

Engineering Encyclopedia

Saudi Aramco DeskTop Standards

Maintaining Cathodic Protection Systems

Note: The source of the technical material in this volume is the Professional Engineering Development Program (PEDP) of Engineering Services.

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ENSURING ADEQUATE PROTECTION OF BURIED PIPELINES

Annual surveys of pipelines are conducted to monitor the effectiveness of cathodic protection systems and to identify the sources of any problems. Monitoring surveys consist of taking pipe-to-soil potential readings, verifying rectifier outputs, and measuring anode bed current output.

A typical pipeline survey includes the measurement of pipe-to-soil potentials at one kilometer intervals. Potential readings are recorded on the Pipelines Survey Data Sheet shown in Figure 1. Rectifier and solar systems operation checks are also recorded on Pipelines Survey Data Sheets. A separate Pipelines Survey Data Sheet is completed for each pipeline. For cathodically protected pipelines, the following data are entered on the Pipelines Survey Data Sheet for each test station beginning with the "0" kilometer test location:

- | | | |
|----|-----------------------------|---|
| 1. | KM | kilometer location of test station/bond box. |
| 2. | T. S. TYPE | type of test station (Standard Drawing AA-036907). |
| 3. | SOIL TYPE | |
| 4. | PIPE-TO-SOIL POTENTIAL (mV) | |
| | a. PIPELINE - ON | voltage of the pipeline that is being surveyed with the current flowing. |
| | b. CROSSING PIPELINE | identification of any crossing pipeline (NAME) and the voltage with current flowing (ON). |
| 5. | SHUNT | |
| | a. RATING | shunt rating in amperes (A) and millivolts (mV). |
| | b. READING | measurement taken and recorded in millivolts (mV) and amperes (A). |
| 6. | RECT | identification of the rectifier. |
| 7. | OUTPUT | rectifier output in Volts and Amps. |
| 8. | SUPP | support. |
| | a. AG | (above ground) to show whether a support is insulated (I) or equipped with a current drain (D.) |
| 9. | REMARKS | any additional data pertinent to survey. |

PIPELINES SURVEY DATA SHEET									
JOB INFORMATION									
DATE									
JOB NO.									
JOB NAME									
JOB LOCATION									
JOB STATUS									
JOB COMMENTS									
JOB CONTACT									
JOB APPROVAL									
JOB SIGNATURE									
JOB DATE									
JOB TIME									
JOB WEATHER									
JOB EQUIPMENT									
JOB MATERIALS									
JOB SAFETY									
JOB COST									
JOB BUDGET									
JOB VARIANCE									
JOB RISK									
JOB MITIGATION									
JOB MONITORING									
JOB REPORTING									
JOB RECORDING									
JOB ARCHIVING									
JOB BACKUP									
JOB RECOVERY									
JOB DISASTER									
JOB BUSINESS									
JOB CONTINUITY									
JOB RESILIENCE									
JOB ADAPTABILITY									
JOB INNOVATION									
JOB SUSTAINABILITY									
JOB ETHICS									
JOB COMPLIANCE									
JOB TRANSPARENCY									
JOB ACCOUNTABILITY									
JOB INTEGRITY									
JOB HONESTY									
JOB FAIRNESS									
JOB RESPECT									
JOB EMPLOYMENT									
JOB LABOR									
JOB UNION									
JOB CONTRACT									
JOB AGREEMENT									
JOB COOPERATION									
JOB COLLABORATION									
JOB PARTNERSHIP									
JOB ALLIANCE									
JOB NETWORK									
JOB COMMUNITY									
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JOB BELONGING									
JOB PURPOSE									

Pipelines Survey Data Sheet
Figure 1

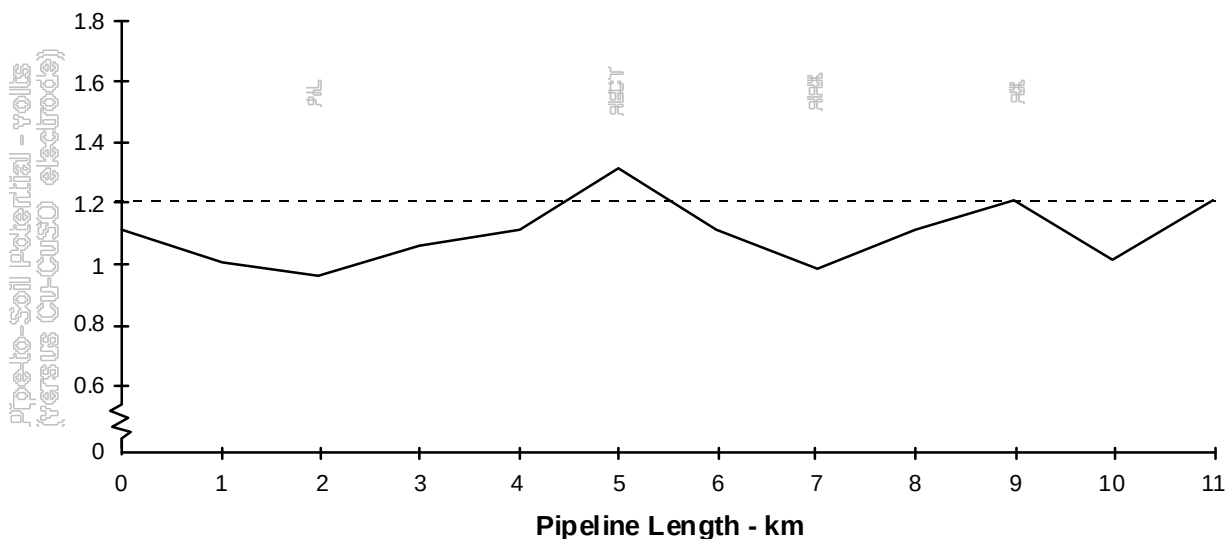
Criteria for Adequate Protection

According to Section 4.5.1 of Cathodic Protection of Buried Pipelines, SAES-X-400, a minimum negative pipe-to-soil potential of 1.2 volts and a maximum of 3.0 volts (with current applied and with reference to a copper-copper sulfate reference electrode) are required for buried pipelines. In General Instruction (G.I.) 428.003, Section 5, the following criteria are specified for cross-country pipelines.

- 5.1.1 In soil resistivity environments of 5,000 ohm-cm or greater, achieve a minimum of -1.2 volts pipe-to-soil potential with reference to a copper/copper sulfate reference electrode.
- 5.1.2 In soil resistivity environments of 5,000 ohm-cm or less, achieve a minimum of -1.0 volt pipe-to-soil potential with reference to a copper/copper sulfate half cell.

The Saudi Aramco cathodic protection criteria differ from other international standards. Many cathodic protection experts accept a potential of -0.85 volt or more negative as a criterion for adequate corrosion protection. The stricter Saudi Aramco criterion of -1.20 volts compensates for special local conditions found in Saudi Arabia. These conditions include high reference electrode contact resistance and large "IR" drops in dry soil.

Sections of a buried pipeline that require additional protection may be determined by plotting the measured potentials versus location. For example, the data from the Pipelines Survey Data Sheet in Figure 1 are plotted in Figure 2. According to the criteria in SAES-X-400, any readings less negative than -1.2 volts versus Cu-CuSO₄ indicate areas where corrosion is possible.



Plot of Potential Survey Readings
Figure 2

By comparing the most recent pipe-to-soil survey data with data from previous surveys, areas where there has been a reduction or loss of protection can be identified. Comparison of the data may also indicate the source of the trouble (e.g., a change in the rectifier or anode bed output). The remainder of this section will provide examples of cathodic protection abnormalities in rectifiers and anode beds and will explain corrective actions that should be taken to adequately protect buried pipelines.

Identifying Abnormalities in Cathodic Protection of Buried Pipelines

The following failures or defects in CP system components can cause a decrease or complete loss of cathodic protection current:

- AC failure
- Rectifier failure
- Failure of other power sources
- Failure of cables and cable connections
- Failure of anode lead wire or anode-to-lead wire connection
- Complete anode consumption
- Soil that has become too dry
- Gas blockage

Typical troubleshooting techniques and corrective actions for these failures and defects are described below.

AC Failure

If there is no rectifier output voltage and current, it is possible that the ac is interrupted. To verify ac power, the rectifier breaker is turned off and the voltage is measured across the ac input terminals. If there is no voltage across the ac input terminals, the ac has been interrupted. If there is voltage across the ac input terminals, the problem is not with the ac source.

Corrective Action - If AC has been interrupted, CP personnel should notify the electric company.

Rectifier Failure

Most rectifier troubles are simple and do not require extensive troubleshooting procedures. If there is ac but no rectifier output voltage and/or current, the problem is within the rectifier. One of the most common operating problems is rectifier voltage output with no current output. When there is rectifier voltage output but no current output, the rectifier voltage is turned down as far as possible. A short is created between the negative and positive dc output terminals of the rectifier. If current flows across the short, the problem is not with the rectifier.

Corrective Action - If the trouble is within the rectifier, CP personnel will troubleshoot and repair or replace the rectifier.

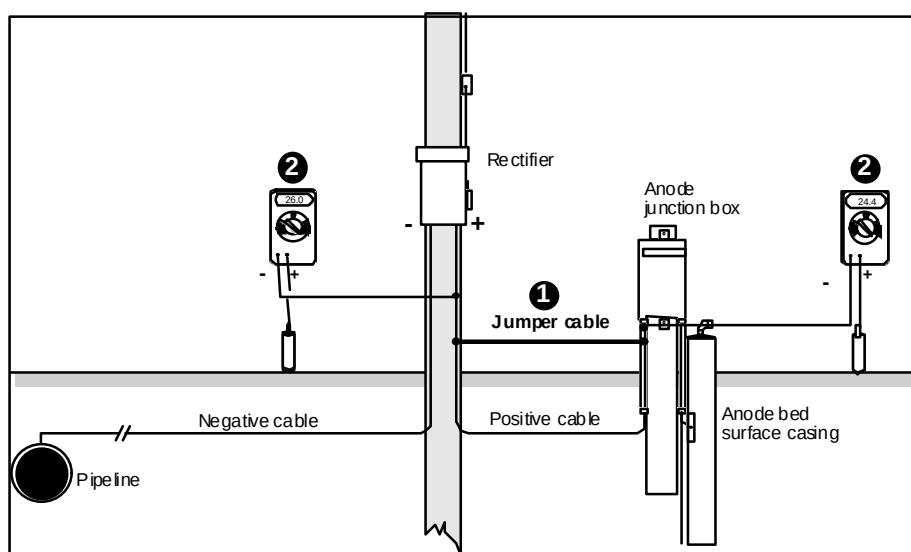
Failure of Other Power Sources

In Saudi Aramco, other power sources are used for cathodic protection systems (e.g., photovoltaic power systems and diesel motor driven generators.) A photovoltaic power system failure is diagnosed similar to a rectifier failure. A diesel motor driven generator failure is diagnosed similar to an ac power failure.

Corrective Action - If the trouble is within the power source, CP personnel should troubleshoot and repair the power source.

Failure of Cables and Cable Connections

Positive Rectifier Cable Failure - To determine if the positive cable has failed, a jumper cable is connected from the positive terminal of rectifier output to the positive terminal of the anode bed junction box (See "1" in Figure 3). If current flows through the jumper cable, the positive cable is damaged between the rectifier and the junction box. To verify that the positive cable is defective, a soil potential reading is taken at the rectifier positive terminal with reference to a Cu-CuSO₄ electrode (See "2" in Figure 3). This potential reading should almost be equal to the output rectifier voltage. A second potential reading is taken at the positive terminal of the anode bed junction box with reference to a Cu-CuSO₄ electrode. This potential should be at least 90% of the reading taken at the rectifier. All measurements are taken with the rectifier "on" and with everything operating as found. If the anode bed potential is zero volts or significantly less than the potential at the rectifier, the positive cable is defective. If the anode bed and rectifier potentials are the same, the problem is usually not the positive cable.



