

Engineering Encyclopedia

Saudi Aramco DeskTop Standards

Designing 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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Designing Cathodic Protection Systems for Buried Pipelines

This section is divided into two parts. The first part covers galvanic anode system designs for short pipeline segments such as road and camel crossings. Galvanic anodes are used if the cathodic protection current requirement is small and the soil resistivity is low. The second part will cover impressed current systems for buried pipelines which require much more cathodic protection current. Normally, Saudi Aramco protects onshore pipelines with impressed current systems.

Designs for galvanic anode and impressed current systems designs are prepared after the following has been accomplished:

- the cathodic protection current requirements have been calculated
- the effective resistivity of the soil has been determined
- the anode bed location has been selected
- the allowable anode bed resistance has been calculated

In Module 107.01, you calculated the current requirements for various structures. In Module 107.02, you selected an anode bed site based on soil resistivity, current distribution, and available utilities. You also represented proposed CP systems as equivalent electrical circuits and calculated their allowable anode bed resistance. In this section, you will be given the above information and other criteria that will allow you to design cathodic protection systems for buried pipelines.

Galvanic Anode System Design for Road and Camel Crossings

Design standards and practices for galvanic anode systems for road and camel crossings are presented below. The design of galvanic anode systems for pipelines involves determining the following:

- design requirements using Saudi Aramco standards and drawings
- the number of galvanic anodes required
- circuit resistance
- galvanic anode current output
- galvanic anode life

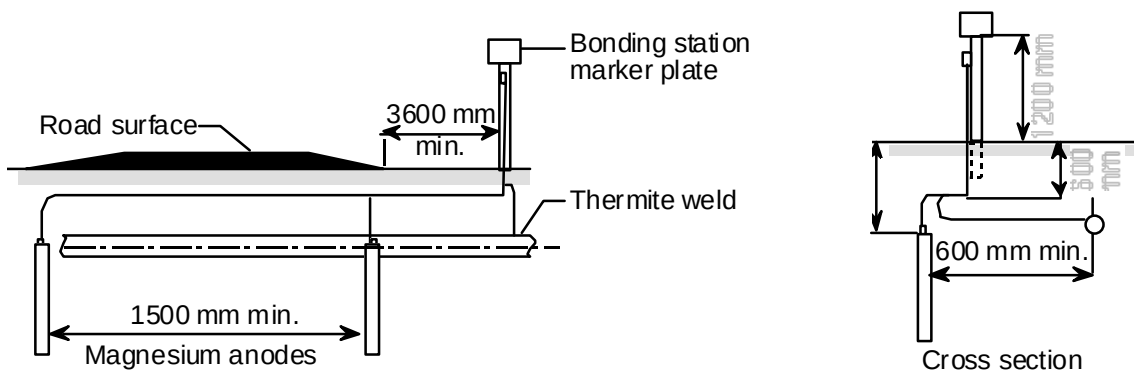
After describing these requirements and calculations, an example is provided which demonstrates the design of a galvanic anode system for a section of pipeline.

Saudi Aramco Engineering Standards and Drawings

Saudi Aramco Engineering Standard SAES-X-400 provides minimum design requirements that govern CP systems for buried onshore pipelines. CP systems inside plant facilities are not included. SAES-X-400 requires galvanic anodes at the following sites:

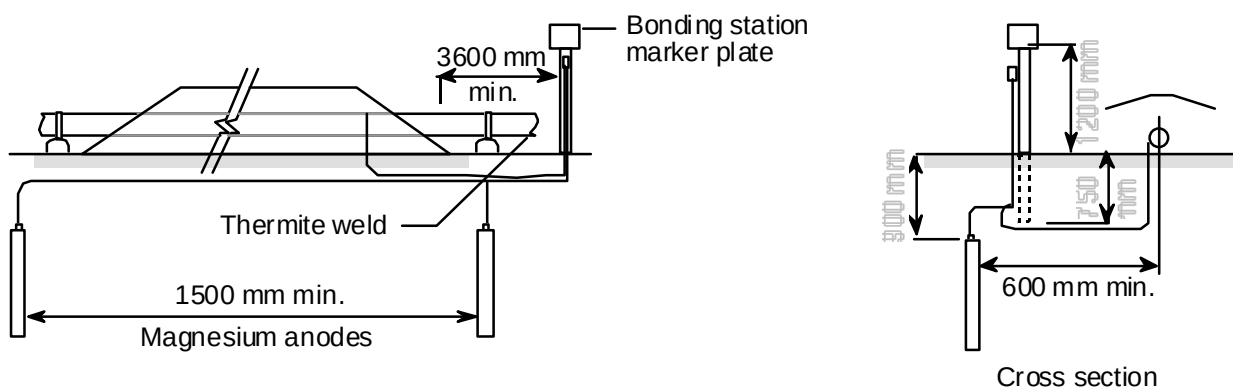
- buried pipelines at paved road crossings
- buried pipelines at camel crossings
- short segments of pipelines that are not part of an impressed current system

Saudi Aramco uses either pre-packaged or bare magnesium anodes to protect short pipeline segments. Bare anodes are used only in Subkha areas. The design calculations in this module are based on construction standards in Standard Drawing AA-036352 - Galvanic Anodes for Road & Camel P/L Crossings, P/L Repair Locations. Figures 1A, 1B, and 1C show typical galvanic anode installations from Standard Drawing AA-036352.

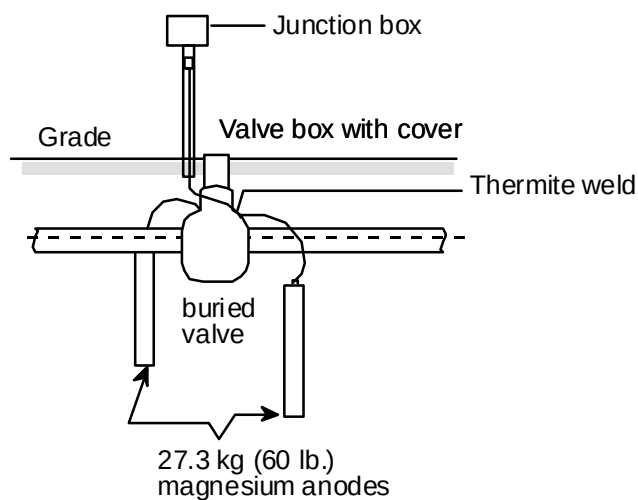


Typical Galvanic Anode Installation for a Road Crossing

Figure 1A



Typical Galvanic Anode Installation for a Camel Crossing

Figure 1B

Typical Galvanic Anode Installation for Buried Valve Locations

Figure 1C

Number of Galvanic Anodes Required

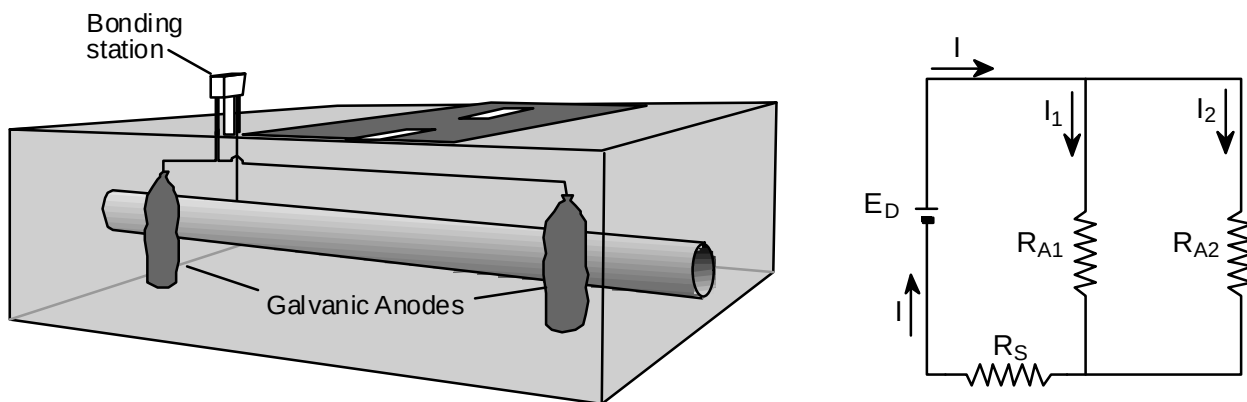
The number of galvanic anodes required depends on the following:

- the size (weight) of the anodes
- the length of the pipe
- the diameter of the pipe

At least two anodes are required for any installation. Work Aid 1A provides a table from Standard Drawing AA-036352 and a procedure for determining the number of magnesium anodes required.

Circuit Resistance

The circuit resistance of the galvanic anode system, R_C , is represented by the electrical circuit in Figure 2.



