survey. During the 2020 survey, most of the instant-off potentials measured through two profile tubes met the -0.850 V off criterion; however, only a few potentials measured through the third profile tube met the -0.850 V off-potential criterion. Regarding the perimeter instant-off potentials, all but three instant-off potentials during 2019 and 2020 met the -0.850 V off criterion, and one out of eight instant-off potentials met the -0.850 V off criterion in 2018. None of the potentials measured in 2021 met the 0.850 V off criterion in 2021; this may have been due to lock-out-tag-out (LOTO) of the CP system. Regarding the perimeter potentials, all but two polarized potentials during 2019 and 2020 met the 100-mV criterion, and two out of eight met the criterion in 2018. Only one out of eight polarized potentials measured during 2021 met the 100-mV criterion; LOTO of the CP systems may have depolarized the tank bottom, and hence perimeter polarized potentials were below the 100-mV threshold.

The tank CP system anode layout is presented in Figure 1. The anode currents were measured during 2020 and 2021 survey and differed with each other. The anode currents measured during 2020 and 2021 CP survey are listed in Table 3. The data in Table 3 confirm that anode loop JB1-1 to JB-11 and JB1-14 failures were recorded during 2020 and 2021 survey, and anode loops JB1-12 failure was detected during 2021 survey. It is most likely that current distribution towards the center of the tank was compromised due to the failure of the several anodes. The failed anodes are marked in Figure 1. The tank bottom's instant-off and polarized potentials were measured through the three profile tubes located below the tank bottom. The 2020 potentials are overlaid on the floor layout and presented in Figure 2.

The soil-side corrosion areas marked by green shades and dots in Figure 2 where the instant-off potentials are marked by dash lines, red and green dashes denote non-compliance and compliance with the -0.850 V off criterion, respectively. Similarly, the polarized potentials are marked by solid green lines, denoting compliance with the 100-mV criterion. Most of the corrosion was noticed near the perimeter of tank. It was noticed that one large zone of bottom plates, including the near center plates where most of the anodes had failed, did not experience soil-side corrosion; the zone is marked by purple zig-zag lines in Figure 2.

Following is noted from the analysis of the sample tank CP data and overlay of the CP data on the bottom layout:

- Most of the corrosion occurred within 20 to 30-ft from the perimeter of the tank. The first eleven anodes starting from the center of the tank had failed, but the bottom plate corrosion was focused near the tank shell.

- All the polarized potentials measured through the profile tubes in 2020 met the 100-mV criterion, however, the corrosion occurred on the plates where the polarized potential criterion was met. Similarly, two of the three profile-tube polarized potentials met the -0.850 V off criterion, and yet corrosion occurred on the plates even with compliance with the -0.850 V off criterion.

- Several sets of perimeter instant-off and polarized potentials were compliant with the respective criteria, and yet most of the corrosion was within 30 ft from the tank shell.

Table 3
Sample Tank Anode Currents Measured in 2020 and 2021 Surveys

Anode Number	2020 CP Current (A)	2021 CP Current (A)	Anode Number	2020 CP Current (A)	2021 CP Current (A)
JB1-01	0.0	0.0	JB1-11	0.0	0.0
JB1-02	0.0	0.0	JB1-12	4.9	0.0
JB1-03	0.0	0.0	JB1-13	4.6	4.7
JB1-04	0.0	0.0	JB1-14	0.0	0.0
JB1-05	0.0	0.0	JB1-15	6.5	4.6
JB1-06	0.0	0.0	JB1-16	6.0	6.9
JB1-07	0.0	0.0	JB1-17	13.5	15.1
JB1-08	0.0	0.0	JB1-18	6.4	5.9
JB1-09	0.0	0.0	JB1-19	6.2	6.1
JB1-10	0.0	0.0			