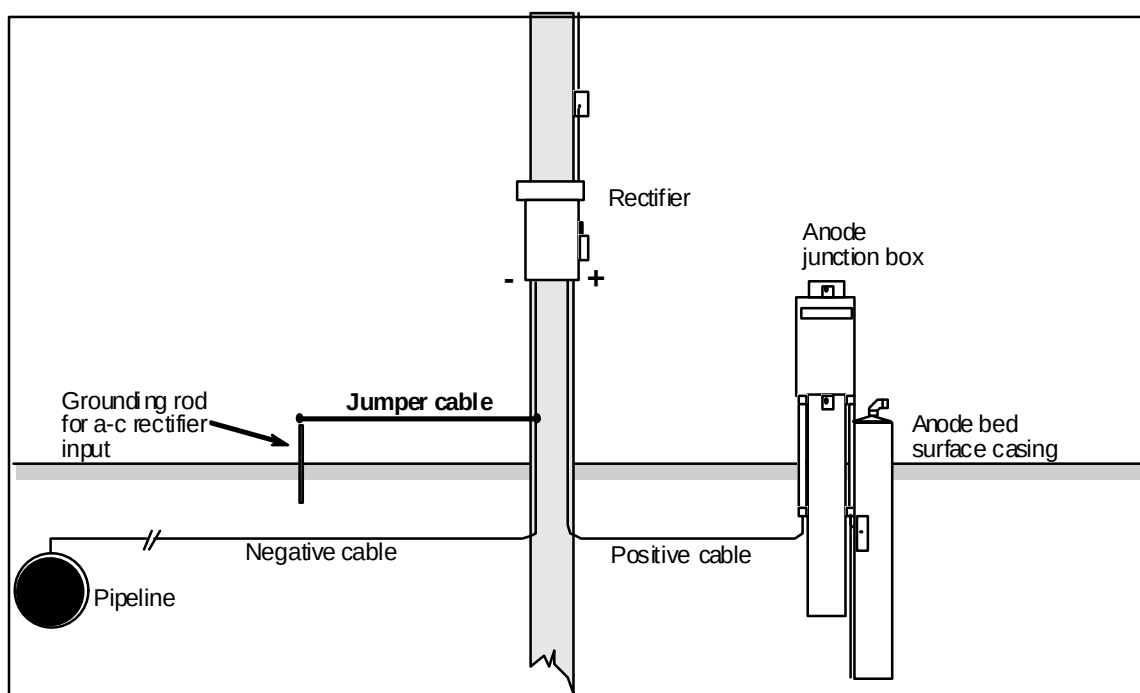
Troubleshooting the Positive Rectifier Cable

Figure 3

Corrective Action for Positive Rectifier Cable Failure - A broken positive cable causes a sudden failure of the CP system. In most cases, a broken positive cable is related to present or recent construction. If the cable has been cut and exposed, the cable damage can be identified quickly. If cable damage can not be visually detected, a pipe and cable locator is used to find the defect. Once the cable defect is found, it is repaired with a splice box. Below grade splices are not acceptable.

Negative Rectifier Cable Failure - To determine if there is a problem with a negative rectifier cable, the negative rectifier output terminal is shorted to a grounding rod (Figure 4). If current flows across the short, the problem is with the negative return line from the structure.

Corrective Action for Negative Rectifier Cable Failure - The cable defect is located with a pipe and cable locator. Once the cable defect is found, it must be spliced using a splice box. Below grade splices are not acceptable.



Troubleshooting the Negative Rectifier Cable

Figure 4

If the problem is not with the AC source, rectifier, or the positive and negative rectifier cables, then the anode bed is defective.

Failure of Cable Connections - Cable connections are located at each cable's termination points. For a typical CP rectifier system, cable connections can be found at the following locations:

- the rectifier ac input terminals and the dc positive and negative terminals,
- the rectifier positive cable and anode loads at the junction box, and
- the negative cable connection at the protected structure.

All of these connections are mechanically held and may loosen during the system operation. Loose mechanical connections increase the system's circuit resistance and reduce the output current. Also, due to the higher contact resistance of a loose cable connection, heat will develop. The heat will burn the surfaces and components near it, and may develop into a fire.

Corrective Action for Loose Cable Connections - All cable connections (ac & dc) in all the CP system equipment should be checked and tightened periodically, preferably during scheduled preventive maintenance.

Failure of Anode Lead Wire or Anode-to-Lead Wire Connection

Failures of anode lead wires or anode-to-lead wire connections are usually found when the individual anode current output readings are taken. The failure of an anode lead wire or anode-to-lead wire connection is revealed by a zero millivolt reading across the anode shunt in the anode bed junction box (see the Anode Bed Survey form in Figure 5).

Corrective Action - If the system output is the same and the remaining anodes are not being overdriven, no corrective action is required. If several anodes have failed and/or the remaining anodes are being overdriven to maintain adequate CP potentials, lead wire cuts are located and spliced.

In a deep anode bed, it is impossible to replace a single anode because of the manner in which the anode bed is constructed. The cause of the anode failure should be determined so that similar failures can be avoided in the future.

Complete Anode Consumption

Complete anode consumption is revealed by a zero or very low millivolt reading across the anode shunt (see the Anode Bed Survey form in Figure 5). A history of the annual anode readings should also show that the projected anode life has nearly been reached. Normally, the entire anode bed is affected at the same time. The life of a galvanic anode can be approximated by using the anode's average current output over the period of its operation.

Corrective Action - Complete anode consumption should be anticipated and a replacement anode bed should be planned. Anodes are replaced when they can no longer provide enough current to maintain the required level of protection.

ANODE BED SURVEY

UNIT NO.: _____

DATE: 05/10/87ANODE BED POTENTIAL: 27.4RECT. OUTPUT 30 V 22.6 A

ANODE OUTPUT POT: _____	ANODE OUTPUT _____	ANODE OUTPUT _____	ANODE OUTPUT _____	ANODE OUTPUT _____
1 = 0.0 ←	1 =	1 =	1 =	1 =
2 = 0.0 ←	2 =	2 =	2 =	2 =
3 = 4.5	3 =	3 =	3 =	3 =
4 = 3.1	4 =	4 =	4 =	4 =
5 = 0.0 ←	5 =	5 =	5 =	5 =
6 = 5.1	6 =	6 =	6 =	6 =
7 = 2.2	7 =	7 =	7 =	7 =
8 = 2.2	8 =	8 =	8 =	8 =
9 = 1.5	9 =	9 =	9 =	9 =
10 = 0.2 ←	10 =	10 =	10 =	10 =
11 = 2.2	11 =	11 =	11 =	11 =
12 = 0.1 ←	12 =	12 =	12 =	12 =
SUBTOTAL:				

TOTAL: 19.1 mV

Total current output = 19.1 A

REMARKS:

Anode shunts - 50A/50mV

Anode Bed Survey Form Showing Failed or Completely Consumed Anodes

Figure 5

Soil Has Become Too Dry

Soils in Saudi Arabia often become very dry in the summer. Surface anode beds installed in dry soil have a high anode bed resistance and may not provide sufficient current output for complete cathodic protection. High current output from an anode bed will also dry the soil near the anodes because of anodic chemical reactions.

Corrective Action - In anode beds that will be affected by seasonal dry soil, anode bed watering systems should be installed at the same time that the anodes are installed (see Saudi Aramco Standard Drawing AA-036346). The anode bed watering systems are designed to provide water to the area immediately around each anode. A regular watering schedule should be established for this type of anode bed during the dry season.

Gas Blockage

Anodes generate oxygen or chlorine gases on their surface as a result of chemical reactions with water in the soil. These gases normally migrate through the soil to the surface and the air. If the gas is trapped in the soil around the anode, the anode becomes insulated from the soil. As a result, increasingly higher voltages are required to deliver sufficient current to the structure being protected.

Gas blockage is generally caused in one of the following ways:

- The soil over the anode is sealed with asphalt or concrete.
- The anode is operated at a high current output so that it generates more gas than can quickly migrate through the soil to the surface.

Corrective Action - Deep anodes must be vented to the surface to prevent gas blockage. For surface anodes that are covered by asphalt, an area for venting should be provided.

Ensuring Adequate Protection of Onshore Well Casings

The most reliable method to ensure adequate protection of well casings is the casing potential profile; however, this method is extremely expensive and time consuming. A more practical method is to measure the casing potential at the wellhead using a remote Cu-CuSO₄ reference electrode.

Potential readings taken at the wellhead must be performed properly because these readings are used to monitor and adjust the level of cathodic protection for the entire casing. The remote electrode is placed at least 150 meters from the wellhead and away from anode beds, flowlines, and other buried structures. Wellhead potential readings should be taken at the same locations where potential readings were taken during the commissioning survey.

Casing potential readings are recorded on the Well Casing Annual Survey form shown in Figure 6. Potential readings are taken with the CP current "on" and "off." The "on" casing potential may include the potential due to any current returned through the flowline to another CP system. The "off" casing potential is checked for current returned to other CP systems through the flowline or bond boxes/junction boxes. A Swain Meter is used to measure dc returned by the well casing. When the current is "off," readings are taken to ensure that the well casing is returning less than 5 amperes to another CP system. If more than 5 amperes are measured, nearby CP system(s) that may be the source(s) of the current drain are turned off until less than 5 amperes are measured.

WELL CASING ANNUAL SURVEY (Single Well System)

WELL: _____ DATE: _____ SURVEYED BY: _____

A: AS FOUND WITH CP SYSTEM "ON"

1. System output: _____ Volts _____ Amps
2. Remote "ON" casing potential: _____ mV
- 3A. Swain meter (current flow) reading around the flowline: _____ A
- B. Swain meter (current flow) reading around the gas line: _____ A
(+ current flow is from well to flowline ; - current flow is from flowline to well)
4. List individual anode outputs on back:

B: TURN THE CP SYSTEM “OFF”

5. Voltmeter and ammeter reading: _____ Volts _____ Amps
6. Remote "OFF" casing potential: _____ mV
- 7A. Swain meter (current flow) reading around the flowline: _____ A
- B. Swain meter (current flow) reading around the gas line: _____ A
- NOTE: Total + current return must be less than 5 Amps (KHURAI/SOUTHERN fields must be less than 2 Amps)
- If current is - record reading, stop survey and inform CP engineer.
- C. Swain meter reading around wellhead (should be below 5 Amps): _____ A

SKETCH: show the flowline and other pipelines and the reference electrode location:

WELL HEAD

X
CP SYSTEM

C: TURN THE CP SYSTEM BACK "ON"

8. Flowline potential at wellhead (where it goes below grade): _____
9. Flowline potential, 2 km from well head: _____
10. Flowline potential at the GOSP: _____

Well Casing Annual Survey Sheet

Figure 6

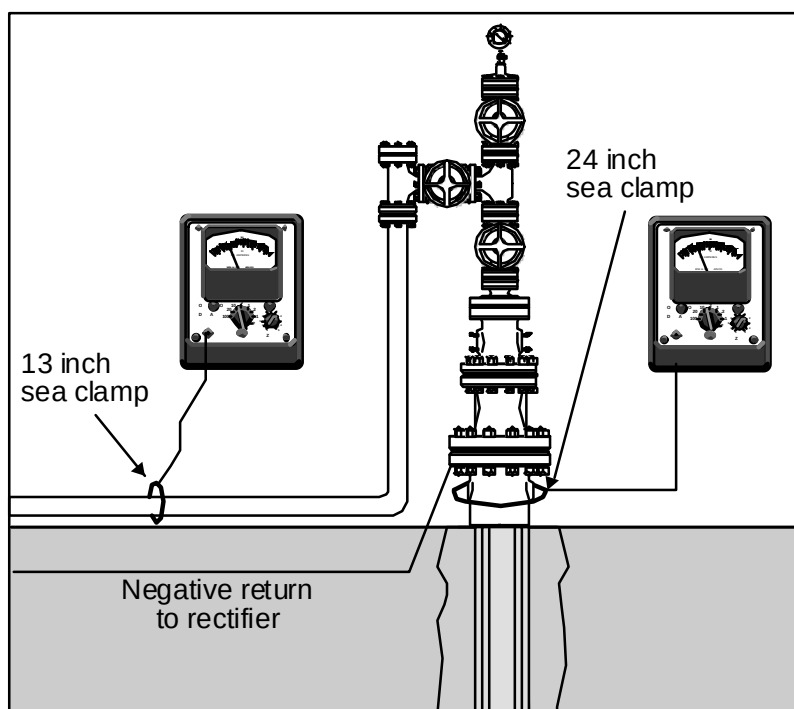
Criterion for Adequate Protection

According to Section 5.1.3 in Saudi Aramco G.I. 428.003, the well casing cathodic protection criterion is a minimum -1.0 volt casing-to-soil potential reading taken with a remote Cu-CuSO₄ reference electrode after the current has been off for at least 10 seconds.