Galvanic Anodes at a Road Crossing and an Equivalent Electrical Circuit

Figure 2

The structure-to-electrolyte resistance is represented by R_S in the electrical circuit. The anode resistances are R_{A1} and R_{A2} . Because the anodes are connected in parallel, their equivalent resistance is obtained from the following formula:

$$\frac{1}{R_{eq}} = \frac{1}{R_{A1}} + \frac{1}{R_{A2}} + \dots + \frac{1}{R_{AN}}$$

If the anodes' resistances are equal, the equivalent resistance is given by the following formula.

$$\frac{1}{R_{eq}} = \frac{1}{R_A} + \frac{1}{R_A} + \dots + \frac{1}{R_{AN}} = \frac{N}{R_A} \quad \therefore R_{eq} = \frac{R_A}{N}$$

The anode resistance, R_A , is determined by the following formula:

$$R_A = R_{LW} + R_V,$$

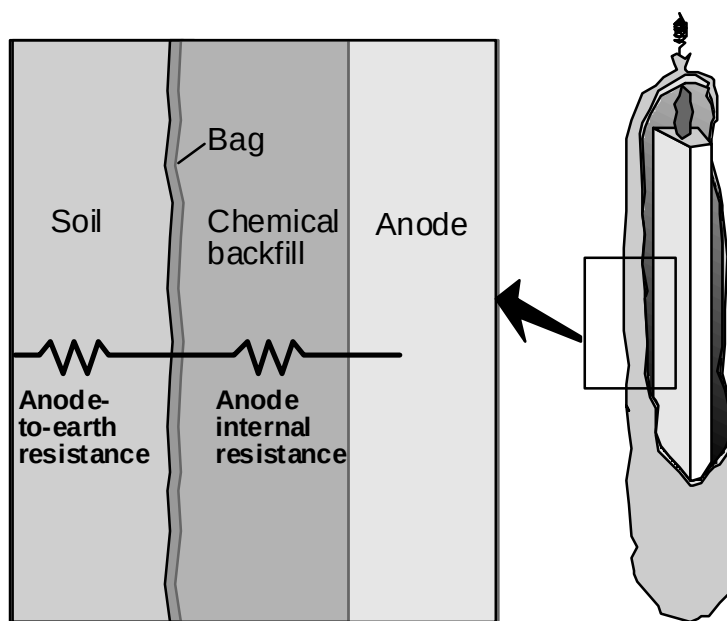
where -

- R_{LW} = the average anode lead wire resistance in ohms
- R_V = the anode-to-electrolyte resistance of one vertical anode in ohms

Therefore, the circuit resistance is determined by the following equation:

$$R_c = R_s + \left(\frac{R_A}{N} \right) = R_s \left(\frac{R_{LW} + R_V}{N} \right)$$

For an anode buried in chemical backfill as shown in Figure 3, the total resistance between the anode and electrolyte includes (1) the resistance from the anode to the outer edge of the backfill package and (2) the resistance between the backfill package and the soil. The resistance from the anode to the outer edge of the backfill is called the *anode internal resistance*. The resistance between the backfill and the soil is commonly called the *anode-to-earth resistance*.



Total Resistance of a Pre-Packaged Galvanic Anode
Figure 3

Because the contribution of the anode internal resistance is very small, Saudi Aramco only considers the anode-to-earth resistance. The anode-to-earth resistance of a single vertical anode is calculated using the Dwight Equation as follows:

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

where -

- R_V = resistance of one vertical anode to earth in ohms
- ρ = resistivity of backfill material (or soil) in ohm-cm
- L = length of anode (or backfill column) in centimeters
- d = diameter of anode (or backfill column) in centimeters

Prepackaged magnesium anodes are used in most soil installations. Therefore, L and d above will be the nominal length and diameter of the anode backfill package.

You can calculate the anode bed resistance of two or more vertical anodes in parallel by using the Sunde Equation as follows:

$$R = \frac{0.159\rho}{NL} \left[\left(\ln \frac{8L}{d} - 1 \right) + \frac{2L}{S} (\ln 0.656N) \right]$$

where -

- R = resistance, in ohms, of N vertical anodes in parallel and spaced S centimeters apart along a straight line.
- ρ = soil resistivity in ohm-cm
- N = number of anodes
- L = length of anode (or backfill column) in centimeters
- d = diameter of anode (or backfill column) in centimeters
- S = anode spacing in centimeters

Anodes are usually cast in the shape of a trapezoid rather than a cylinder. If an anode is installed in Subkha without a backfill package, its effective diameter must be calculated. For example, a trapezoidal anode with nominal 7.5 cm sides has a circumference of $4 \times 7.5 \text{ cm} = 30 \text{ cm}$. The effective diameter is $30 \text{ cm}/\pi$, or 9.5 cm.

Galvanic Anode Current Output

SAES-X-400 and SADP-X-100 require a calculation of the anode current output. The current output of a galvanic anode system is a function of its driving potential and circuit resistance, as shown in the following formula:

$$I_A = E_D/R_C$$

where -

I_A = anode current output
 E_D = the anode driving potential
 R_C = the circuit resistance

The driving potential, E_D , is the difference between the anode's solution potential and the protected potential of the pipeline.

Galvanic Anode Life

The life of a galvanic anode can be estimated if its weight and current output are known. The expected life of a galvanic anode is given by the following equation from SADP-X-100, section 4.2, Eqn. 23.

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

where -

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

The actual consumption rate, C , of standard and high potential magnesium anodes is 7.1 kg per ampere-year. An anode needs to be replaced when there is not enough of it remaining to produce the required current. The utilization factor, UF , is the percentage of the anode that is consumed before it needs to be replaced. For magnesium anodes, the utilization factor is 85%.

Example

We will use the following data to determine the number and current output of pre-packaged 27.3 kg (60 lb.) magnesium anodes required to protect a 15-meter section of 12" pipe. Use the following engineering data:

Driving potential: 0.50 V versus Cu-CuSO₄
 Lead wire resistance: 0.025 ohm
 Structure-to-electrolyte resistance: 2.67 ohms
 Backfill package dimensions: 8" dia. x 84" (20.33 cm dia. x 213.36 cm)
 Soil resistivity: 1,000 ohm-cm

Number of Anodes

According to the table in Work Aid 1A, two anodes are required for 15 meters of 12" pipe.

Circuit Resistance

The anode-to-earth resistance of one anode is given by the Sunde Equation as shown below:

$$R_V = \frac{0.159\rho}{NL} \left[\left(\ln \frac{8L}{d} - 1 \right) + \frac{2L}{S} (\ln 0.656 N) \right]$$

$$= \frac{0.159(\text{ohm-cm})}{2(213.36 \text{ cm})} \left[\left(\ln \frac{8(213.36 \text{ cm})}{20.33 \text{ cm}} - 1 \right) + \frac{2(213.36)}{1,500} (\ln 1.312) \right]$$

$$R_V = 1.307 \text{ ohm}$$

The circuit resistance of the galvanic anode system is

$$R_C = 2.67 + 0.025 + 1.307 = 4.00 \text{ ohms.}$$

Galvanic Anode Current Output

The current output of the two galvanic anodes is:

$$I = E_D / R_C = 0.50 / 4.00 = 0.13 \text{ A. (or 0.065 A for each anode)}$$

Saudi Aramco normally uses magnesium anodes in areas where soil resistivity is less than 5,000 ohm-cm. In 5,000 ohm-cm soil, the anode-to-earth resistance in the example above would be 6.53 ohms (five times as much as in 1,000 ohm-cm soil). The circuit resistance would increase to 9.21 ohms and the current output would decrease as follows:

$$I = 0.50 / 9.21 = 0.05 \text{ A}$$

Galvanic Anode Life

The expected lifetime of one 27.3 kg anode with a current output of 0.065 A in 1,000 ohm-cm soil is shown below:

$$Y = \left(\frac{27.3 \text{ kg} \times 0.85}{7.1 \text{ kg / amp} - \text{yr} \times 0.065 \text{ amp}} \right)$$
$$Y = 50 \text{ years}$$

The anode requirements, formulas, and procedure needed to design galvanic anode systems for short sections of buried pipelines are provided in Work Aid 1A.

Impressed Current System Design for Buried Pipelines

Design standards and practices for impressed current systems for buried pipelines are presented below. These standards and practices include the following determinations:

- design requirements using Saudi Aramco standards and drawings
- the minimum number of impressed current anodes
- anode bed resistance (based on number of anodes and anode spacing)
- the amount of coke breeze required

After a discussion of the above information, an example is provided that includes a more efficient method, using an anode design chart for designing impressed current anode beds.

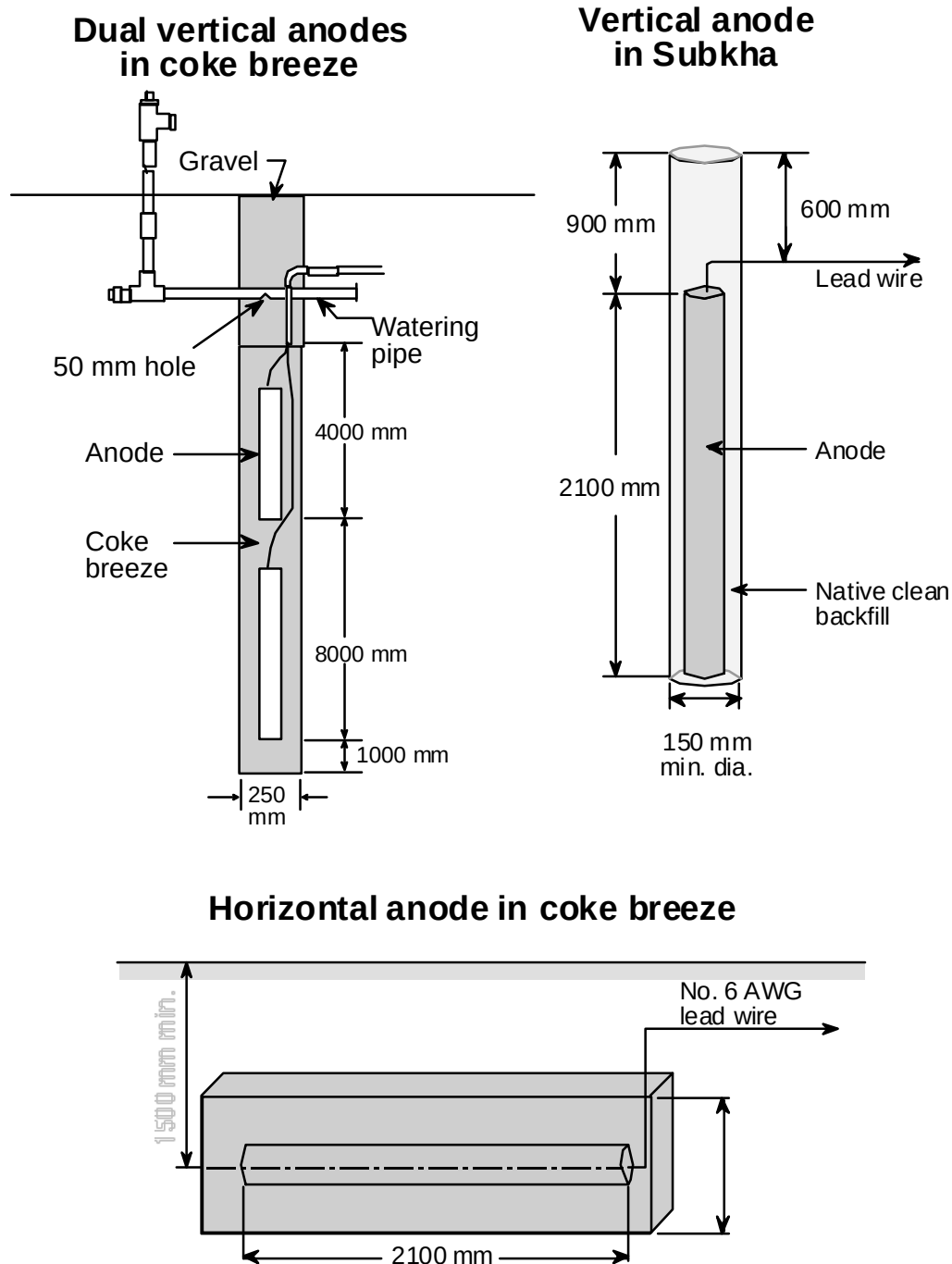
Saudi Aramco Engineering Standards and Drawings