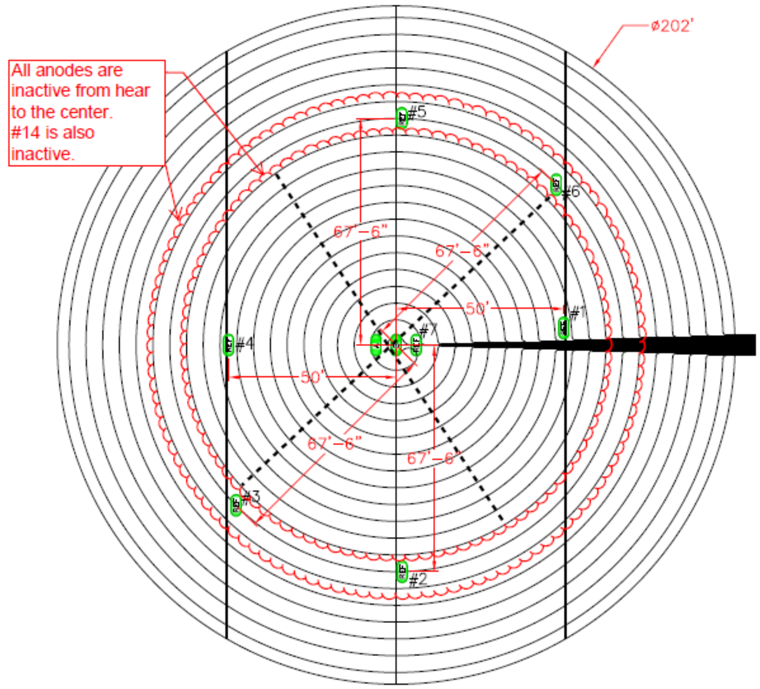


Figure 1: Sample tank CP anode layout with inactive anodes marked in red

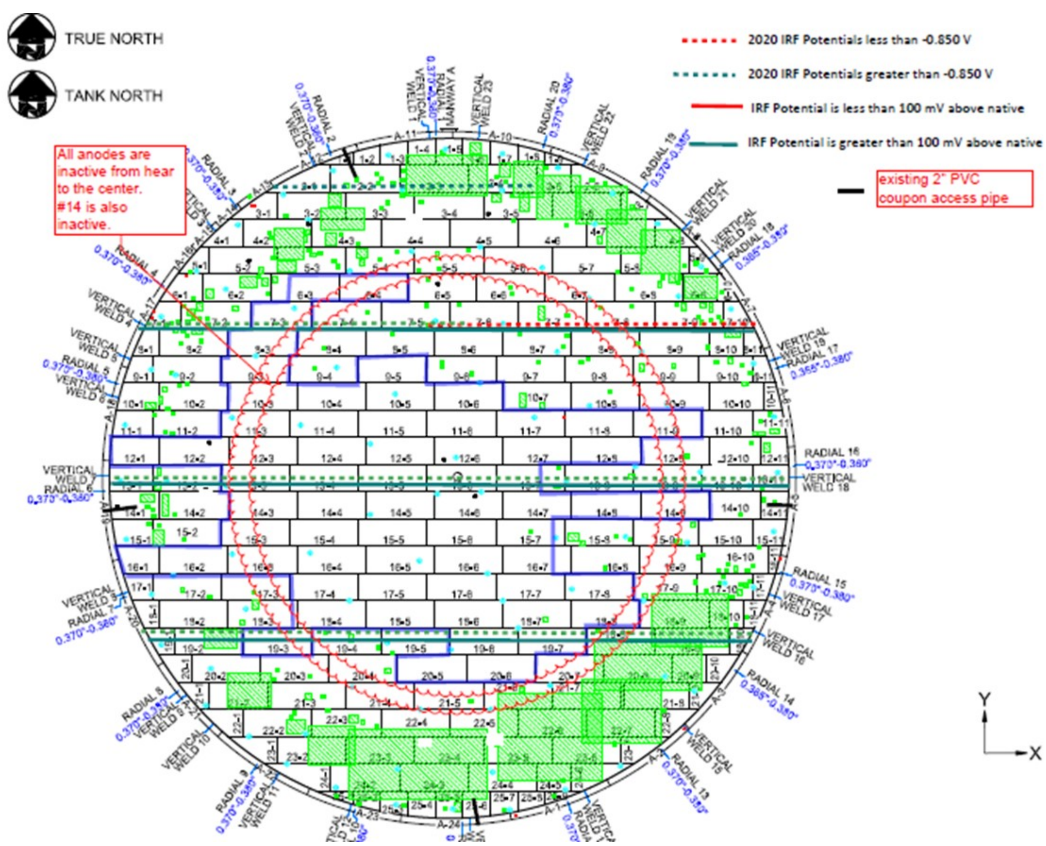
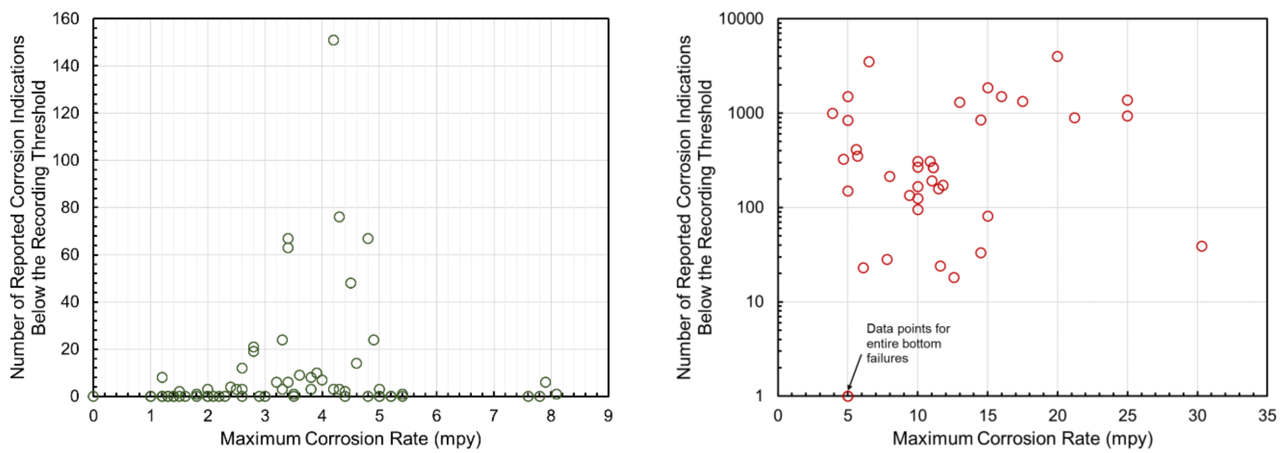