Identifying Abnormalities in Cathodic Protection of Well Casings

The same rectifier and anode bed abnormalities that occur with pipelines can also occur with well casings. The troubleshooting techniques that were previously discussed for pipeline CP systems also apply to CP systems for well casings. Therefore, rectifier and anode bed troubleshooting techniques will not be described again in this section.

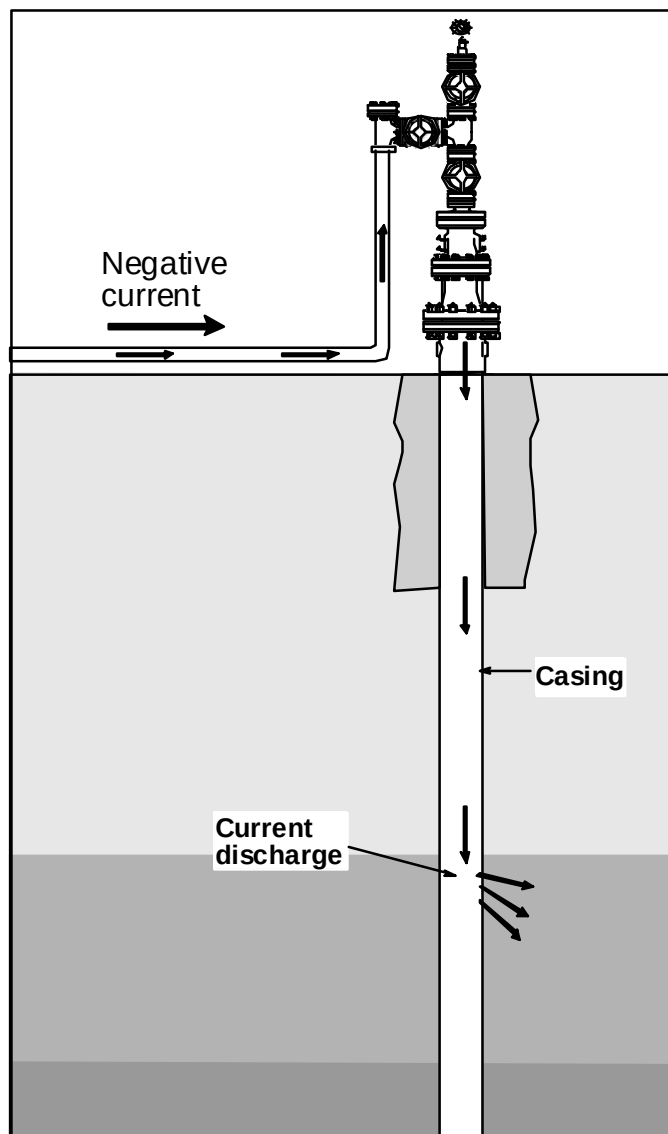
It is important to know exactly how much current is being returned to the rectifier. In interference situations, the current that is returned by the casing may be greater than the current output of the rectifier. For example, if the rectifier current output is 15 amperes and casing returns 18 amperes, the extra 3 amperes are probably being picked up by the casing from another CP system. The Swain Meter is used to measure the current returned by the well casing. Swain Meters can be used with various sizes of clamps. As shown in Figure 7, a 24 inch-clamp can be placed around the well casing. A 13-inch clamp can be placed around the flowline.



Swain Meters Around Flowline and Wellhead

Figure 7

The Swain Meter reading gives the algebraic sum of dc flowing in a well casing or wellhead flowline. To determine the magnitude and direction of the dc, Swain Meter readings are taken with the well casing cathodic protection dc source "on" and with the dc source "off." These readings are recorded on the Well Casing Annual Survey form. Positive current is defined as current which flows onto the well casing and returns to the well casing's cathodic protection dc source. Negative current is defined as current which flows in the opposite direction (from the flowline to the well casing and off the casing into the soil). Current which flows in the negative direction is discharged from the well casing as corrosion current as shown in Figure 8. In cases where negative current readings are taken with the well casing cathodic protection dc source "on," CP personnel should notify a corrosion engineer immediately because serious casing corrosion may be occurring.



Direction of Current Flow Measured by Swain Meter
Figure 8

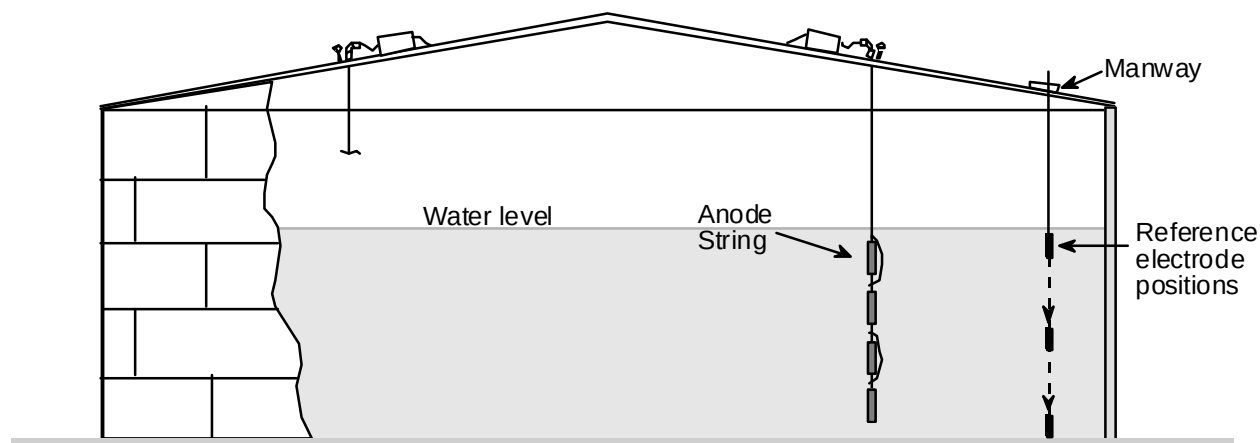
Ensuring Adequate Protection of Vessel and Tank Interiors

Tanks and vessels that contain water with a resistivity of 1,500 ohm-cm or less are required to have cathodic protection. These tanks and vessels may be protected by cathodic protection alone or by the combined use of cathodic protection and protective coatings. Cathodic protection may be provided by either galvanic or impressed current systems. Galvanic anodes are usually the most economical choice except for very large, uncoated tanks. For coated tanks and vessels, galvanic anodes (Galvalum III or Hydral 2B) have lower driving potentials and offer an adequate means of corrosion protection.

The methods that are used to ensure adequate protection of tank and production vessel interiors are different. It is relatively easy to measure structure-to-electrolyte potentials for tank interiors. It is more difficult to measure interior potentials of pressurized vessels. The following information will present the different techniques that are used to ensure adequate cathodic protection of vessel and tank interiors.

Tank Interiors

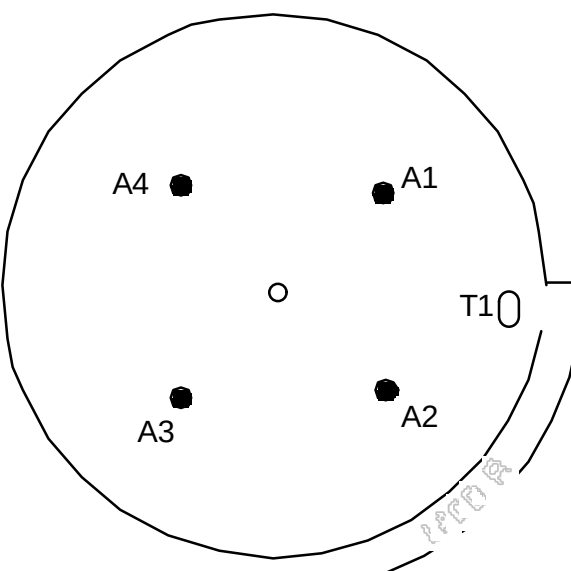
To obtain a potential profile inside a water storage tank, a silver-silver chloride electrode is lowered into the tank through a hatch or manway. (The silver-silver chloride electrode is used because it is not subject to contamination by water as a copper-copper sulfate electrode would be.) The hatch or manway should be as far away as possible from the anodes and close to the tank wall. Potential readings are taken near the bottom, center, and top of the water level as shown in Figure 9.



Potential Readings in a Water Storage Tank

Figure 9

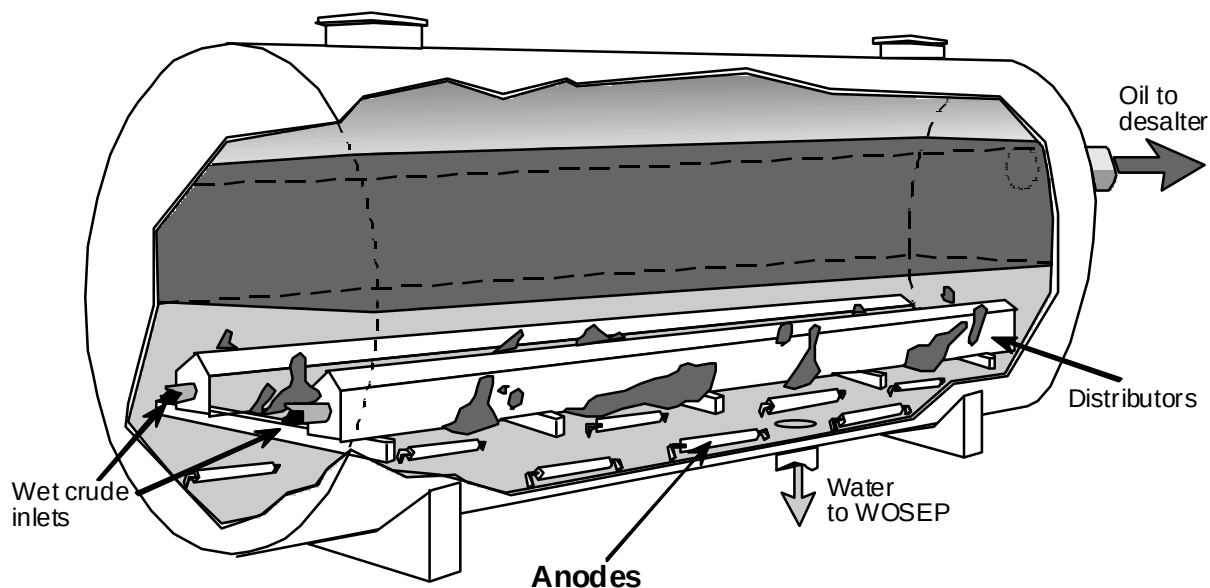
The potential readings are recorded on the Tank Internal Survey Data Sheet shown below in Figure 10.