Saudi Aramco Engineering Standard SAES-X-400 states the following:

- Total circuit resistance for a rectifier CP system shall not exceed 1.0 ohm.
- Total circuit resistance for a solar CP system shall not exceed 0.5 ohm.
- Impressed current systems shall provide a minimum negative pipe-to-soil potential of 1.2 volts and a maximum of 3.0 volts versus a Cu-CuSO₄ half-cell.
- Impressed current anode beds shall be sized to discharge 120% of the rated current output of the dc power source.
- Impressed current systems shall have a design life of 20 years.

Saudi Aramco Design Practice SADP-X-100 states that surface anode beds less than 15 meters deep should always be used unless they are uneconomical. Surface anode beds with watering facilities are usually more economical than deep anode beds. Deep anode beds are much more expensive to install than surface anode beds.

Anode bed design calculations are based on construction standards set by Saudi Aramco in Standard Drawing AA-036346, Surface Anode Bed Details. AA-036346 contains diagrams of vertical and horizontal anode installations as shown in Figure 4.



Vertical and Horizontal Anode Installations from Standard Drawing AA-036346

Figure 4

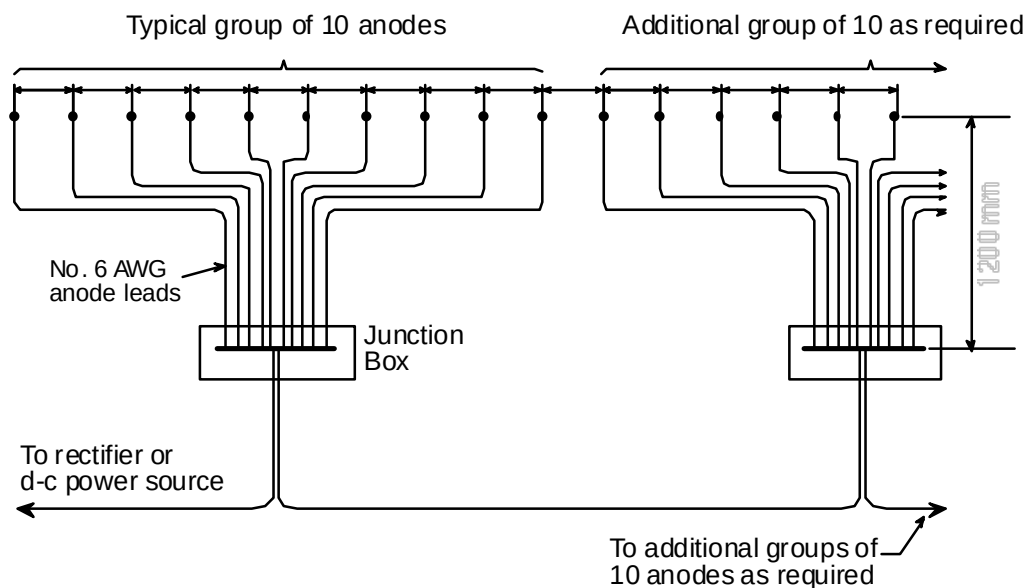
Impressed current anode beds should be remote from the protected structure to provide uniform current distribution. Figure 5 gives the minimum distances allowed between anode beds and buried structures. These criteria cover both surface and deep anode beds.

<u>Anode Bed Capacity</u>	<u>Minimum Distance from Underground Structures</u>
35 amperes	35 meters
50 amperes	75 meters
100 amperes	150 meters
150 amperes	225 meters

Minimum Anode Bed Distance from Underground Structures in SAES-X-400

Figure 5

SAES-X-400 states that remote surface anode beds shall be used where soil resistivity is compatible with system design requirements and economic considerations. Figure 6 shows a typical anode bed of 10 vertical anodes from Standard Drawing AA-036346. Additional groups of 10 anodes can be installed as required to meet current output requirements. SAES-X-400 requires that adjacent anode beds, powered by separate rectifiers, must be separated by at least 50 meters. If the output capacity of either anode bed is greater than 50 amperes, they must be separated by at least 100 meters.



Surface Anode Bed Detail from Standard Drawing AA-036346

Figure 6

Minimum Number of Impressed Current Anodes

There are two ways to calculate the minimum number of impressed current anodes required. One method considers the anode's maximum current output in the electrolyte and the other method considers the anode's consumption rate. It is best to use the method that gives the more conservative value (the greatest number of anodes).

To calculate the minimum number of anodes based on the anode's maximum current density, the following formula is used:

$$N = I / (\pi d L \times \gamma_A)$$

where -

- N = number of impressed current anodes
- I = total current required in milliamperes*
- d = anode diameter in centimeters
- L = anode length in centimeters
- γ_A = anode maximum current density in mA/cm² (Appendix I of SAES-X-400)

To calculate the minimum number of anodes based on the anode's consumption rate, the following formula is used:

$$N = \left(\frac{Y \times I \times C}{W} \right)$$

where -

- N = number of impressed current anodes
- Y = the impressed current system design life in years
- I = total current required in amperes*
- C = anode consumption rate in kg/A-yr (Appendix I of SAES-X-400)
- W = weight of a single anode in kg

* The total current required is usually multiplied by 120% to adequately size the anode bed.

Anode Bed Resistance

The current output of an impressed current system is a function of the dc power source driving voltage and the circuit resistance. The current output, I , is given by the following formula:

$$I = E_D / R_C$$

where -

E_D = the rated voltage of the dc power source (minus 2 volts if the anodes are installed in coke breeze)

R_C = the circuit resistance

In Module 107.02, we used the following formula to calculate circuit resistance, R_C , of an impressed current system circuit.

$$R_C = R_S + R_{LW} + R_{gb}$$

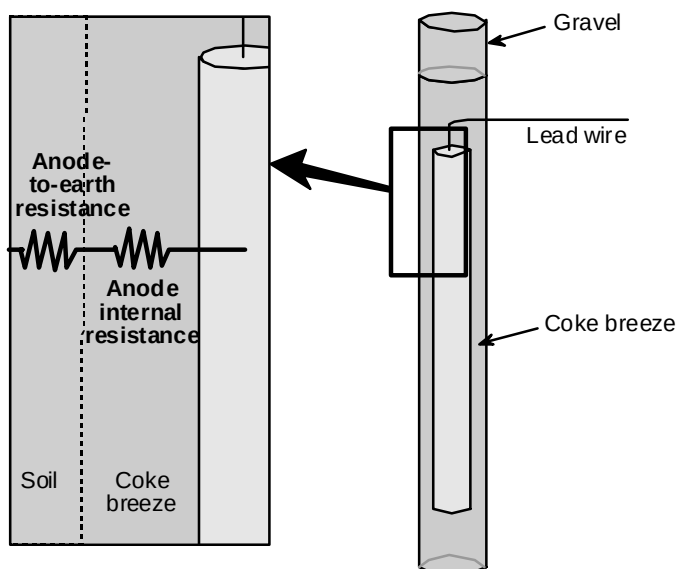
where -

R_S = structure-to-electrolyte resistance

R_{LW} = total lead wire resistance

R_{gb} = the anode bed resistance

The anode bed resistance, R_{gb} , is the total resistance of all the anodes in the anode bed. If the anodes are surrounded by a coke breeze column as shown in Figure 7, the resistance between each anode and electrolyte includes the anode internal resistance and the anode-to-earth resistance.



Resistance of an Impressed Current Anode in Coke Breeze Backfill
Figure 7

As with galvanic anodes, the internal resistance does not add significantly to the anode's total resistance. Therefore, Saudi Aramco only considers the anode-to-earth resistance. You can calculate the anode-to-earth resistance of a single vertical impressed current anode by using the Dwight Equation as follows:

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

where -

R_V	=	resistance of one vertical anode to earth in ohms
ρ	=	resistivity of soil in ohm-cm
L	=	length of anode (or backfill column) in centimeters
d	=	effective diameter of anode (or backfill column) in centimeters

You can calculate the anode bed resistance of two or more vertical anodes in parallel by using the Sunde Equation as follows:

$$R = \frac{0.159\rho}{NL} \left[\left(\ln \frac{8L}{d} - 1 \right) + \frac{2L}{S} (\ln 0.656N) \right]$$

where -

R	=	resistance, in ohms, of N vertical anodes in parallel and spaced S centimeters apart along a straight line.
ρ	=	soil resistivity in ohm-cm
N	=	number of anodes
L	=	length of anode (or backfill column) in centimeters
d	=	diameter of anode (or backfill column) in centimeters
S	=	anode spacing in centimeters

According to the Sunde Equation, the anode bed resistance decreases with an increase in the number of anodes and/or an increase in the anode spacings. By adjusting the number and spacing of anodes, you can achieve a desired anode bed resistance. The desired anode bed resistance should be less than the allowable anode bed resistance given by the following formula:

$$R_{agb} = R_{max} - (R_S + R_{LW})$$

where -

R_{agb}	=	the allowable anode bed resistance
R_{max}	=	the maximum allowable circuit resistance (the rectifier's rated voltage minus 2 volts, divided by its rated current output)
R_S	=	structure-to-electrolyte resistance
R_{LW}	=	total lead wire resistance

Amount of Coke Breeze Required

To calculate the net volume of coke breeze in each backfill column, the anode volume is subtracted from the volume of the backfill column. This net volume is multiplied by the number of anodes and the coke breeze density to obtain the weight of coke breeze required. An extra 20% is added to cover spills and other waste.