Figure 2: Sample tank bottom layout with soil-side corrosion areas marked by green shades and dots. The instant-off potentials marked by dashed green lines indicate compliance with the –0.850 V off criterion. The polarized potentials marked by solid green lines indicate compliance with the 100-mV criterion.

Soil-Side Corrosion Rate Distribution

The number of soil-side corrosion indications versus maximum corrosion rate data for the effective and CP effectiveness questionable tanks are presented in Figure 3(a) and Figure 3(b), respectively. The number of indications for the tanks with effective CP systems are generally less than 30. For a few tanks with effective CP, the indications are more than fifty, but the maximum corrosion rate is less than 5 mpy for those tanks. The soil-side indications for the CP effectiveness questionable tanks are generally much higher and so is the maximum corrosion rate compared to the effective CP system tanks. Logarithmic scale is used to represent the indications for the CP effectiveness questionable tanks in Figure 3(b).

Distributions of the indications with respect the corrosion rates for the tanks with effective CP and CP effectiveness questionable are presented in Figure 4(a) and Figure 4(b), respectively. As seen in Figure 4(a), most of the indications fall in the range of 1-5 mpy for the tanks with effective CP system. For the tanks with CP systems' effectiveness questionable in Figure 4(b), the indications have a wider range of distribution with respect to the corrosion rates. Nearly half of the corrosion rates are below 5 mpy, and remaining half are above 5 mpy, and almost 25% of the indications have corrosion rates higher than 10 mpy. It is obvious that the tank bottoms with the CP systems' effectiveness questionable had much more severe corrosion than the tanks with effective CP.