<u>TANK INTERNAL SURVEY DATA SHEET</u>																								
PLANT: _____		TANK NO. _____		DATE _____																				
TYPE OF CATHODIC PROTECTION SYSTEM: <u>Impressed current</u>																								
RECTIFIER OUTPUT: (If Applicable): _____ 3 _____ VOLTS _____ 10 _____ AMPS																								
TYPE OF REFERENCE ELECTRODE: <u>Ag-AgCl</u>																								
				<table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="padding: 5px;">CODE</th> <th style="padding: 5px;">ANODE OUTPUT (AMPS)</th> </tr> </thead> <tbody> <tr><td style="text-align: center;">A1</td><td style="text-align: center;">2.5</td></tr> <tr><td style="text-align: center;">A2</td><td style="text-align: center;">2.5</td></tr> <tr><td style="text-align: center;">A3</td><td style="text-align: center;">2.5</td></tr> <tr><td style="text-align: center;">A4</td><td style="text-align: center;">2.5</td></tr> <tr><td> </td><td> </td></tr> <tr><td> </td><td> </td></tr> <tr><td> </td><td> </td></tr> <tr><td> </td><td> </td></tr> </tbody> </table>			CODE	ANODE OUTPUT (AMPS)	A1	2.5	A2	2.5	A3	2.5	A4	2.5								
CODE	ANODE OUTPUT (AMPS)																							
A1	2.5																							
A2	2.5																							
A3	2.5																							
A4	2.5																							
TEST No.	STRUCTURE -TO-WATER POTENTIAL (mV)																							
	TOP		MIDDLE		BOTTOM																			
	ON	OFF	ON	OFF	ON	OFF																		
1	1000		975		900																			
2																								
3																								
4																								
POTENTIAL OF PERMANENT REFERENCE ELECTRODE																								

Tank Internal Survey Data Sheet
Figure 10

Vessel Interiors

Vessels in wet, sour service are protected with both coatings and galvanic anodes. These vessels include wet crude production traps, dehydrators, desalters, and water-oil separators. The water separated inside dehydrators (Figure 11) is particularly corrosive because the water contains H_2S and CO_2 .

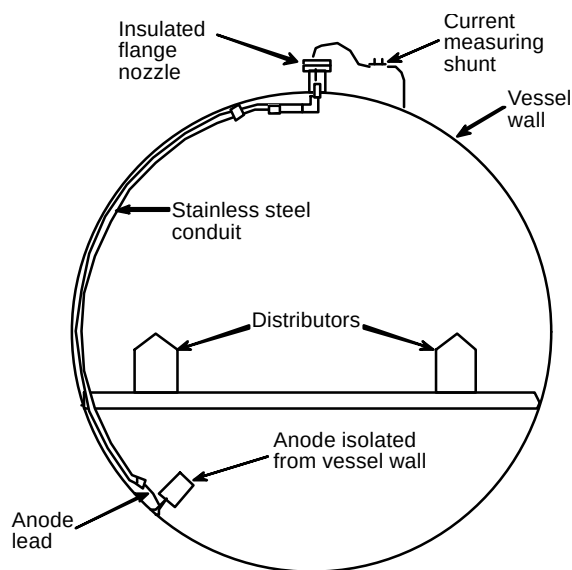


Sacrificial Anodes in a Crude Oil Dehydrator

Figure 11

Potential readings are not usually taken inside production vessels. Instead, the vessels are inspected and the anodes are replaced during scheduled Testing and Inspection (T&I), usually at five-year intervals. In June 1993, Saudi Aramco completed experimentation with zinc alloy anodes for dehydrators. The high temperature zinc anode efficiency was greater than 90%. It is recommended that vessels in Saudi Aramco be fitted completely with zinc anodes, which (according to calculations) can last for 12 years.

The only way to determine the current output of a galvanic anode inside a vessel is by attaching a lead from the anode to the outside of the vessel, as shown in Figure 12. The anodes must be electrically isolated from the vessel wall. A lead wire is installed from the anode body to the bottom of an insulated flange on top of the vessel. On the outside of the vessel, a wire that contains a shunt is connected from the top of the flange to the vessel wall. The current output of the anode is measured across the shunt so that the anode life and capacity can be determined. This procedure is only used during field testing of galvanic anodes.



Galvanic Anode Current Output Measurement in a Dehydrator

Figure 12

During a field testing program started in 1987, 10 kg and 22 kg Hydral 2B and Galvalum III anodes were installed in several hot, wet, sour crude dehydrators. The purpose of the test was to determine the life of the anodes and the size of anode that was required for a five-year life. The field test results showed that the life and efficiency of Hydral 2B and Galvalum III anodes were much less than that predicted by laboratory tests.

Criteria for Adequate Protection

The following criteria are found in SAES-X-500, Cathodic Protection of Vessel and Tank Internals:

- Section 4.3.1 - The design life of galvanic or impressed current anode systems shall be either 5 years, or the testing and inspection period, whichever is greater.
- Section 4.3.2 - Galvanic anodes in dehydrator vessels shall be designed using a 20% efficiency factor. Designs for all other wet crude handling vessels shall use an efficiency factor of 50%.
- Section 4.5.1 - The steel-to-water potential shall be more negative than -0.90 V (on) with reference to a silver-silver chloride electrode, or +0.15 V (on) with reference to a zinc electrode.

Identifying Abnormalities in Cathodic Protection of Vessel and Tank Interiors

Tank Interiors

When cathodic protection is applied to coated tank interiors, the CP current output should be adjusted to avoid excessively high structure-to-electrolyte potentials. Some coatings may be damaged if they are subjected to high current densities (high structure-to-electrolyte potentials). For coated tanks that are protected by impressed current systems, potentials are normally controlled at or near the criteria in Section 4.5.1 of SAES-X-500. Occasionally, magnesium galvanic anodes can cause localized coating damage due to high current densities on the metal close to the anodes. Aluminum alloy anodes seldom cause coating damage.

Vessel Interiors

Anode systems inside vessels are designed to protect the vessel for 5 years or the T & I period, whichever is greater. The anodes are inspected during T & I. If the anodes are not completely consumed, and if there are no visual signs of interior corrosion, the anodes may be replaced with similar anodes. If the anodes are completely consumed, and if there are no visual signs of interior corrosion, larger anodes should be considered. If the anodes are completely consumed, and if there are visual signs of corrosion, larger or additional anodes are definitely needed.

Ensuring Adequate Protection of In-Plant Facilities

Saudi Aramco electrically connects all below grade in-plant structures and cathodically protects them as a single unit. These structures include the following:

- Tank bottoms
- Piping/pipelines
- Rebar in foundations
- Bare copper grounding systems

Because some of these structures do not require cathodic protection, they are not monitored for adequate cathodic protection levels (e.g., copper grounding systems). Structures that are monitored include the following:

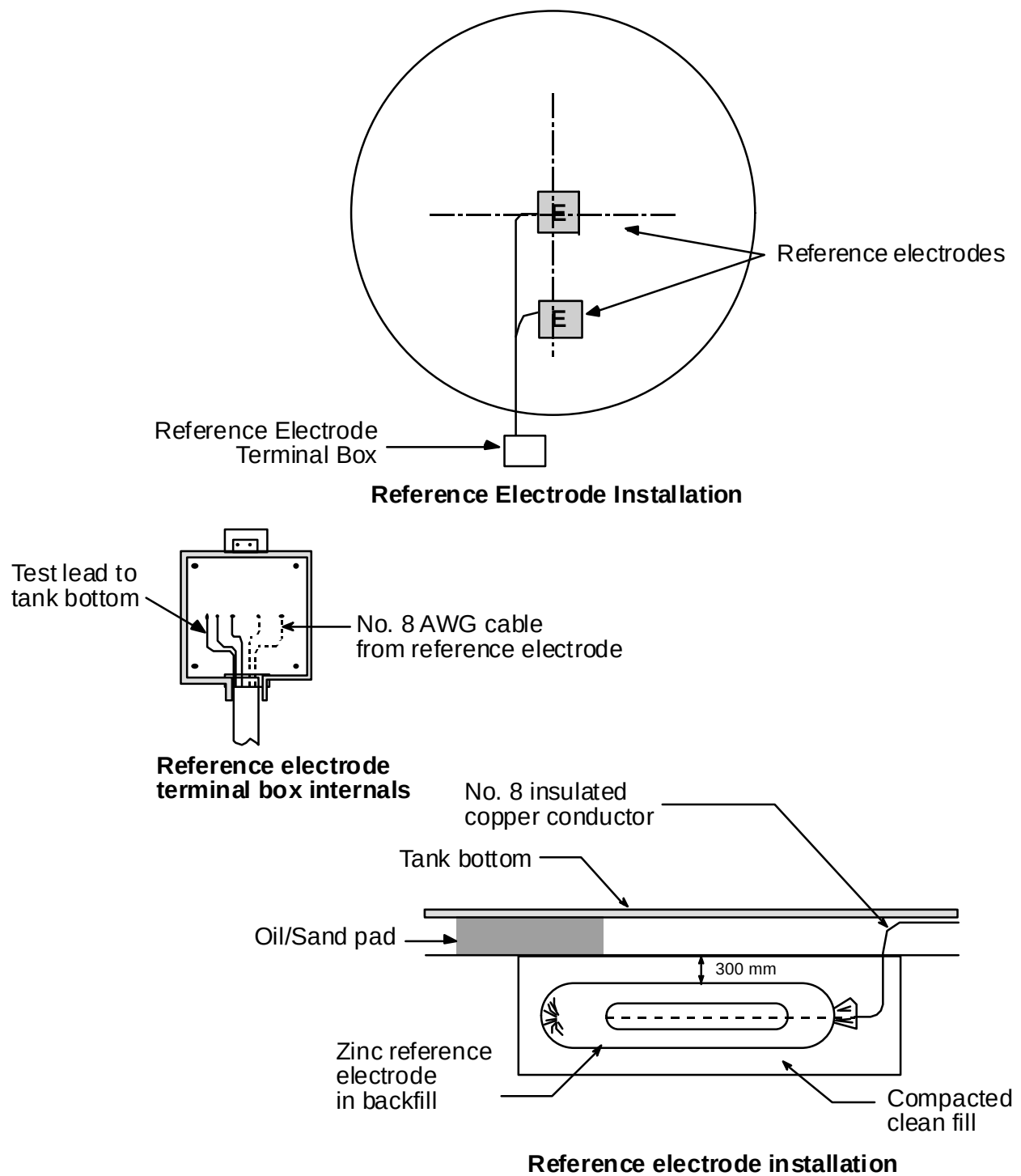
- Tank bottoms
- Hydrocarbon pipelines
- Firewater piping
- Buried valves

Tank bottom potentials are monitored with the use of permanent reference electrodes under the tank. Table 4.9.5 in Cathodic Protection In-Plant Facilities, SAES-X-600 states that all tanks shall have reference electrode(s) buried under the tank bottom plates as follows:

<u>Tank Dia. (Meters)</u>	<u>No. of Electrodes</u>	<u>Location of Electrodes</u>
< 20	2	Center and midway between center and edge
20 - 39	3	Center and equally spaced on radius line between center and edge.
40 - 79	4	Center and one each, equally spaced on 120 degree radius lines between center and edge.
80 - 99	7	Center and two each, equally spaced on 120 degree radius lines between center and edge.
> 100	9	Center and two each, equally spaced on 90 degree radius lines between center and edge.