Example

The following example assumes that the structure-to-electrolyte resistance and the lead wire resistance are known and the maximum allowable anode bed resistance has been determined. We will determine the number and spacing of anodes needed so that the anode bed resistance does not exceed the allowable anode bed resistance. Use the following engineering data.

CP current required: 16.5 amperes
Anode material: Silicon iron
Anode dimensions: 7.6 cm dia. x 152 cm length
Anode consumption rate: 1 kg/A-yr
Max. anode current density: 1 mA/cm²
Anode weight: 50 kg
Backfill dimensions: 20 cm dia. x 300 cm
Soil resistivity: 5,000 ohm-cm
Allowable anode bed resistance: 0.84 ohm
Coke breeze density: 730 kg/m³

Minimum Number of Impressed Current Anodes

We will design the anode bed so that it can discharge 20 amperes 120% of the 16.5 amperes required. To estimate the number of anodes required, multiply the total current requirement by the design life and consumption rate of the anode material as follows.

$$N = \left(\frac{Y \times I \times C}{W} \right) = (20 \text{ years})(20 \text{ A})(1 \text{ kg / A - yr}) / 50 \text{ kg} = 8 \text{ anodes}$$

We will use 10 anodes for the first calculation. (Using the current density method to calculate the minimum number of anodes would result in 6 anodes.)

Anode Bed Resistance

Substitute 10 anodes for N, 305 cm (10 ft.) spacing for S, and the backfill dimensions into the Sunde Equation as follows.

$$\begin{aligned}
 R &= \frac{0.159\rho}{NL} \left[\left(\ln \frac{8L}{d} - 1 \right) + \frac{2L}{S} (\ln 0.656 N) \right] \\
 &= \frac{0.159(5,000)}{(10)(300)} \left[\left(\ln \frac{8(300)}{20} - 1 \right) + \frac{2(300)}{(305)} (\ln(0.656)(10)) \right] \\
 R &= 1.984 \text{ ohms}
 \end{aligned}$$

This anode bed resistance exceeds the maximum allowable anode bed resistance of 0.84 ohms. However, according to the Sunde Equation, increasing the number of anodes can lower the resistance. If we substitute values of 20, 30, and 40 anodes for N at the 305 cm spacing, we obtain the following values.

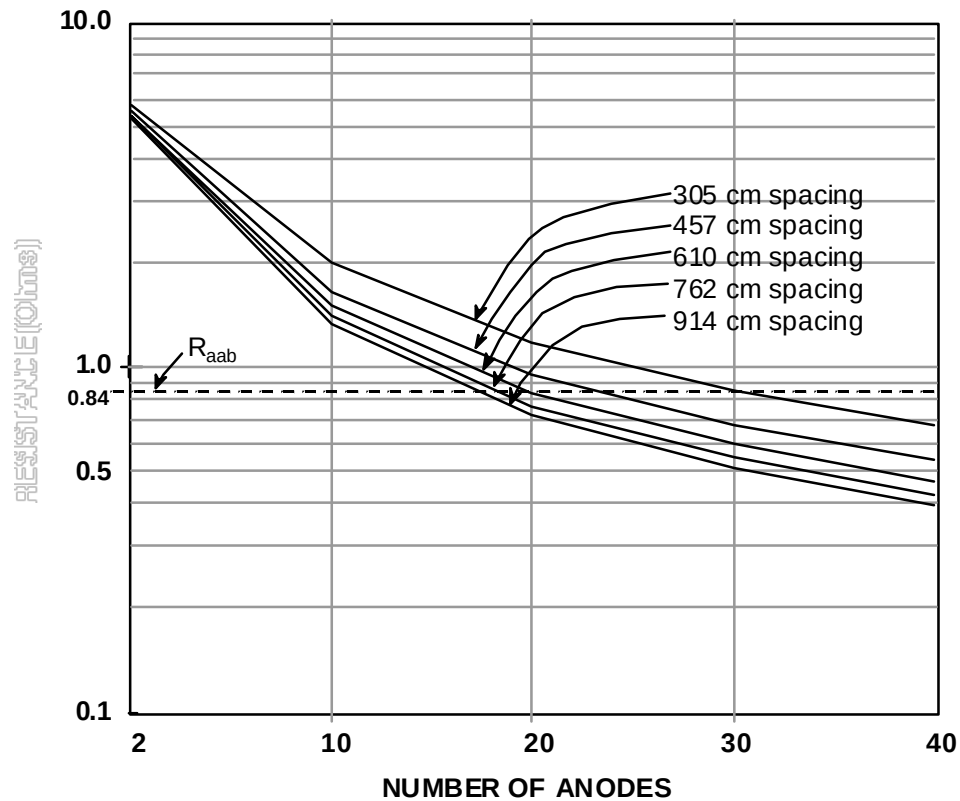
No. of Anodes	Anode Bed Resistance at 305 cm Spacing
10	1.984
20	1.173
30	0.852
40	0.677

The calculated anode bed resistance of 40 anodes installed with 305 cm spacings is less than the allowable resistance of 0.84 ohm. However, remember that increasing the anode spacing also decreases the anode bed resistance. If we repeat the calculations for spacings of 457, 610, 762, and 914 cm, (15, 20, 25, and 30 ft.) we obtain the following table.

Vertical Anode Bed Calculations

No. of Anodes	Anode Spacing in Centimeters				
	<u>305</u>	<u>457</u>	<u>610</u>	<u>762</u>	<u>914</u>
10	1.984	1.658	1.494	1.396	1.331
20	1.173	0.950	0.837	0.770	0.726
30	0.852	0.680	0.593	0.542	0.507
40	0.677	0.535	0.464	0.421	0.393

Based on the allowable anode bed resistance of 0.84 ohms, one option appears to be 20 anodes with 610 cm spacings. Another option—30 anodes with 457 cm spacings—would result in an anode bed resistance of 0.68 ohm. We can graph the values in the table to create a design chart as shown in Figure 8.



Vertical Anode Design Chart for an Impressed Current Anode Bed
in Soil with a Resistivity of 5,000 ohm-cm

Figure 8

Design charts are an efficient alternative to making several calculations for each anode bed design. The design chart in Figure 8 is based on a soil resistivity of 5,000 ohm-cm. To use this chart for other soil resistivities, the allowable anode bed resistance, R_{agb} , must be converted to a value that corresponds to a soil resistivity of 5,000 ohm-cm. The Sunde Equation can be used to show that anode bed resistance is directly proportional to soil resistivity as follows:

$$\frac{R_{\rho} \text{ ohm} - \text{cm}}{R_{5,000} \text{ ohm} - \text{cm}} = \frac{\rho \text{ ohm} - \text{cm}}{5,000 \text{ ohm} - \text{cm}}$$

Therefore,

$$R_{5,000} \text{ ohm} - \text{cm} = R_{\rho}(5,000/\rho)$$

In summary, the allowable anode bed resistance is determined for 5,000 ohm-cm soil. Then the design chart in Figure 8 is used to select the optimum number and spacing of anodes to achieve an anode bed resistance less than or equal to the allowable anode bed resistance. Work Aid 1B provides a procedure for using a design chart to determine the optimum number and spacing of impressed current anodes.

Amount of Coke Breeze Required

Next, we will calculate the amount of coke breeze required. Assume that the anode dimensions are 7.6 cm dia. x 152 cm and the coke breeze column dimensions are 20 cm. dia. x 300 cm length. First, the anode volume is subtracted from the volume of the anode backfill column.

The volume of one anode is

$$\pi(d^2/4)(L) = \pi(7.6^2/4)(152) = 6,895 \text{ cm}^3 = 0.007 \text{ m}^3.$$

The volume of one coke breeze column is

$$\pi(20^2/4)(300) = 94,247 \text{ cm}^3 = 0.09 \text{ m}^3.$$

The net volume of coke breeze in the column is

$$0.09 - 0.007 = 0.083 \text{ m}^3.$$

To obtain the weight of coke breeze required, this net volume is multiplied by the number of anodes and the coke breeze density. An extra 20% is added to cover spills.

$$(0.083 \text{ m}^3)(20 \text{ anodes})(730 \text{ kg/m}^3)(120\%) = 1,454 \text{ kg}$$

The formulas and procedure to design impressed current anode beds are provided in Work Aid 1B.

Designing Cathodic Protection Systems for Onshore Well Casings

Saudi Aramco cathodically protects all onshore well casings with impressed current systems. Saudi Aramco's goal is to protect both well casings and associated flowlines and pipelines as an integrated system. This is accomplished by minimizing the use of pipeline insulating devices. If an insulation device is installed, a bonding box is used in case it becomes necessary to short circuit the insulator. Saudi Aramco normally uses an individual impressed current system to protect each well. However, multiple wells are sometimes protected by a single impressed current system.

Saudi Aramco uses both surface and deep anode beds to protect onshore well casings. The type of anode bed and its location are determined by the following:

- its current output capacity
- the surface soil resistivity
- the number of well casings to be protected
- the physical layout of the wells and facilities
- economics

Saudi Aramco uses remote surface anode beds where soil resistivity is low enough for adequate current distribution. Where surface soil resistivity is high, deep anode beds are used. Deep anode beds are also used in congested areas such as pipeline corridors and in-plant areas to provide better current distribution.