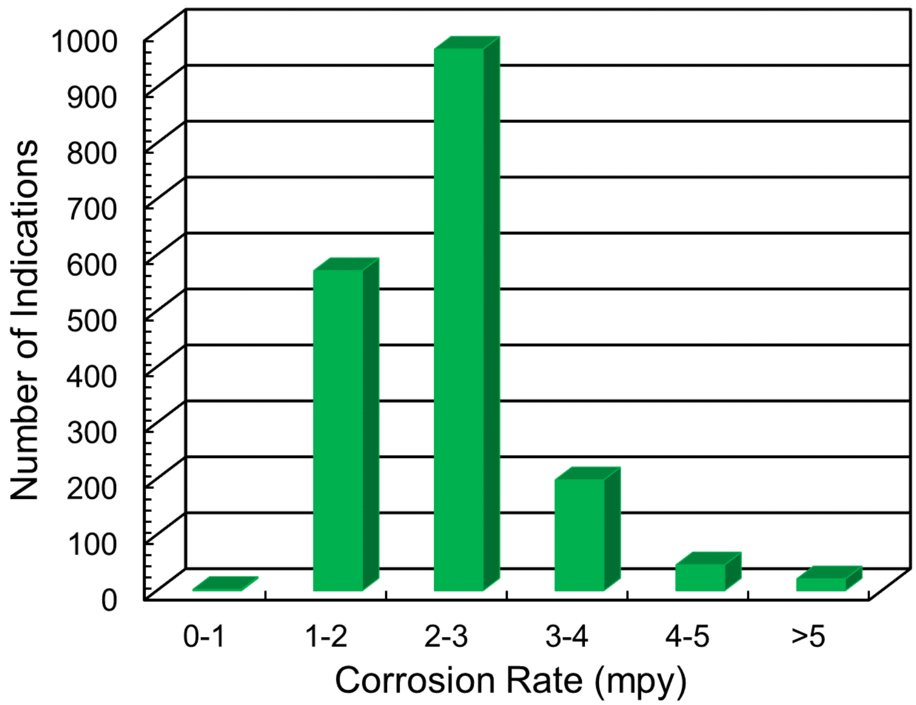
(a) Effective CP Tanks

(b) Tanks with CP Effectiveness Questionable

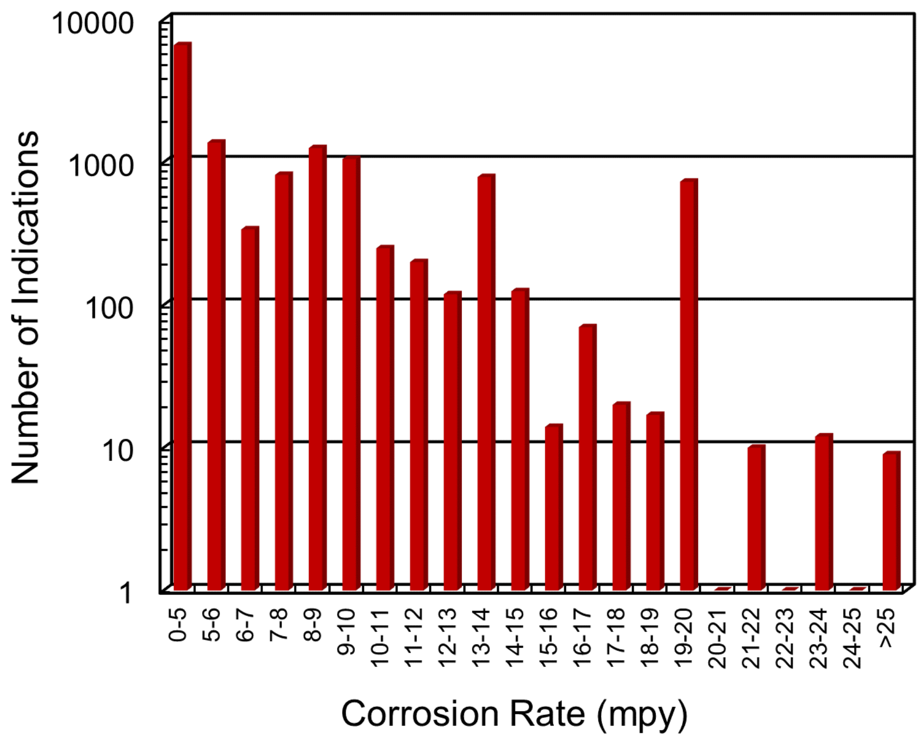
Figure 3: Number of soil-side corrosion indications versus maximum corrosion rate for (a) effective CP, and (b) CP effectiveness questionable tanks.