Two additional reference electrodes shall be installed inside the ring walls at the tank periphery, spaced at 180 degrees.

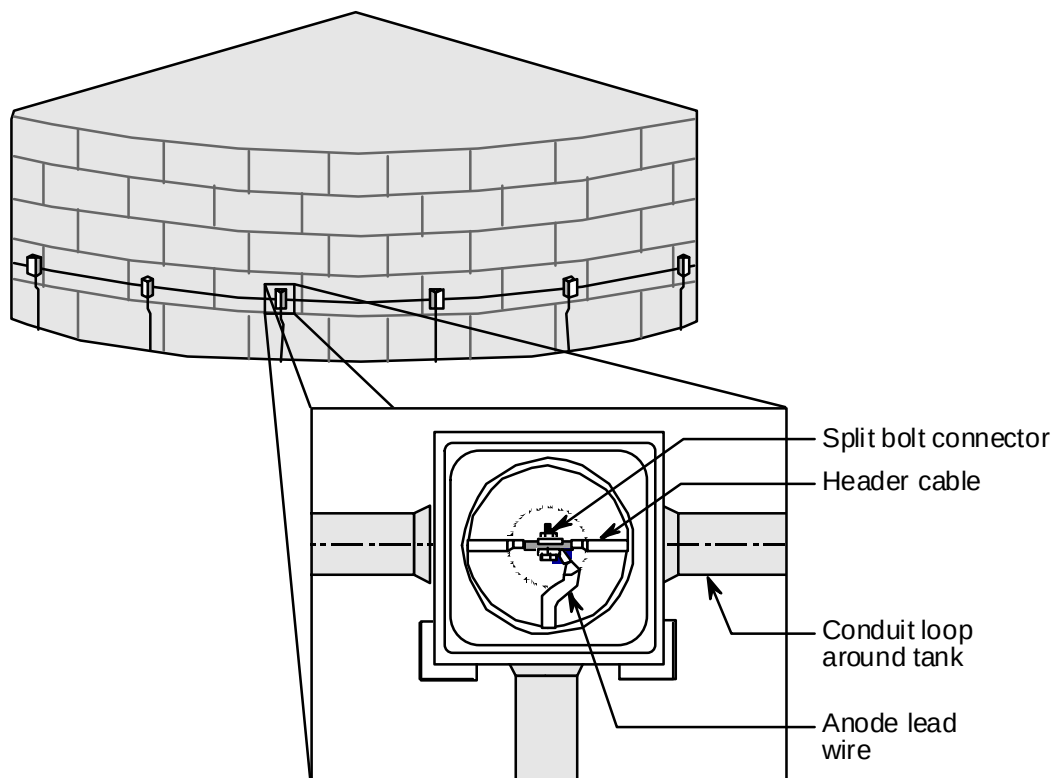
Figure 13 shows installation details for permanent reference electrodes from Saudi Aramco Standard Drawing AA-036355.



Reference Electrode Installation from Saudi Aramco Standard Drawing AA-036355

Figure 13

For anodes that protect exterior tank bottoms, Saudi Aramco has redesigned the anode lead wire-to-header cable connection, as shown in Figure 14. This design allows the current output of individual anodes to be measured by placing a Swain clamp on ammeter around the anode lead wire in the anode cable connection junction box.



Anode Cable Connection Junction Box from
Saudi Aramco Standard Drawing AA-036355

Figure 14

If permanent copper sulfate reference electrodes are not installed under the tank, readings are taken at the tank periphery at a point equidistant from the nearest anodes. The potential readings are recorded on the Tank Bottom Survey Data Sheet shown in Figure 15.

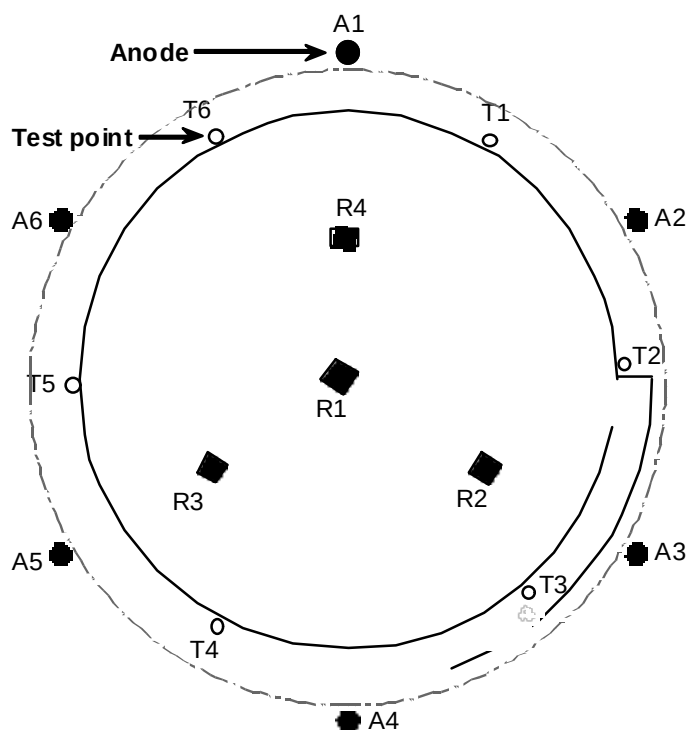
TANK BOTTOM SURVEY DATA SHEET

PLANT: Ju'aymah TANK NO. 1 DATE 01/22/88

RECTIFIER RATING: _____ VOLTS _____ AMPS

OPERATING OUTPUT 10.5 VOLTS 21.2 AMPS

TYPE OF REFERENCE ELECTRODE: _____



Copper sulfate reference electrode

TEST No.	TANK-TO-SOIL POTENTIAL (mV)	
	On	Off
T1	-1090	-802
T2	-1073	-811
T3	-1081	-818
T4	-1085	-805
T5	-1085	-800
T6	-1078	-799
T7		
T8		

ANODE No.	ANODE OUTPUT (AMPS)	ANODE No.	ANODE OUTPUT (AMPS)
1	3.8	5	3.3
2	3.7	6	2.5
3	2.9		
4	3.0		

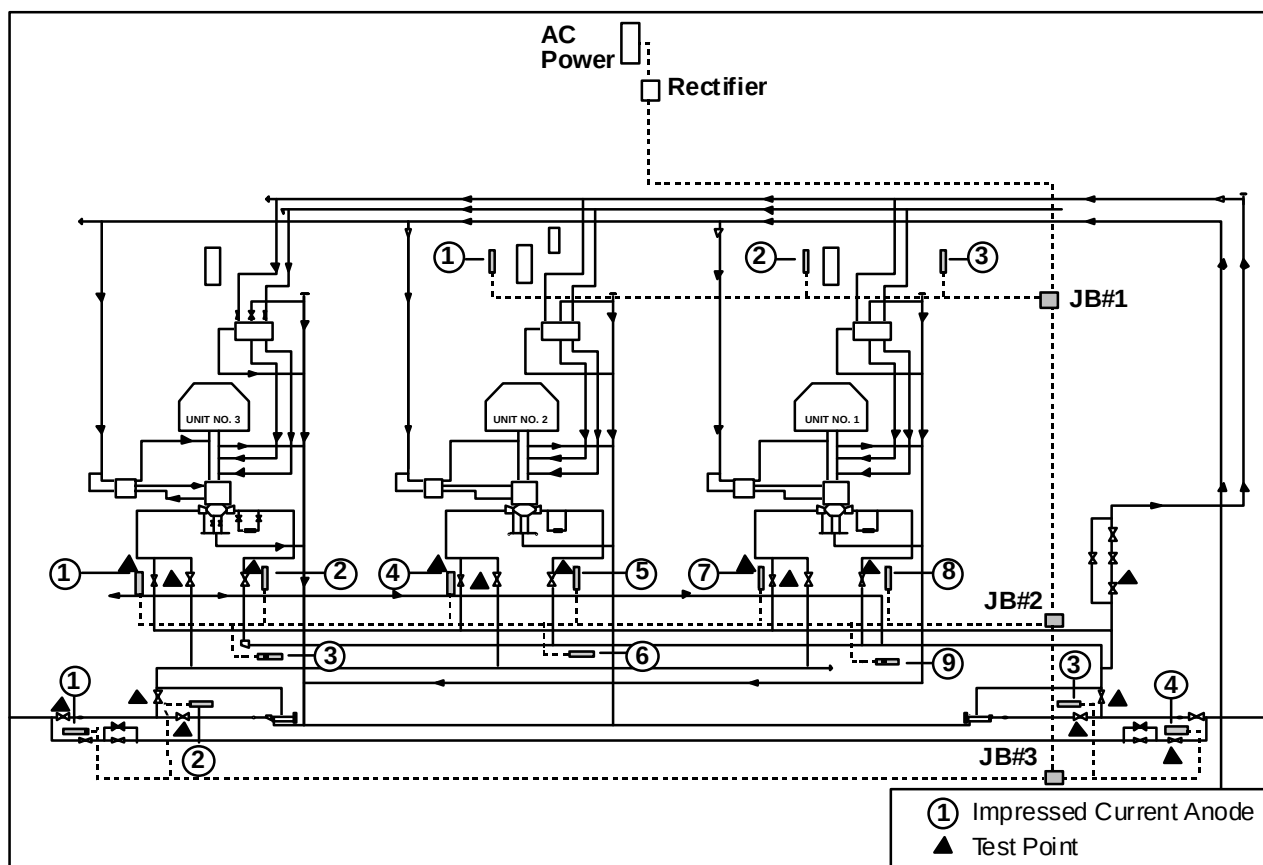
Zinc reference electrode

REF No.	TANK-TO-REF. POTENTIAL (mV)	
	On	Off
R1	+200	+219
R2	+197	+217
R3	+192	+221
R4	+194	+212

Tank Bottom Survey Data Sheet

Figure 15

In-plant hydrocarbon pipelines should have designated sites at least every 15 meters, where "close" pipe-to-soil potential readings can be made. Firewater pipeline potentials are measured at every riser. A numbering system for all test points and a plot plan are important parts of an in-plant cathodic protection survey plan. The plot plan should show the location of all protected structures, cathodic protection rectifiers, anode beds, and test points. Without a plot plan, it is very difficult to evaluate cathodic protection performance. An example of an in-plant plot plan is shown in Figure 16.



Pump Station Impressed Current System

Figure 16

During an in-plant CP survey, pipe-to-soil potential readings are recorded on the Plant Survey Data Sheet shown in Figure 17.

PLANT SURVEY DATA SHEET

DATE: _____ RECTIFIER RATING: _____ VOLTS _____ AMPS

PLANT : _____ OPERATING OUTPUT: _____ VOLTS _____ AMPS

[illegible]

* CHANGE

** ADDITION

NEW INSTRUCTION ☐

COMPLETE REVISION ☐

Plant Survey Data Sheet

Figure 17

Criteria for Adequate Protection

Section 4.5 of SAES-X-600 states the following Saudi Aramco cathodic protection criteria for buried pipelines and external tank bottoms.

Pipelines

The minimum pipe-to-soil potential shall be -0.85 volt (on) with reference to a Cu-CuSO₄ reference electrode that is located in test holes over the pipeline.