Both surface and deep anode bed designs involve the following determinations:

- design requirements using Saudi Aramco Engineering Standards and Drawings
- cathodic protection current requirements

Descriptions of both requirements are provided in this section. After the information on cathodic protection current requirement is presented, surface and deep anode bed designs are discussed separately. Surface anode bed design for a well casing is similar to surface anode bed design for a buried pipeline, which was covered in the first section of this module. Therefore, this section focuses mainly on the design of deep anode beds.

Saudi Aramco Engineering Standards and Drawings

The design of cathodic protection systems for onshore well casings is governed by Saudi Aramco Engineering Standard SAES-X-700. SAES-X-700 states the following:

- the design capacity of impressed current systems shall be 50 amperes per well with uncoated casings and 10 amperes per well with coated casings. The Consulting Services Department may approve designs for lower capacity systems if adequate protection is verifiable.
- a single impressed current system may be used to protect more than one well if the wells are less than 200 meters apart.
- impressed current anode beds shall be sized to discharge 120% of the rated current output of the dc power source.
- impressed current systems shall have a design life of 20 years.

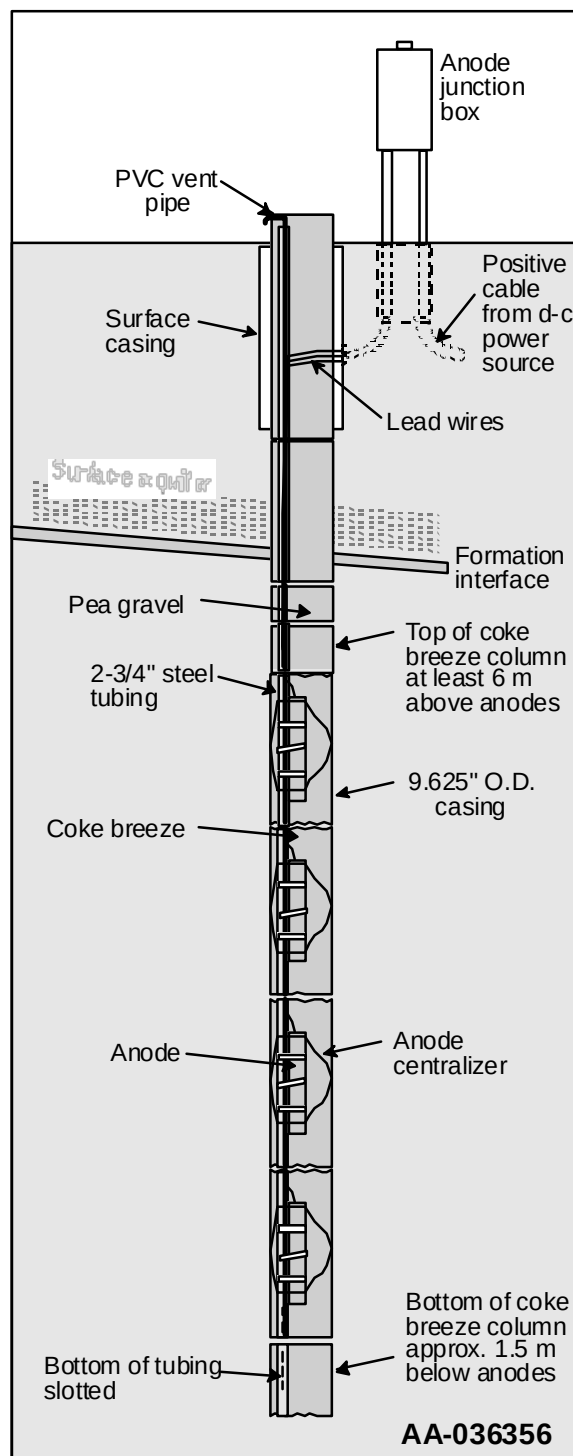
According to G.I. 428.003, a minimum negative casing-to-soil potential of 1.0 volt (current off) versus Cu-CuSO₄ is required.

A minimum distance of 150 meters is required between a deep anode bed and the well casing it is to protect. A minimum distance of 150 meters is also required from the anode bed to plant (GOSP, etc.) perimeter fencing. In addition, SAES-X-700 requires that deep anode beds are located remote from other buried structures. A distance of 50 meters is required for deep anode beds with a design current output of less than 30 amperes. A distance of 100 meters is required for anode beds with capacities between 30 and 50 amperes.

Surface anode beds should be designed in accordance with Standard Drawing AA-036346. Scrap steel surface anode beds should be designed in accordance with Standard Drawing AA-036278.

There are two types of deep anode beds: aquifer penetrating and non-aquifer penetrating. An aquifer penetrating deep anode bed is shown in Figure 9. Impressed current anodes and a PVC vent pipe are strapped to 2-3/4" steel tubing and surrounded by coke breeze inside 9-5/8" casing. A water and coke breeze slurry is pumped in the hole from the bottom up through the steel tubing. An individual lead wire connects each anode to the junction box.

Anode reactions with water or brine generate chlorine gas and oxygen. If these gases cannot escape, they will surround the anodes and increase the anode bed resistance. The anodes are mounted on a perforated PVC pipe so that the gas can escape freely. Saudi Aramco rarely uses aquifer penetrating deep anode beds. Aquifer penetrating deep anode installations must be approved by Saudi Aramco's Hydrology Department. The Hydrology Department regulates the drilling depth to minimize the chances of communication between subsurface aquifers.

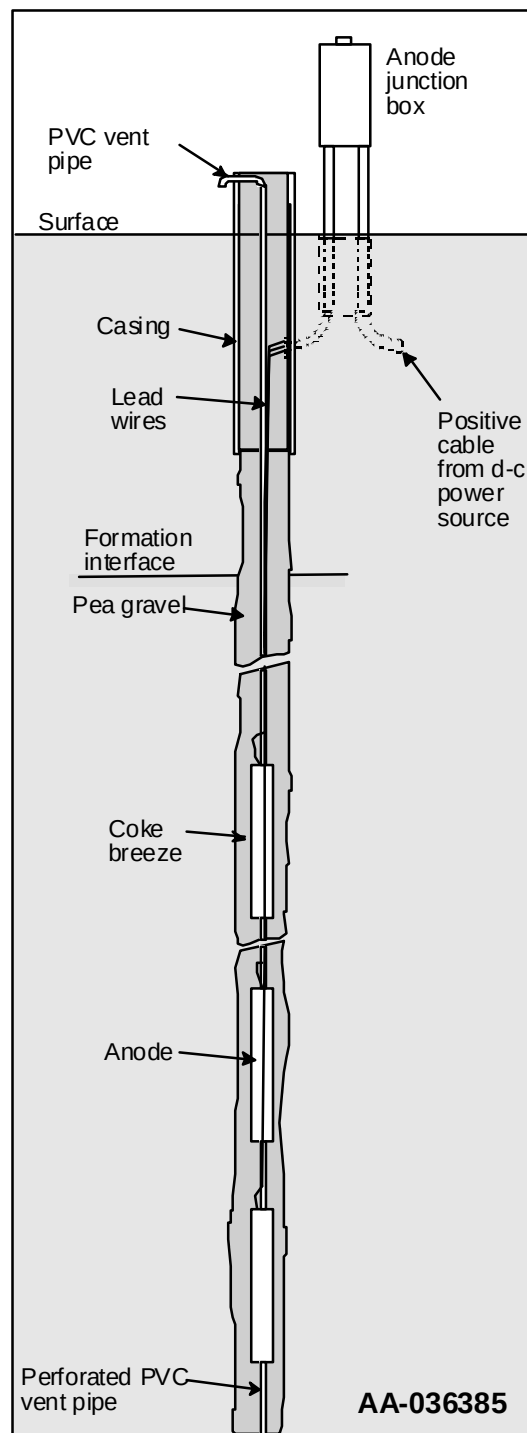


Aquifer Penetrating Deep Anode Bed from Standard Drawing AA-036356

Figure 9

Non-aquifer penetrating deep anode beds contain anodes and coke breeze without a full length of casing (Figure 10). Saudi Aramco installs a PVC vent pipe to allow gases formed by anodic reactions to escape. A separate loading pipe is run to the bottom of the hole and used to pump a water slurry of coke breeze into the hole. The loading pipe is slowly withdrawn from the hole as it is filled with coke breeze. This procedure allows the slurry to be pumped upward from the bottom of the well until the anodes are completely surrounded.

The Hydrology Department regulates the acceptable depth of the deep anode bed. The location of the anode bed is approved in writing.



Non-Aquifer Penetrating Deep Anode Bed from
Standard Drawing AA-036385.