Distribution of Effective CP and CP Effectiveness Questionable Tanks with Instant-Off and Polarized Potential Evaluation

The tank data were segregated for the instant-off potential evaluations listed in Table 1, and a distribution plot representing the number of tanks with effective CP versus instant-off potential evaluation is presented in Figure 5(a). Similarly, a distribution plot representing number of tanks with effective CP versus 100-mV polarized potential evaluation is presented in Figure 5(b). Regarding the instant-off potential evaluation, most tanks with effective CP fall in the category of instant-off potential being mostly yes, followed by the tanks in the categories of instant-off potential being yes. The tanks in the categories of mostly no and not enough data rank third, followed by the tanks in the category of sometimes yes. There are two tanks each in the categories of no and sometimes no, there was no data for the remaining four tanks. Regarding the polarized potential evaluation, most tanks with effective CP fall in the category no data, followed by the tanks in the category of polarized potential being mostly yes. The tanks in the category of not enough data rank third. There was one tank each in the categories of yes, sometimes yes, and mostly no. There was no tank in the categories of no and sometimes no.

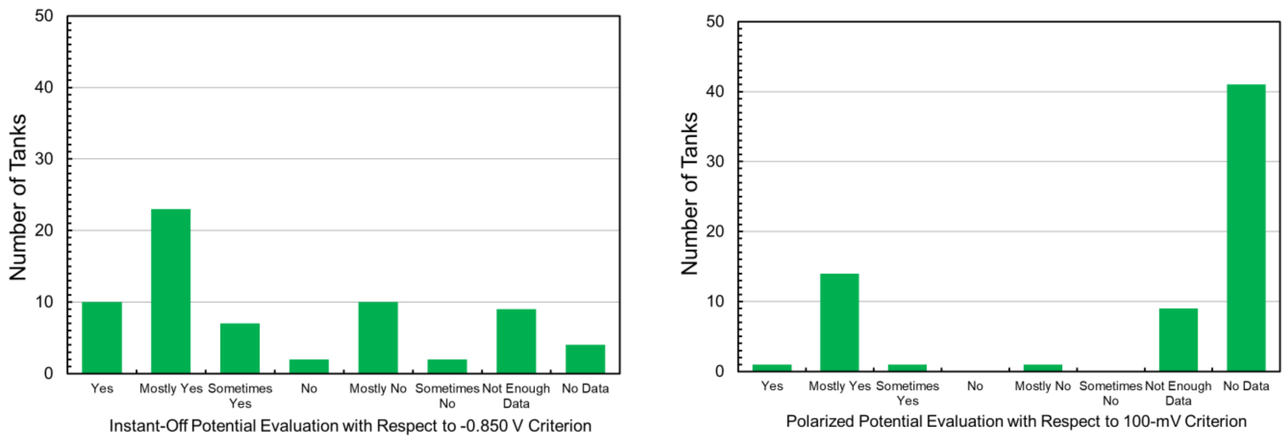


(a) Effective CP Tanks



(b) Tanks with CP Effectiveness Questionable

Figure 4: Distribution of soil-side corrosion indications with respect to the corrosion rates for tanks with (a) effective CP, and (b) CP effectiveness questionable tanks.



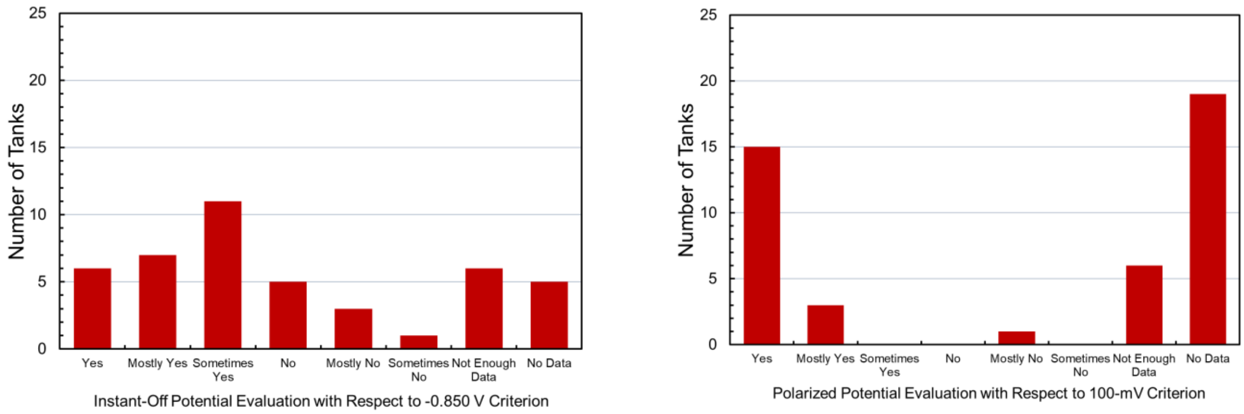
(a) Instant-off Potential **(b) Polarized Potential**

Figure 5: Distribution of the effective CP tanks with respect to (a) instant-off and (b) polarized potential evaluation.