External Tank Bottoms

The minimum criterion for adequate protection shall be one of the following:

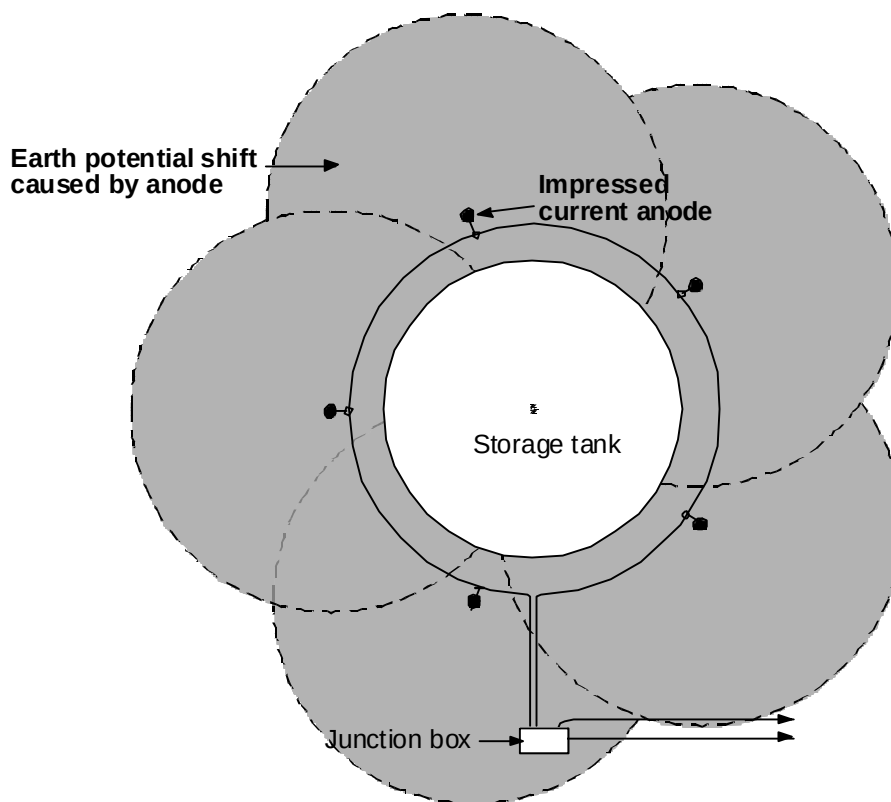
- -1.0 volt (on) at the periphery of the tank with reference to a Cu-CuSO₄ reference electrode. For tanks with ring walls, the reference electrode must be located inside the ring wall next to the tank periphery. Or
- -.85 volt (on) with reference to a permanent Cu-CuSO₄ reference electrode.
- +20 volt (on) or more negative with reference to a zinc reference cell installed under the tank bottom.
- A change in structure potential of -0.350 V between current "on" and current "off" conditions, with reference to a Cu-CuSO₄ reference electrode.

Identifying Abnormalities in Cathodic Protection of In-Plant Facilities

Electrical shielding in congested areas prevents effective protection with remote anode beds. Distributed impressed current anode systems are installed so that the structure to be protected is within the high potential gradients that surround the anodes. A distributed anode system does not prevent current from being picked up by another nearby structure such as an electrical grounding system. Instead, a distributed anode system is designed so that a major portion of the current is collected by the tank bottom or pipeline that needs protection.

External Tank Bottoms

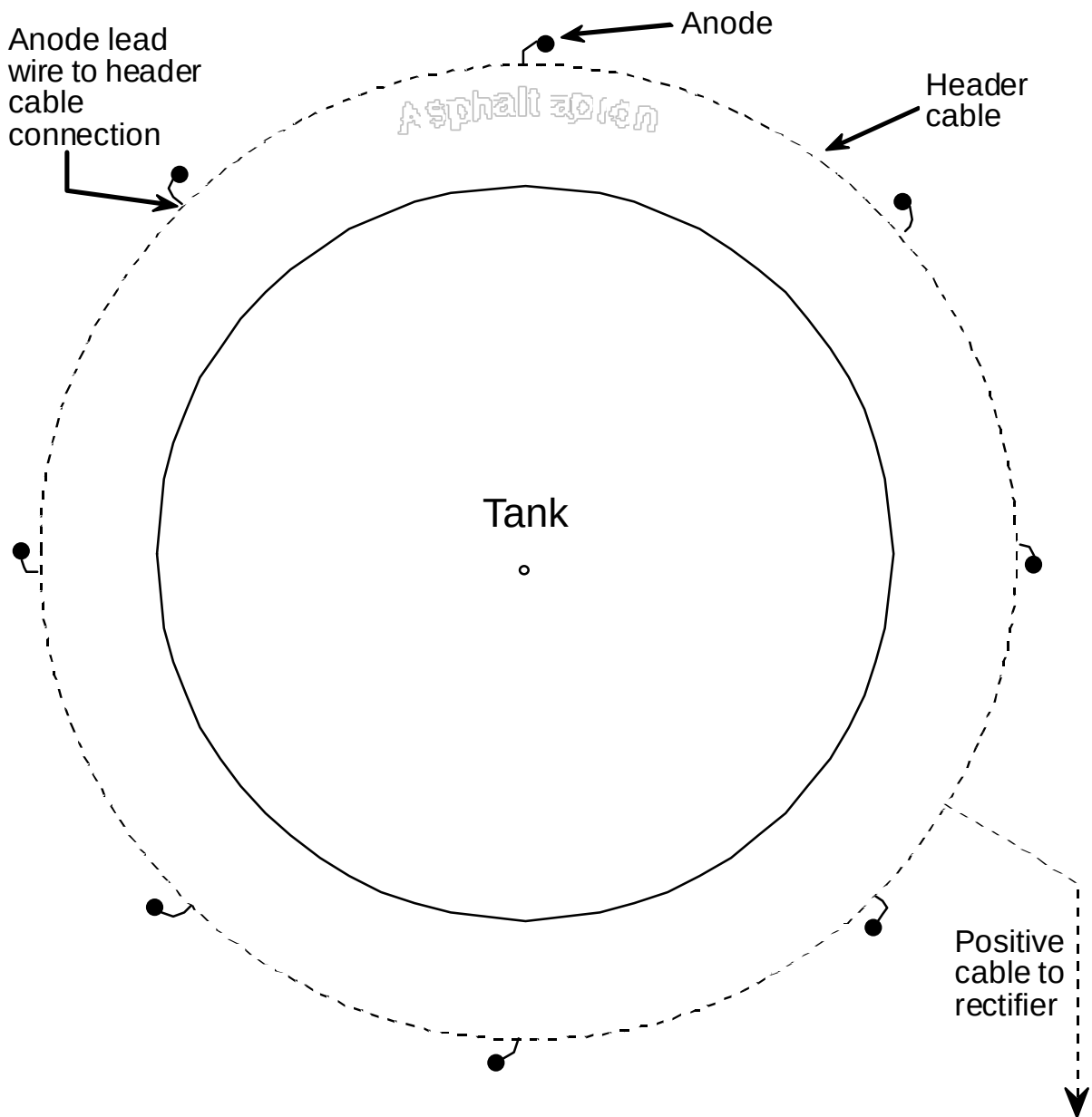
The purpose of distributed anode systems is to change the potential of the structure by changing the earth potential around the structure. The amount of earth potential change is dependent on the size and shape of the anode, its position relative to the structure, the soil resistivity, and the anode current output. Anodes must be placed so that adequate potential shift is achieved at all points on the structure (Figure 18). (The earth potential change at any point on the structure may be influenced by several nearby anodes.)



Distributed Impressed Current Anode System

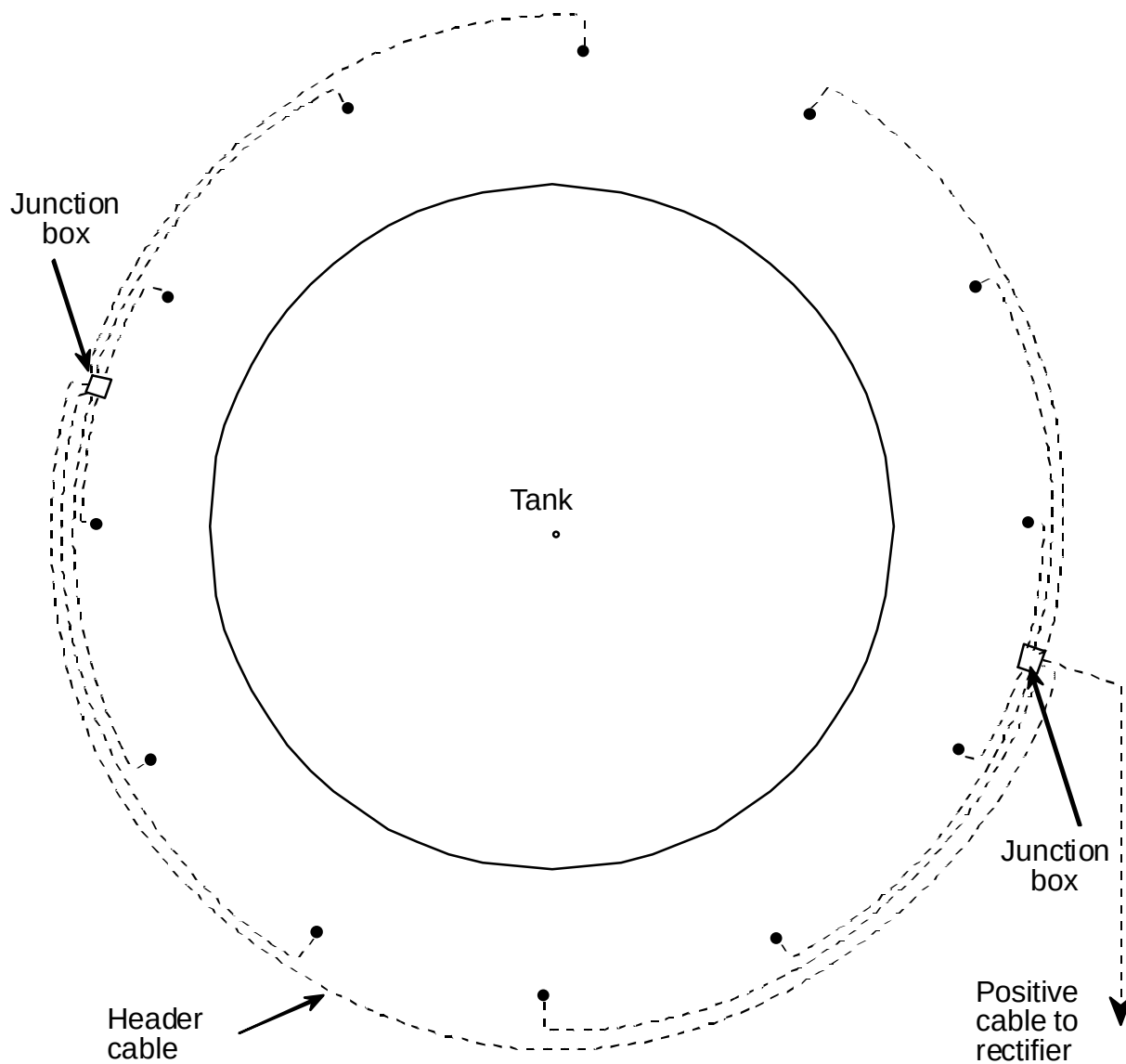
Figure 18

One distributed anode system design that is used to protect external tank bottoms is shown in Figure 19. In this design, the anode leads are directly connected to a header cable that encircles the tank. Failure of the header cable may cause early failure of the entire anode bed. Also, if one or more of the anodes fail, the current output from the remaining active anodes would increase. It is not possible to determine the current output of the active anodes because this design does not allow individual anode outputs to be measured. As a result, the active anodes may be operated beyond their maximum rated current densities. Over-driving of the anodes would result in the premature failure of the anode bed.