Figure 10

Cathodic Protection Current Requirements

The current required to protect an onshore well casing depends on its environment. The operating environment can be very complex. Environmental considerations include the following:

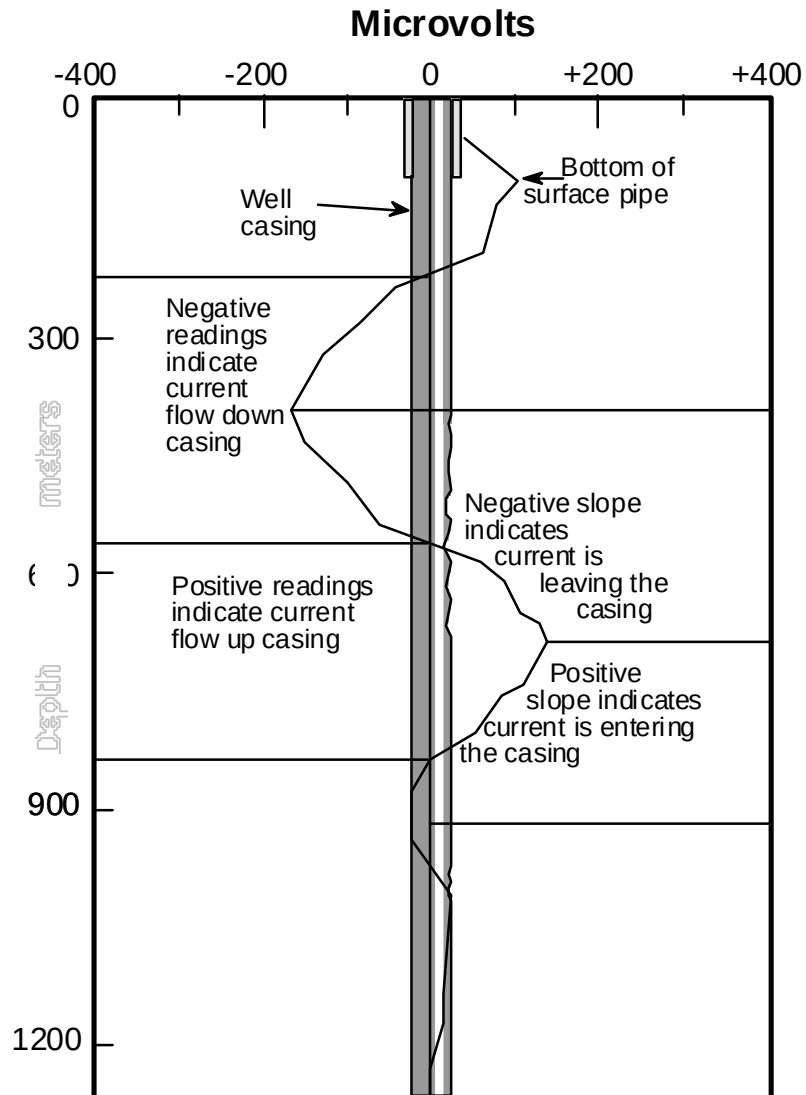
- well spacing
- the size, area, and depth of well casings, cementing information, and coatings (if used)
- nearby pipelines with or without cathodic protection systems
- process plants
- storage tanks
- electrical power lines, substations, etc.
- hazardous or unique requirements at proposed sites

Current requirements can be determined for a particular producing area since formation conditions and well completion methods are usually similar. Saudi Aramco uses casing potential profile techniques to determine current requirements. Casing profiles are similar to line current surveys for buried pipelines. These tests are expensive so they are not performed on every well. The tubing must be pulled so that the potential profile tool can contact the internal casing wall. Saudi Aramco now uses a new logging tool which does not require the well bore to be filled with a non-conducting fluid.

Basically, a downhole logging tool measures the voltage (IR drop) at regular intervals in the casing. The logging tool contains spring-loaded knife blades or hydraulically-activated contacts that are located several feet apart.

Once the well bore has been prepared, the logging tool is lowered into the well. The voltage between the blades or contacts is measured by using a sensitive voltmeter. Readings are usually taken from the bottom to the top of the casing. The tool also measures casing resistance so an accurate current flow can be calculated ($I=V/R$).

Current that flows onto the casing is assumed to be cathodic protection current. Current that flows away from the casing is assumed to be corrosion current. Current must flow onto the entire casing for it to be adequately protected. Figure 11 shows how the readings are plotted and interpreted.



Casing Potential Profile

Figure 11

Surface Anode Bed Design

Surface anode beds that protect well casings are designed similarly to anode beds that protect buried pipelines. The number and spacing of anodes can be adjusted so that the total circuit resistance is less than the maximum allowable circuit resistance. As with anode beds for buried pipelines, Saudi Aramco only considers the anode-to-earth resistance. The resistance of a surface anode bed is given by the Sunde Equation.

$$R = \frac{0.159\rho}{NL} \left[\left(\ln \frac{8L}{d} - 1 \right) + \frac{2L}{S} (\ln 0.656N) \right]$$

where -

- R = resistance, in ohms, of N vertical anodes in parallel and spaced S centimeters apart along a straight line.
- r = soil resistivity in ohm-cm
- N = number of anodes
- L = length of anode (or backfill column) in centimeters
- d = diameter of anode (or backfill column) in centimeters
- S = anode spacing in centimeters

The formulas and procedure used to design surface anode beds for onshore well casings are similar to those used for buried pipelines, which are provided in Work Aid 1B.

Deep Anode Bed Design

Deep anode bed design includes determining the following:

- length of the coke breeze column (based on the number of anodes required)
- circuit resistance
- amount of coke breeze required

After describing how the above information is determined, an example, which demonstrates the design of a deep anode bed, is provided.

Length of the Coke Breeze Column

The length of the coke breeze column depends on the number and spacing of anodes in the deep anode bed. The anode spacing is determined in the field. Anodes are usually vertically spaced on 5 meter centers. As with surface anode beds, the number of anodes needed can be calculated by using the anode's maximum current output in the electrolyte or the anode's consumption rate. It is best to use the method that gives the more conservative value or the greater number of anodes.

To calculate the minimum number of anodes based on the anode's maximum current density, the following formula is used:

$$N = I / (\pi d L \times \gamma_A)$$

where -

N	=	number of impressed current anodes
I	=	total current required in milliamperes times 120%
d	=	anode diameter in centimeters
L	=	anode length in centimeters
γ_A	=	anode maximum current density in mA/cm ²

To calculate the minimum number of anodes based on the anode's consumption rate, the following formula is used:

$$N = \left(\frac{Y \times I \times C}{W} \right)$$

where -

N	=	number of impressed current anodes
Y	=	the impressed current system design life in years
I	=	total current required in amperes times 120%
C	=	anode consumption rate in kg/A-yr
W	=	weight of a single anode

Circuit Resistance

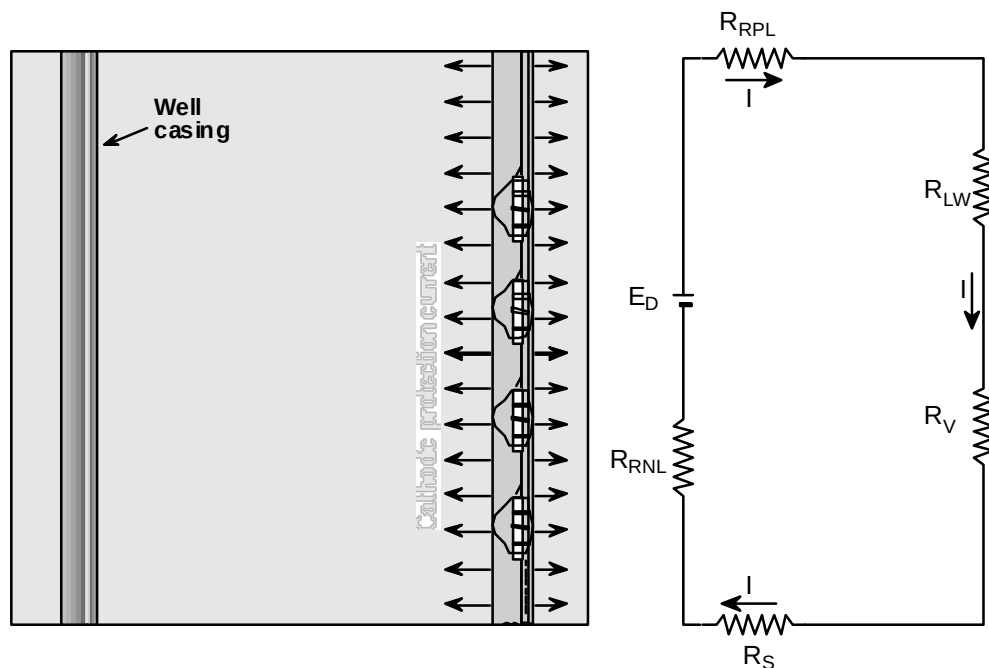
The total current output of a deep anode impressed current system is given by the formula:

$$I = E_D / R_C$$

where -

- E_D = the voltage capacity of the dc power source minus 2 volts
- R_C = circuit resistance of the deep anode impressed current system

The circuit resistance, R_C , is represented by the equivalent electrical circuit in Figure 12. For design purposes, a deep anode bed is treated as if it were a single vertical anode.



Deep Anode Impressed Current System and Equivalent Electrical Circuit

Figure 12

The circuit resistance, R_C , is given by the following formula:

$$R_C = R_{RPL} + R_{LW} + R_V + R_S + R_{RNL}$$

where -

- R_{RPL} = the resistance in the positive lead wire from the rectifier to the junction box
- R_{LW} = the equivalent resistance of the anode lead wires in parallel
- R_V = the resistance of the anode bed column as a single vertical anode
- R_S = structure-to-electrolyte resistance
- R_{RNL} = the resistance in the negative lead wire from the well casing to the rectifier

Because the anode bed is treated as a single vertical anode, the anode bed resistance can be calculated by using the Dwight Equation as follows:

$$R_V = \frac{0.159\rho_{\text{eff}}}{L} \left(\ln \frac{8L}{d} - 1 \right)$$

where -

R_V	=	resistance of vertical anode to earth in ohms
ρ_{eff}	=	effective soil resistivity of the interval in ohm-cm
L	=	length of coke breeze column in centimeters
d	=	diameter of deep anode hole in centimeters

The effective soil resistivity, ρ_{eff} , is the average resistivity over the interval where the anodes will be placed. The soil resistivity is measured by using Geonics instruments.

The circuit resistance, R_C , must be less than the maximum allowable circuit resistance. The maximum circuit resistance, R_{max} , is given by the following formula:

$$R_{\text{max}} = E_D/I$$

where -

E_D	=	the driving voltage of the dc power source
I	=	the current output rating of the dc power source

Amount of Coke Breeze Required

Normally, the amount or weight of coke breeze required is calculated by multiplying the net volume of coke breeze (plus an extra 20% because of spillage) by the coke breeze density. The net volume of coke breeze required is calculated by subtracting the volumes of the anodes and vent pipe from the total volume of the backfill column. However, for our purposes, we will use the total volume of the backfill column to calculate the weight of coke breeze required.