A distribution plot representing the number of tanks with CP systems' effectiveness questionable versus instant-off potential evaluation is presented in Figure 6(a). Similarly, a distribution plot representing number of tanks with CP systems' effectiveness questionable versus 100-mV polarized potential evaluation is presented in Figure 6(b). Regarding the instant-off potential evaluation, most tanks with questionable CP effectiveness fall in the category of instant-off potential being sometimes yes, followed by the tanks in the categories of instant-off potential being mostly yes. There are equal number of tanks in the categories of yes, no, and not enough data. There are three tanks in the mostly no and one tank in the sometimes no category. The remaining four tanks fell in the category of no data. Regarding the polarized potential evaluation, most tanks with CP effectiveness questionable fell in the category no data, followed by the tanks in the category of polarized potential being yes. The tanks in the category of not enough data rank third. There were three tanks in the category of mostly yes, and one in the category of mostly no. Figure 5 and Figure 6 data are summarized in Table 4.

Table 4
Distribution of the Tanks in the Instant-Off and Polarized Potential Evaluation Categories

Category	Instant-off Potential		Polarized Potential	
	Effective CP	CP Effectiveness Questionable	Effective CP	CP Effectiveness Questionable
Yes	10	6	1	15
Mostly Yes	23	7	14	3
Sometimes Yes	7	11	1	0
Sometimes No	2	1	0	0
Mostly No	10	3	1	1
No	2	5	0	0
Not Enough Data	9	6	9	6
No Data	4	5	41	19



(a) Instant-off Potential **(b) Polarized Potential**

Figure 6: Distribution of the CP systems' effectiveness questionable tanks with respect to (a) instant-off and (b) polarized potential evaluation.

Distribution of Effective CP and CP Effectiveness Questionable Tanks with Cathodic Protection Current Density

Cathodic protection current density data were available for thirty-four (34) tanks. A distribution plot of the CP effective and CP effectiveness questionable tanks with respect to the CP current density range is presented in Figure 7. The CP current density ranged between 0.5 to 3.7 mA/ft^2 for the twenty-one tanks with CP systems' effectiveness questionable, and the current density ranged between 0.16 to 1.6 mA/ft^2 for the twelve tanks with effective CP systems. The current density data for the two sets of the tanks overlapped each other.

The CP effective and CP effectiveness questionable tanks versus current density data were further partitioned with respect to the instant-off potential evaluations. The distribution of effective tanks versus current density and instant-off potential evaluation categories is presented in Figure 8(a). As seen in Figure 8(a), for mostly yes and no categories, there is one tank each, and for the sometimes yes and mostly no categories, there are three and four tanks, respectively, and three tanks with the no data category. The distribution of CP effectiveness questionable tanks versus current density and instant-off potential evaluation categories is presented in Figure 8(b). As seen in Figure 8(b), there are five tanks each in the mostly yes and no categories, and six tanks in the sometimes yes category, the current density range for the four categories of the tanks overlap with each other; there are four tanks in the no data category and one tank in the yes category.

The CP effective and CP effectiveness questionable tanks versus current density data were further partitioned with respect to the polarized potential evaluations. The distribution of effective tanks versus current density and polarized potential evaluation categories is presented in Figure 9(a). As seen in Figure 9(a), there are seven tanks in the mostly yes category, one tank each in the sometimes yes and mostly no categories, and four tanks in the no data category; the current density range for the four categories of the effective tanks overlap with each other. The distribution of CP effectiveness questionable tanks versus current density and polarized potential evaluation categories is presented in Figure 9(b). As seen in Figure 9(b), there are fourteen and three tanks in the yes and mostly yes category categories, respectively, and four tanks in the no category; the current density range for the three categories overlap with each other.