Distributed Anode Installation
Figure 19

Corrective Action - In cases where the design of the CP system does not allow individual anode outputs to be measured (as in Figure 20), the rectifier output may be increased until adequate potential readings are achieved on the tank bottom. Increasing the rectifier output is only a temporary corrective measure. Eventually, the anode bed will have to be replaced. Ideally, distributed anode beds should be designed so that the current output from individual anodes can be measured. An appropriate installation would use one or more junction boxes that are connected to individual anode lead wires, as shown in Figure 14.



Distributed Anode System with Multiple Junction Boxes

Figure 20

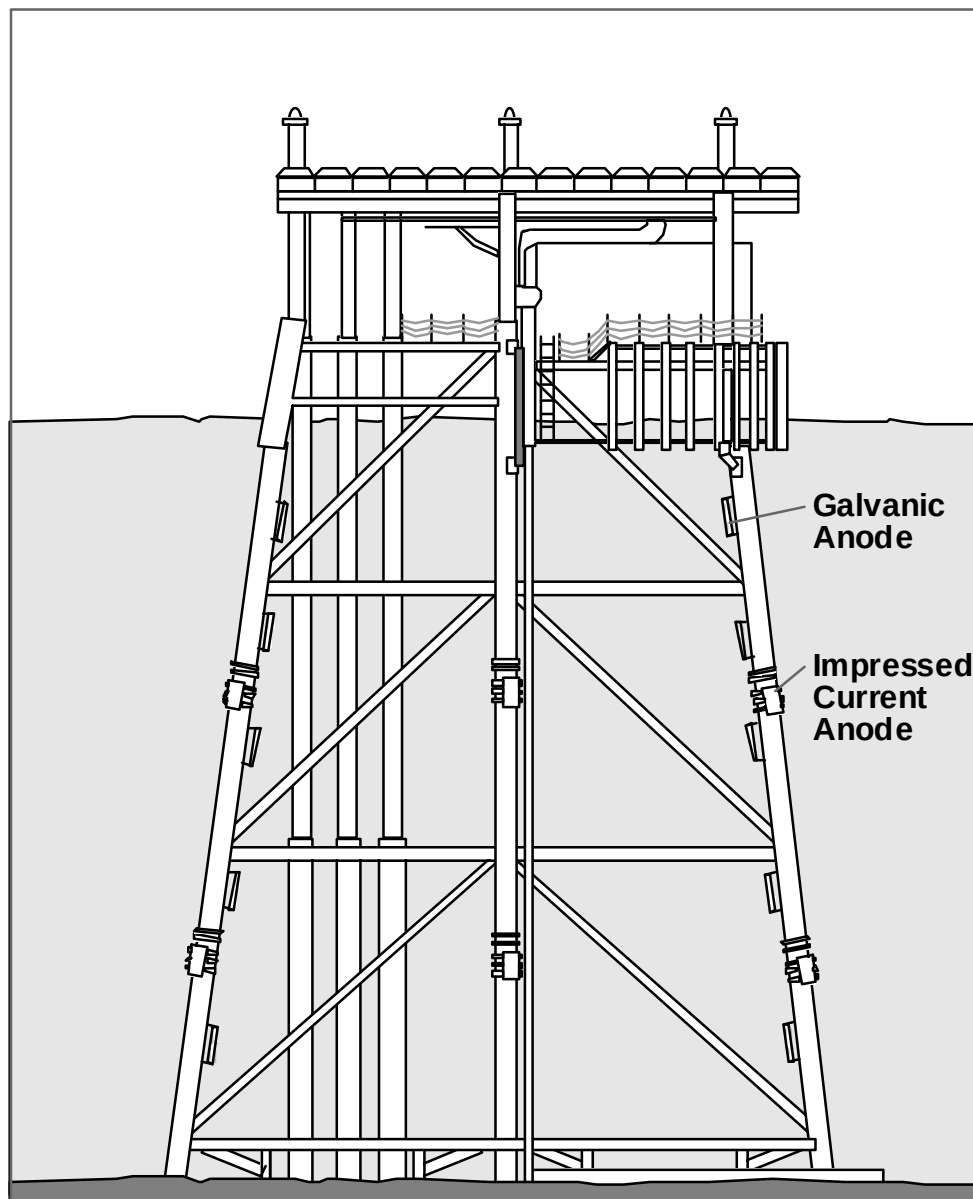
Buried Piping

Cathodic protection of piping within a plant area has a unique set of problems. Usually, an extensive, underground copper grounding grid is installed to protect personnel in case of an electrical ground fault. Without cathodic protection, buried steel piping becomes anodic to this copper ground grid and experiences accelerated corrosion. Also, several pipes may be buried close to each other within the plant. Cathodic protection current from remote anode beds may not reach all metal surfaces because of electrical shielding.

Corrective Action - The most effective method for providing cathodic protection to buried pipe within a plant is a distributed impressed current anode system. Installation of galvanic anodes may be necessary in certain areas (e.g., buried metallic valves, metallic hydrant risers in an otherwise non-metallic piping system, or between closely spaced parallel lines). Galvanic anodes are also recommended for above-grade steel lines that are partially covered by a berm or road crossing.

Ensuring Adequate Protection of Marine Structures

Saudi Aramco cathodically protects most marine structures with galvanic anodes. Impressed current systems are used if they are economically justified. All impressed current systems for fixed offshore platforms are hybrid systems. A hybrid system contains enough galvanic anodes to protect the structure for several months until the impressed current system is energized. Galvanic anodes also protect the structure when the impressed current system is turned off or is not operating for short periods of time. A hybrid system is shown in Figure 21.

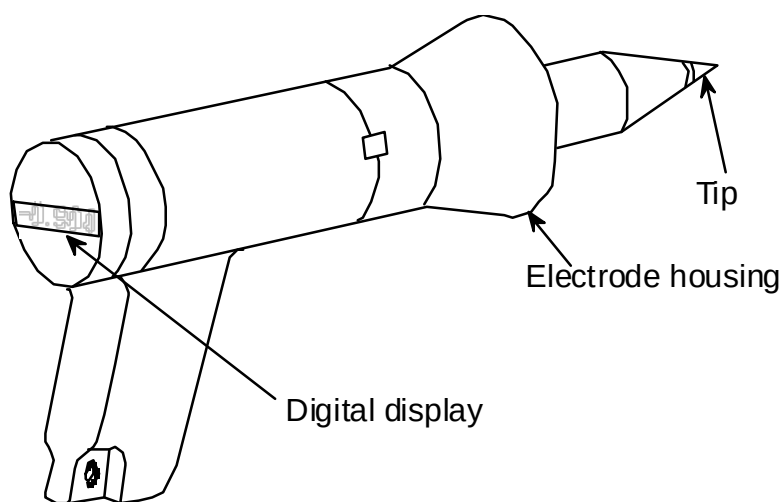


Hybrid Cathodic Protection System for a Fixed Offshore Platform
Figure 21

Offshore cathodic protection systems are designed to provide sufficient current density to all parts of a submerged structure so that the minimum protection potential is easily achieved. Anodes are carefully located on a structure before it is placed in the marine environment to be sure that protective potentials can be obtained. Periodic potential surveys are made after installation to verify that all areas of the structure are receiving adequate cathodic protection. These surveys are helpful for identifying defective anodes or unusual anode consumption.

Potential Measurements

Offshore potential measurements require the use of a silver-silver chloride reference electrode because chlorides in seawater can contaminate copper sulfate electrodes. Portable and fixed potential measuring equipment is used. A portable reference electrode, as shown in Figure 22, can be held by a diver or a remote control vehicle (RCV). Most diver-held probes are in the form of a pistol with a tip spike, Ag-AgCl reference electrode and a digital voltmeter. The Ag-AgCl reference electrodes are placed as close as possible to the structure to eliminate ohmic drops.



Digital Diver-Held Probe
Figure 22

Criteria for Adequate Protection

The Saudi Aramco criteria for cathodic protection for marine structures are given in Section 4.5 of SAES-X-300 and Section 6.2 of G.I. 428.003. For all offshore platforms, sea islands, and submarine pipelines, the criterion is a minimum structure potential of -0.900 V with reference to a silver-silver chloride reference electrode. For sheet piling, trestles, and piers where no submarine pipelines are terminating, the criterion is a minimum structure potential of -0.800 V with reference to a silver-silver chloride reference electrode.

According to G.I. 428.003, where impressed current installations exist, both "on" and "off" potential readings should be taken. The reference cell is placed as close as possible to the structure. Synchronized current interrupters are useful for potential surveys of submarine pipelines under the influence of multiple rectifiers so that true "off" readings are obtained. During CP surveys of submarine pipelines and other marine structures, potential readings are often taken at locations that are most remote from anodes. These remote potential readings allow the areas that receive the least amount of protective current to be tested. For example, potential measurements are taken at the midpoint between anodes on submarine pipelines that are protected by galvanic bracelets. Potential readings are also taken in nodal areas of marine platforms where protective current density is expected to be low.

Identifying Abnormalities in Cathodic Protection of Marine Structures

Anode Life

Each galvanic anode material will deliver a given amount of useful current per unit mass based upon the material's chemistry, the anode dimensions, and the environment in which the anode is placed. The life of a galvanic anode can be estimated with the use of the following formula if the anode's weight is known and if the current output from the anode can be measured or calculated.

$$Y = \left(\frac{W \times UF}{C \times I_A} \right)$$

where -

- Y = anode life in years
- C = actual consumption rate in kg/amp-yr
- W = anode mass in kg
- I_A = anode current output in amperes
- UF = utilization factor

The consumption rates, C , of anode materials in seawater environments are determined by anode manufacturers. These consumption rates (in kg per ampere-year) are used by the marine cathodic protection designer to determine the amount of anode material needed to provide current over the design life of the CP system. An ampere-year is the product of any current flow and time that is equivalent to 1.0 ampere flowing for 1 year. For example, both 0.5 ampere flowing for 2 years and 2.0 amperes flowing for 0.5 year are equivalent to 1 ampere-year. Anode current output, I_A , can be measured or calculated by using Ohm's Law ($I=E/R$) and Dwight's Equation. The utilization factor, UF , is the percentage of the anode that is consumed before it needs to be replaced. A value of 85 or 90 percent is often used for the utilization factor.

For example, the remaining life of a Galvalum III anode can be estimated given the following information from a CP survey:

Anode consumption rate: 3.46 kg/amp-yr

Anode solution potential: -1.09 V versus Ag-AgCl

Structure potential: -0.90 V versus Ag-AgCl

Original anode dimensions: 28 cm x 28 cm x 304.8 cm

Anode pipe core diameter: 10.2 cm O.D.