Example

This example will demonstrate the design of a deep anode bed to protect an onshore well casing in accordance with Saudi Aramco standards and practices. Using the following data, we will design the anode bed:

Current required: 50 amperes

Well casing-to-soil resistance: 0.08 ohm

Anode material: High silicon chromium cast iron

Anode consumption rate: 0.45 kg/A-yr

Weight per anode: 50 kg

Anode dimensions: 7.6 cm dia. x 152 cm length

Rectifier output rating: 50 V, 50 A

Lead wire resistance: No. 4 AWG - 0.85×10^{-3} ohm/m (rectifier to junction box and well)

No. 6 AWG - 1.35×10^{-3} ohm/m (anodes)

Coke breeze density: 730 kg/m³

Distance from rectifier to junction box: 5 meters

Distance from rectifier to well casing: 150 meters

Depth at top of coke breeze column: 69 meters

Diameter of coke breeze column: 30 cm

Length of the Coke Breeze Column

Eight amperes of current are required to protect the well casing. According to SAES-X-700, we will design the system for 50 amperes. To estimate the number of anodes, the current required is multiplied by the design life and the anode consumption rate. Then the total weight is divided by the mass per anode as follows:

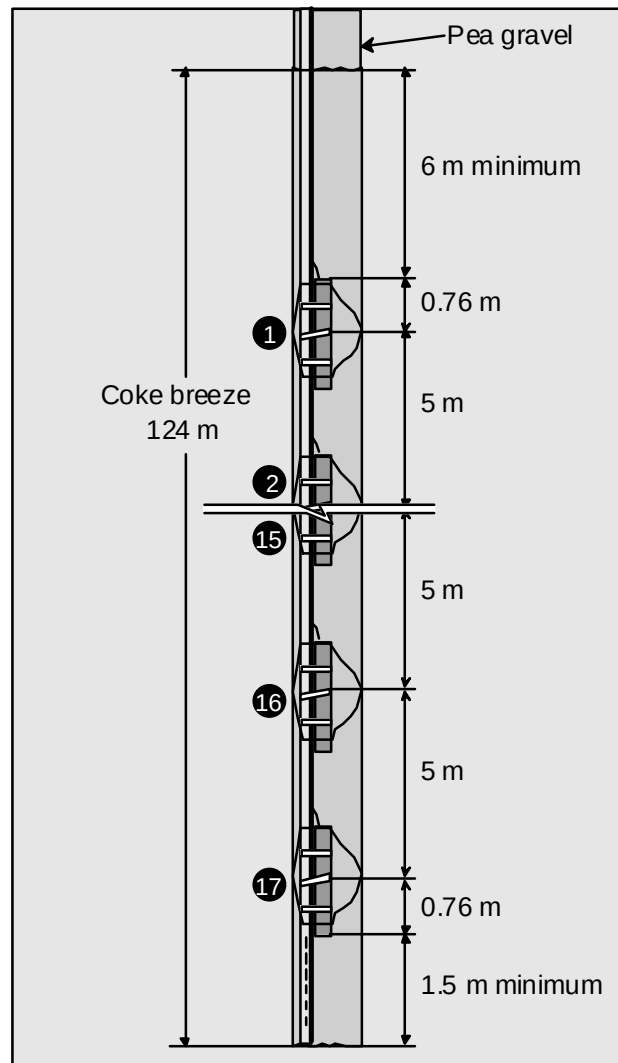
$$(20 \text{ years})(50 \text{ A})(120\%)(0.45 \text{ kg/A-yr})/50 \text{ kg per anode} = 11 \text{ anodes}$$

If we use the current density formula for calculating the number of anodes needed, we get:

$$\begin{aligned} N &= I / (\pi d L \times \gamma_A) \\ &= \frac{(50,000 \text{ mA})(1.2)}{\pi(7.6 \text{ cm})(152 \text{ cm})(1 \text{ mA/cm}^2)} \\ &= 16.5 \text{ anodes round up to 17 anodes} \end{aligned}$$

Since 17 anodes is the larger calculated by the two methods, we will design our anode bed with 17 anodes.

Seventeen high silicon chromium cast iron anodes (1.52 meters long) spaced on 5 meter centers require an interval of 81.5 meters (Figure 13). Standard Drawing AA-036356 requires at least 6 m of coke breeze above the anodes and a minimum of 1.5 m below the anodes. Therefore, the minimum length of this particular coke breeze column is $81.5\text{ m} + 6\text{ m} + 1.5\text{ m} = 89\text{ m}$.



Length of the Coke Breeze Column in a Deep Anode Bed

Figure 13

Circuit Resistance

Assume that the Geonics instrument measured an effective soil resistivity of 2482 ohm-cm. By using ρ_{eff} and treating the anode bed as a single anode, we can calculate the deep anode bed resistance. The anode bed is 30 cm in diameter and 8,900 cm long. Therefore, the anode bed resistance is as follows:

$$R_V = \frac{0.159(2,482)}{8,900} \left(\ln \frac{8(8,900)}{30} - 1 \right) = 0.300 \text{ ohm}$$

Next, we must ensure that the total circuit resistance is less than the maximum allowable circuit resistance and calculate the amount of coke breeze required. The resistance in the rectifier's negative and positive lead wires is calculated as follows:

$$R_{NLW} + R_{PLW} = (150\text{m} + 5\text{m})(110\%)(0.85 \times 10^{-3} \text{ ohm/m}) = 0.145 \text{ ohm}$$

The following is the equivalent resistance of the lead wires from the junction box to the anodes:

$$R_{LW} = \left\{ \frac{(17)(75) + \sum_{i=0}^{16} i(5) \text{ meters}}{17} \right\} (120\%) (1.35 \times 10^{-3} \text{ ohm/m}) = 0.186 \text{ ohm}$$

Including the well casing-to-soil resistance of 0.08 ohm, the total circuit resistance is calculated as follows:

$$R_C = 0.300 + 0.145 + 0.186 + 0.08 = 0.711 \text{ ohm.}$$

The total circuit resistance is less than the maximum allowable circuit resistance, R_{max} .

$$R_{\text{max}} = (50\text{V} - 2\text{V})/50 \text{ A} = 0.96 \text{ ohm.}$$

Amount of Coke Breeze Required

The total volume of the coke breeze column is

$$\pi(d^2/4)H = \pi(.30^2/4)(89 \text{ m}) = 6.291 \text{ m}^3.$$

The weight of coke breeze required is

$$(6.291 \text{ m}^3)(120\%) (730\text{kg/m}^3) = 5,510 \text{ kg.}$$

The formulas and procedure to design deep anode beds are provided in Work Aid 2.

Designing Cathodic Protection Systems for Vessel and Tank Interiors

Production vessels and storage tanks contain fluids that range from very corrosive hot, sour brines to demineralized water or steam condensate. Sometimes, coatings alone can adequately protect vessels. In most cases, both coatings and cathodic protection are required to prevent corrosion.

Galvanic anodes are usually the most economical choice except in very large tanks. In drinking water systems, where contamination from anode corrosion products is a concern, Saudi Aramco uses indium activated aluminum galvanic anodes. Saudi Aramco normally uses high silicon chromium cast iron impressed current anodes to protect the interiors of large tanks. Whenever impressed current systems are considered, an economic analysis should be performed.

This section is divided into two parts. The first part covers galvanic anode system designs for vessel and tank interiors. The second part covers impressed current system designs for tank interiors. The designs for both types of CP systems include determining the following:

- cathodic protection current requirement
- design requirements in accordance with Saudi Aramco Engineering Standards and Drawings

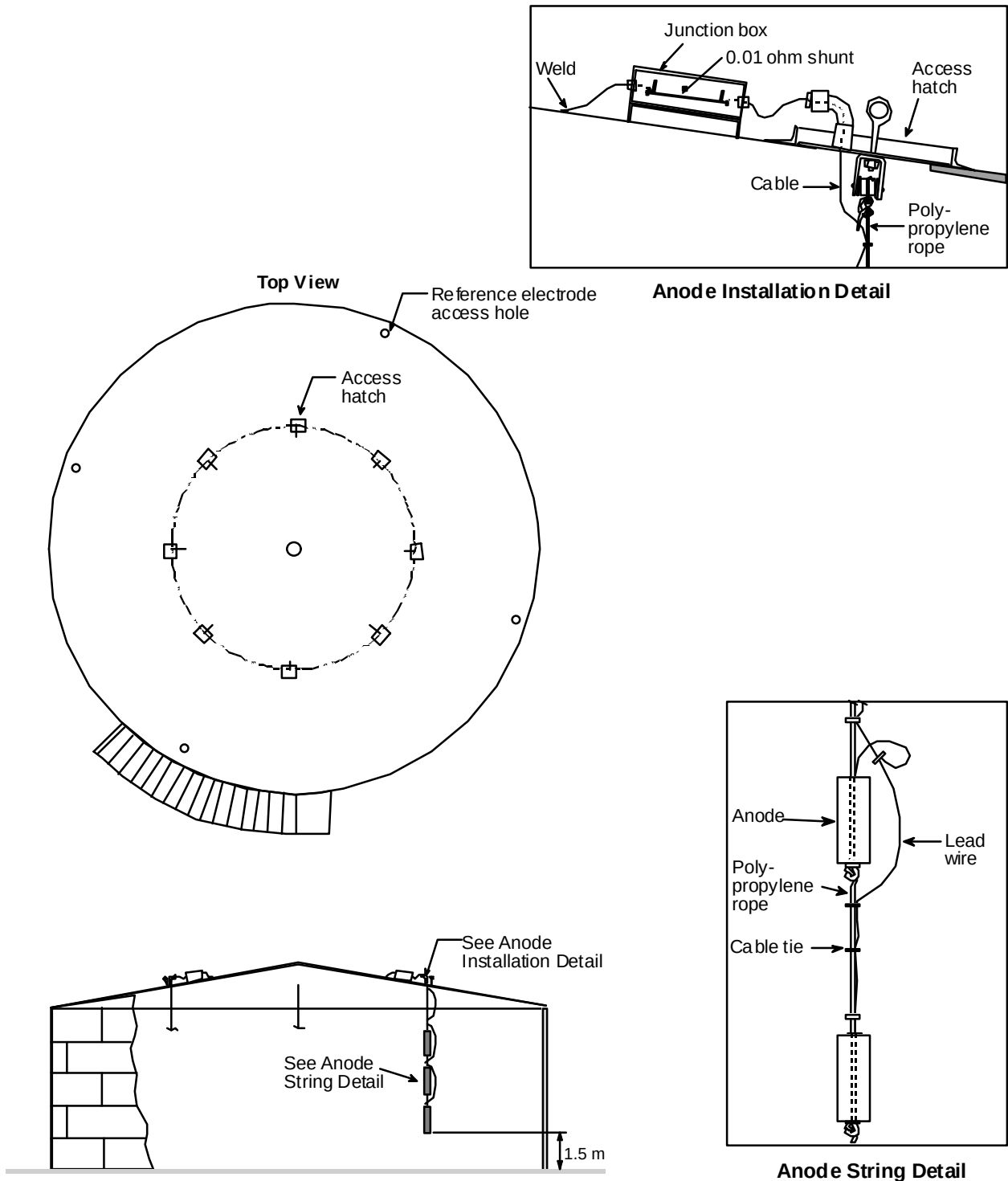
In Module 107.01, we calculated the total current requirement by multiplying the required current density from SAES-X-500 by the water-wetted surface area. Therefore, the designs in this section assume that the total current requirement has been calculated. After the following description of design requirements from Saudi Aramco's standards and drawings, methods and examples for designing galvanic and impressed current systems are presented.