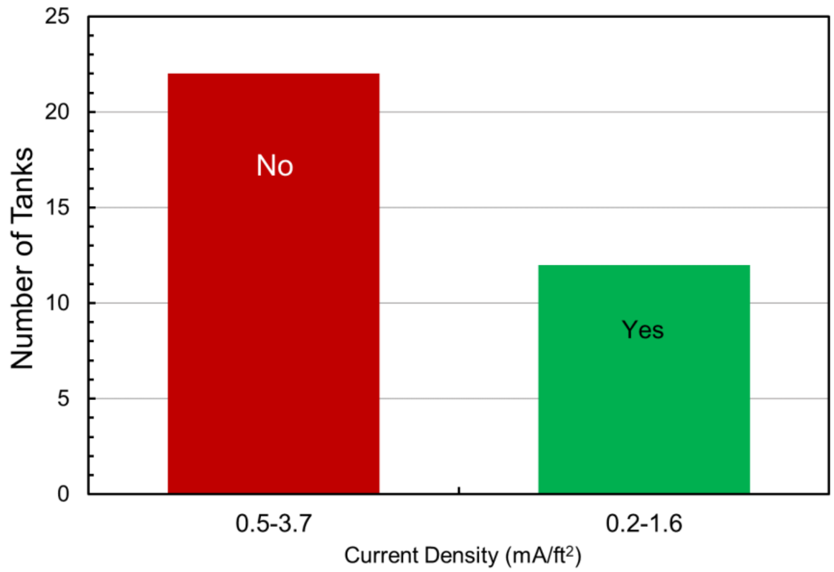
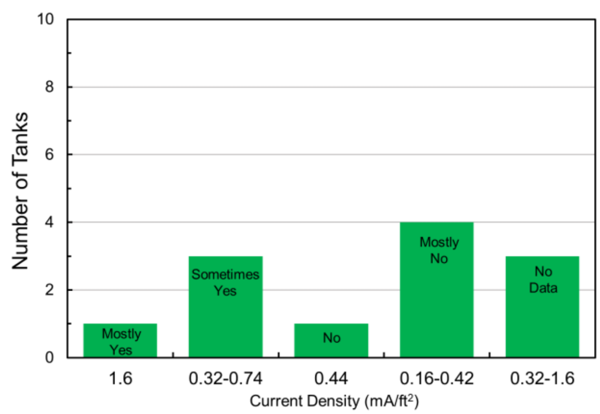
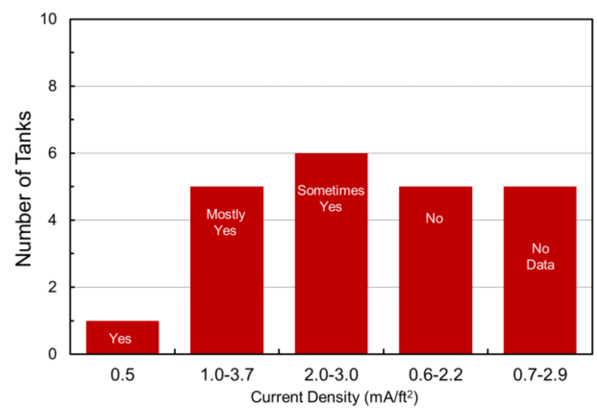


Figure 7: Distribution of the CP effective and CP effectiveness questionable tanks with respect to the cathodic protection current density.