Measured anode circumference: 74 cm

Measured anode length: 304.8 cm

Water resistivity: 15 ohm-cm

Anode material density: 2.70 g/cm³

It is not possible to measure the anode current output; however, this output can be calculated by using Ohm's Law:

$$I_A = E_D/R_C$$

where -

E_D = the anode driving potential

R_C = the circuit resistance

The anode driving potential is calculated by subtracting the structure potential from the anode solution potential:

$$E_D = 1.09 \text{ V} - 0.90 \text{ V} = 0.19 \text{ V versus Ag-AgCl}$$

For seawater, the major portion of the circuit resistance is the anode-to-electrolyte resistance, R_V , which can be found by using Dwight's Equation:

$$R_C = R_V = \frac{0.159(\rho)}{L} \left(\ln \frac{8(L)}{d} - 1 \right)$$

where -

- R_V = anode-to-electrolyte resistance
- ρ = electrolyte resistance
- L = length of the anode in cm
- d = anode diameter in cm (circumference of anode cross-section/ π)

The anode current output is calculated as follows:

$$d = 74\text{cm}/\pi = 74 \text{ cm}/3.14159 = 23.55 \text{ cm}$$

$$R_V = \frac{0.159(15)}{304.8} \left(\ln \frac{8(304.8)}{23.55} - 1 \right) = 0.0285 \text{ ohm}$$

$$I_A = 0.19 \text{ V}/0.0285 \text{ ohm} = 6.67 \text{ amperes}$$

The net volume of anode material is calculated by subtracting the volume of the anode pipe core from the anode volume (based on the measurements taken during the CP survey) as follows:

$$\begin{aligned} \text{Net Volume} &= [\pi d_{\text{anode}}^2/4 \times L] - [\pi d_{\text{core}}^2/4 \times L] \\ &= [\pi (23.55 \text{ cm})^2/4 \times 304.8 \text{ cm}] - [\pi (10.2 \text{ cm})^2/4 \times 304.8 \text{ cm}] \\ &= 132,766 \text{ cm}^3 - 24,906 \text{ cm}^3 = 107,860 \text{ cm}^3 \end{aligned}$$

The remaining weight of anode material is calculated by multiplying the net volume of the anode by the density of the anode material.

$$\text{Weight of anode material} = 107,860 \text{ cm}^3 \times 2.70 \text{ g/cm}^3 = 291,222 \text{ g} = 291 \text{ kg}$$

The remaining anode life is estimated as follows:

$$Y = \left(\frac{W \times UF}{C \times I_A} \right) = \left(\frac{291 \text{ kg} \times .85}{3.46 \text{ kg / amp-yr} \times 6.67 \text{ A}} \right) = 10.7 \text{ years}$$

Work Aid 1: Criteria and Procedure to Ensure Adequate Protection of Buried Pipelines

This Work Aid contains criteria and a procedure to ensure adequate protection of buried pipelines.

Work Aid 1A: Cathodic Protection Criteria from G.I. 428.003

- 5.1.1 The criterion for cathodic protection for cross-country pipelines in soil resistivity environments of 5000 ohm-cm or greater is to achieve a minimum of -1.2 volts pipe-to-soil potential with reference to a copper/copper sulfate half cell.
- 5.1.2 The criterion for cathodic protection for cross-country pipelines in soil resistivity environments of 5000 ohm-cm or less is to achieve a minimum of -1.0 volt pipe-to-soil potential with reference to a copper/copper sulfate half cell.

Work Aid 1B: Procedure to Ensure Adequate Protection of Buried Pipelines

1. Identify areas of inadequate cathodic protection.
 - a. Inspect CP survey data and identify areas of the structure where there is an inadequate level of cathodic protection based on the criteria in Work Aid 1A. If the pipeline is inadequately protected, go to Step 2.
2. Troubleshoot the rectifier and rectifier cables.
 - a. Inspect the rectifier operating data on the CP survey form. If there is ac but no rectifier dc voltage and current output, the problem is within the rectifier. Notify CP personnel. If there is rectifier dc voltage output but the current output is 0 amperes, go to Step 2b.
 - b. If current flows across a short that is created between the positive and negative rectifier output terminals, the problem is not within the rectifier. Go to Step 2c.
 - c. If current flows across a short that is created between the negative rectifier terminal and a grounding rod, the negative return line from the structure is defective. The negative cable should be inspected and repaired. If the negative cable is not defective, go to Step 2d.
 - d. If the soil potential at the positive terminal of the junction box is significantly less than the soil potential at the positive rectifier terminal, the positive cable may be damaged. The positive cable should be inspected and repaired. If the problem is not with the positive cable, go to Step 3.

3. Troubleshoot the anode bed.
 - a. Determine the total anode bed output by multiplying the total of the anode shunt voltages by the shunt rating. If there is more than one junction box, repeat this calculation for all remaining anodes.
 - b. If the current outputs of the rectifier and anode bed(s) differ by less than 10%, and if the working anodes are not being overdriven, the rectifier current output should be increased so that the structure is adequately protected.
 - c. If the current outputs of the rectifier and anode bed(s) differ by less than 10%, and if some of the working anodes are being overdriven, the anode bed(s) should be replaced.

Work Aid 2: Criteria and Procedure to Ensure Adequate Protection of Onshore Well Casings

This Work Aid contains criteria and a procedure to ensure adequate protection of onshore well casings through the use of the Well Casing Annual Survey form.

Work Aid 2A: Cathodic Protection Criterion from Section 5.1.3 in G.I. 428.003

The well casing cathodic protection criterion is to achieve a minimum of -1.0 volt casing-to-soil potential with reference to a remote copper/copper sulfate half cell with the current off for a minimum of 10 seconds.

Work Aid 2B: Procedure to Ensure Adequate Protection of Onshore Well Casings

1. With the CP system "on."
 - a. Inspect the rectifier output voltage and current on line 1 of the Well Casing Annual Survey form. For the procedure to troubleshoot the rectifier and anode bed, see Work Aid 1B.
 - b. If the "on" casing potential (line 2 of the survey form) is inadequate according to the criterion in Work Aid 2A, increase the rectifier output until the casing potential has been shifted enough to meet the criterion. Allow sufficient time for the casing to polarize.
2. With the CP system "off."
 - a. If the Swain Meter current reading is greater than five amperes, nearby CP systems should be turned off (one at a time) until a reading less than five amperes is obtained.
 - b. If the Swain Meter current reading is negative, current is being discharged by the casing. Interference is indicated.

Work Aid 3: Criteria and Procedure to Ensure Adequate Protection of Vessel and Tank Interiors

This Work Aid contains the criteria and procedure to ensure adequate protection of vessel and tank interiors.

Work Aid 3A: Cathodic Protection Criteria from SAES-X-500, Cathodic Protection of Vessel and Tank Internals

- Section 4.3.1 - The design life of galvanic or impressed current anode systems shall be either five years, or the testing and inspection period, whichever is greater.
- Section 4.3.2 - Galvanic anodes in dehydrator vessels shall be designed using a 20% efficiency factor. Designs for all other wet crude handling vessels shall use an efficiency factor of 50%.
- Section 4.5.1 - The steel-to-water potential shall be more negative than -0.90 V (on) with reference to a silver-silver chloride electrode, or +0.15 V (on) with reference to a zinc electrode.

Work Aid 3B: Procedures to Ensure Adequate Protection of Vessel and Tank Interiors

1. Ensuring adequate protection of vessel and tank interiors.
 - a. If the anodes are not completely consumed, and if there are no visual signs of corrosion, the anodes may be replaced with similar anodes.
 - b. If the anodes are completely consumed, and if there are no visual signs of corrosion, larger anodes should be installed. If the same type of anodes are used again, the T & I period may need to be shortened.
 - c. If the anodes are completely consumed, and if there are visual signs of corrosion, larger or additional anodes are needed.

Work Aid 4: Criteria and Procedure to Ensure Adequate Protection of In-Plant Facilities

This Work Aid contains criteria and a procedure to ensure adequate protection of external tank bottoms and buried piping inside plants.

Work Aid 4A: Criteria from Section 4.5 of SAES-X-600

The criterion for cathodic protection for in-plant buried structures and pipelines is to achieve a minimum of -0.85 volts structure-to-soil potential with reference to a copper/copper sulfate electrode. For tank bottoms which have no permanent reference electrodes under them, the criterion for cathodic protection is to achieve a minimum of -1.0 volt structure-to-soil potential with reference to a copper/copper sulfate electrode at the periphery of the tank. A permanent zinc reference electrode shall measure +0.20 volts, or more negative, which is equivalent to -0.85 volts with reference to a copper/copper sulfate electrode.

Work Aid 4B: Procedure to Ensure Adequate Protection of In-Plant Facilities

1. Identify areas of inadequate cathodic protection.
 - a. On the basis of the criteria in Work Aid 4A, inspect CP survey data and identify areas on the structure that are inadequately protected.
 - b. Examine the rectifier output voltage and current readings on the CP survey form. If the rectifier is operating properly, go to Step 3. If there is no or very low rectifier voltage and current output, go to Step 2.
2. Troubleshoot the cathodic protection system by using Steps 2 and 3 in Work Aid 1B.
3. Increase the potential of the structure.
 - a. Determine the current output of the distributed anode(s) closest to the area of inadequate protection. If the anodes are not overdriven, the rectifier current output should be increased to increase the level of cathodic protection on the structure.
 - b. If these anodes have zero or very low current output, the anode bed should be replaced.

Work Aid 5: Formulas, Criterion, and Procedure to Ensure Adequate Protection of Marine Structures

This Work Aid contains formulas, criterion, and a procedure to ensure adequate protection of offshore platforms and pipelines.

Work Aid 5A: Formulas

Galvanic Anode Lifetime

$$Y = \left(\frac{W \times UF}{C \times I_A} \right)$$

where -

- Y = anode life in years
- C = actual consumption rate in kg/amp-yr
- W = anode mass in kg
- I_A = anode current output in amperes
- UF = utilization factor

Anode Current Output

$$I_A = E_D / R_C$$

where -

- E_D = the anode driving potential
- R_C = the circuit resistance

Dwight Equation

$$R_C = R_V = \frac{0.159(\rho)}{L} \left(\ln \frac{8(L)}{d} - 1 \right)$$

where -

- R_V = anode-to-electrolyte resistance
- ρ = electrolyte resistance
- L = length of the anode in cm
- d = anode diameter in cm (circumference of anode cross-section/π)

Volume of an Anode

$$V = \pi(d^2/4)L \text{ or } (C^2/4\pi)L$$

where -

- V = anode volume
- d = anode diameter
- C = anode circumference
- L = anode length

Work Aid 5B: Criterion from Section 6.2 of G.I. 428.003

For all offshore platforms, sea islands, and submarine pipelines, the criterion is to achieve a minimum potential of -0.900 V with reference to a silver-silver chloride reference electrode.

Work Aid 5C: Procedure

1. Estimate the remaining life of a galvanic anode system:
 - a. Obtain the following information:
 - anode consumption rate
 - anode solution potential
 - anode circumference and length
 - anode pipe core dimensions
 -
 -
 - b. Subtract the structure potential (see criterion) from the anode solution potential to obtain the anode driving potential.
 - c. Determine the effective diameter of the anode by dividing its circumference by π . Calculate the anode-to-electrolyte resistance (circuit resistance) of the anode by inserting its effective diameter, length, and the electrolyte resistivity into the Dwight Equation.
 - d. Divide the anode driving potential by the circuit resistance to calculate the current output of the anode.
 - e. Subtract the volume of the pipe core from the volume of the anode to obtain the net volume of anode material. Calculate the net weight of anode material by multiplying the net volume of anode material by the anode material density.
 - f. Insert the anode consumption rate, anode net weight, anode current output, and utilization factor into the galvanic anode lifetime formula to calculate the remaining life of the anode.

GLOSSARY

close interval potential survey	A pipe-to-soil survey that is usually conducted at 5 to 10 meter intervals to determine where current is being picked up or discharged by an unprotected pipeline.
conductor	In reference to oil/gas production, a tubular member through which oil or gas wells are drilled and through which production casing and tubing is inserted.
contact resistance	Resistance at the interface between two materials.
continuity bond	A metallic connection that provides electrical continuity.
current interrupter	A device that is used to switch a current source off and on automatically.
electrical isolation	The condition of being electrically separated from other metallic structures and the environment.
gas blockage	Gas build up around anodes that causes anodes to become insulated from the surrounding soil.
interference	The destructive flow of current from a foreign dc source.
risers	Pipelines that carry gas or oil onto or off of drilling, production or pumping platforms.
stray current	Current that flows through paths other than the intended circuit.
utilization factor	The amount of anode material consumed (in percent) when the remaining anode material is unable to provide the necessary current output for protection.