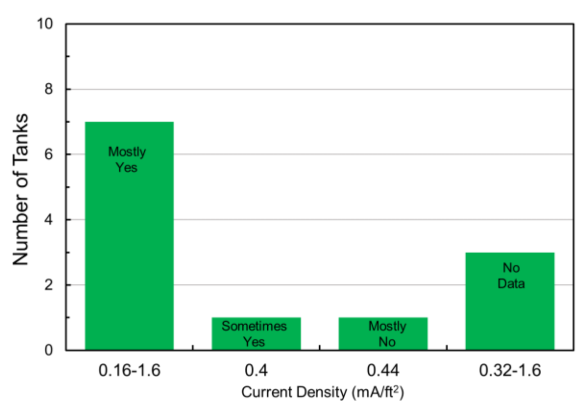


(a) Effective CP tanks

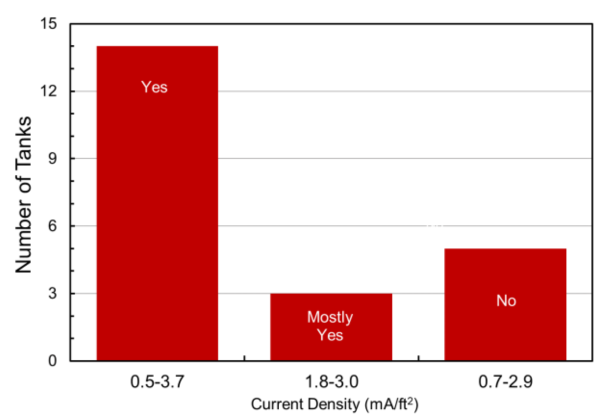


(b) CP Effectiveness Questionable

Figure 8: Distribution of the CP effective and CP effectiveness questionable CP tanks with respect to the current density and instant-off potential evaluations.



(a) Effective CP tanks



(b) CP Effectiveness Questionable

Figure 9: Distribution of the CP effective and CP effectiveness questionable tanks with respect to the cathodic protection current density and polarized potential evaluations.

Overall, it is found that the CP current densities for both effective and ineffective CP tanks overlapped each other. No specific trends with respect to the instant-off and polarized potential evaluations and CP current density range emerge for the effective and ineffective CP tanks.

CONCLUSION

CP is a mature technology successfully used for decades to mitigate corrosion in a wide variety of applications within the oil & gas industry and beyond. CP has proven to be a long-term robust tool for mitigation of AST soil-side corrosion and has benefited from many AST specific improvements over time. However, the effectiveness of this technology is complicated by several factors. These include intermittent contact of floor plates with the tank pad; tank pad chemistry and moisture content; tank pad contamination during construction; in addition, there are sometimes deficiencies in CP system designs specific to the installation, monitoring, evaluation, and maintenance of the AST systems. Further, it was observed in this research that AST CP systems' anode failures are not uncommon. Replacement of anodes in groundbeds that are installed below the tank bottoms are typically impossible to accomplish without the tank bottom removal which is expensive.

Floor scans conducted during API 653 tank inspections provide definitive data with which to evaluate the effectiveness of CP and VCI soil-side corrosion mitigation systems and technologies. The following conclusions were drawn from this work.

- Soil-side corrosion indications as listed in the API 653 inspection reports of one hundred and thirteen (113) tanks were surveyed. When this data was coupled with the CP system annual survey, the specific causes for CP system to adequately mitigate corrosion in forty-four (44) of the tanks were not apparent.

- Floor scan and CP data were also used to evaluate CP effectiveness 10-years after construction on several tank floors. Tank pad sand sample analysis and undertank mass-loss coupon data were also provided and analyzed for six (6) of these ASTs. Interestingly, there was minimal correlation between the distribution of the soil-side corrosion indications from the floor scans with instant-off and polarized undertank potential profiles or perimeter potential data.

- One of the objectives of this study included a fair comparison of VCI performance with CP; such comparison was not possible at the end of the Phase 1 study due to lack of comprehensive published data on CP performance for operational ASTs. This work addressed this gap by comprehensively evaluating CP systems' performance for ASTs by obtaining API 653 tank inspection reports, then studying the floor inspection scan data contained in those reports. To this end, floor scan data from (113) cathodically protected AST floors was collected and analyzed. The data revealed wide ranging soil-side corrosion rates with peak values being as high as 30-mpy.

- It was common practice in the floor inspection data analysis that the remaining wall thickness (RWT) threshold criterion corresponds to a corrosion rate of 3-5 mpy over a multi-year inspection interval. The RWT number is typically selected as the threshold to initiate repairs on all floor plates where corrosion indications indicate metal loss equal to, or in excess, of the RWT. This indicated CP was not as effective as desired within those repair areas, i.e., metal loss exceeding RTW, and led to the use of 5-mpy as the threshold for questionable CP effectiveness in this work. Thousands of corrosion indications in excess of 5-mpy were discovered in this group, i.e., CP effectiveness being questionable upon review of the data for the cathodically protected ASTs.

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