Saudi Aramco Engineering Standards and Drawings

The design of cathodic protection systems for vessel and tank interiors is governed by Saudi Aramco Engineering Standard SAES-X-500. SAES-X-500 states the following:

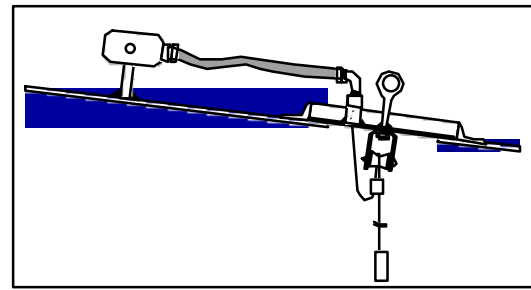
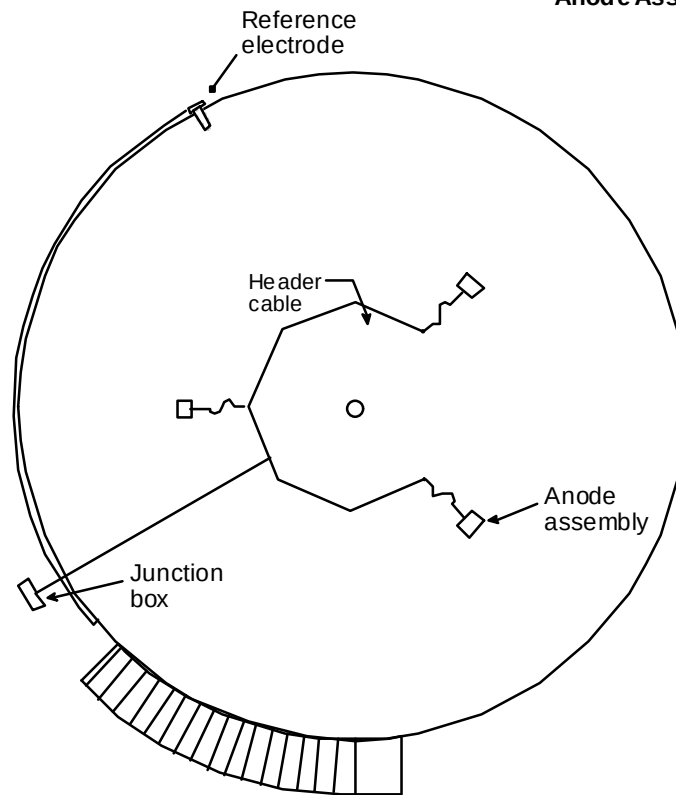
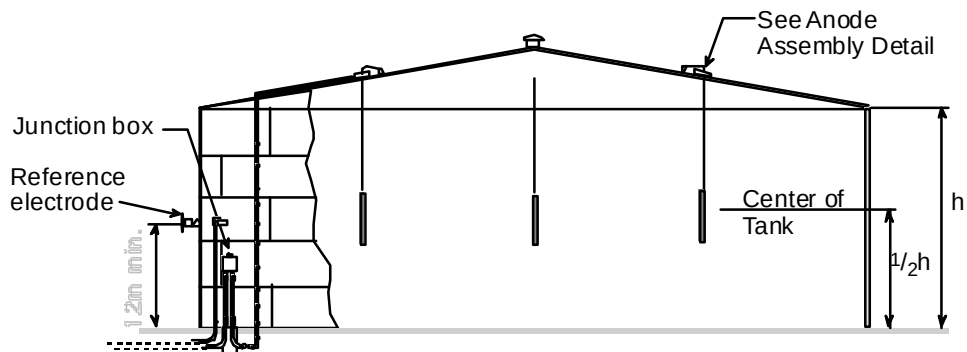
- Section 4.1.1 - Cathodic protection is mandatory if the resistivity of the contents is expected to be 1500 ohm-centimeter or less during the life of the tank or vessel.
- Section 4.3.1 - The design life of galvanic or impressed current anode systems shall be 5 years or the testing and inspection (T&I) period, whichever is greater.
- Section 4.3.2 - Galvanic anodes in dehydrator vessels shall be designed using a 20% efficiency factor. Designs for 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 (current on) versus a Ag-AgCl reference electrode, or +0.15 V (current on) versus a zinc electrode.
- Section 4.6.3 - Aluminum and zinc anodes shall not be used if the water resistivity is more than 1000 ohm-centimeters.
- Section 4.6.4 - Magnesium anodes shall not be used if the water resistivity is less than 500 ohm-centimeters.
- Section 4.6.5 - Zinc anodes shall not be used in environments where the temperature exceeds 49° C.

Cathodic protection designs for tanks are based on construction standards set in the following Standard Drawings: AA-036354 (Water Storage Tanks Galvanic Anodes) and AA-036353 (Water Storage Tanks Impressed Current). The number, depth, and location of galvanic and impressed current anodes are based on tank size, water level variation, and water resistivity. Some diagrams from AA-036354 and AA-036353 are shown in Figures 14 and 15.



Diagrams from Standard Drawing AA-036354, Water Storage Tanks Galvanic Anodes

Figure 14

**Anode Assembly Detail****Top View**

Diagrams from Standard Drawing AA-036353, Water Storage Tanks Impressed Current

Figure 15

Galvanic Anode System Design for Vessel and Tank Interiors

The design of galvanic anode systems for vessel and tank interiors includes determining the following:

- the current output per anode
- the number of galvanic anodes required
- galvanic anode life

After describing these calculations, an example, which demonstrates the design of galvanic anode systems, is provided.

Current Output Per Anode

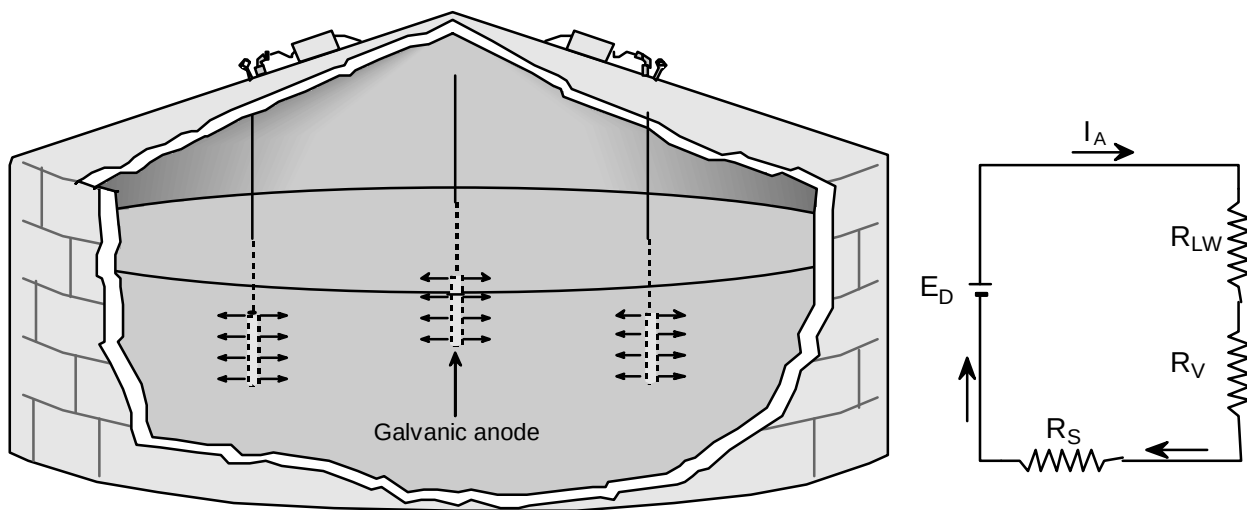
The current output of a single galvanic anode in a vessel or tank is given by the following formula

$$I_A = E_D / R_C$$

where -

- I_A = current output of a single anode
- E_D = anode driving potential
- R_C = circuit resistance

The circuit resistance of a single anode, R_C , is represented in Figure 16 in the equivalent electrical circuit.



Tank Galvanic Anode System and Equivalent Electrical Circuit for Each Anode
Figure 16

The circuit resistance is given by the following formula:

$$R_C = R_S + R_{LW} + R_V$$

where -

- R_S = structure-to-electrolyte resistance in ohms
- R_{LW} = the anode lead wire resistance in ohms
- R_V = the anode-to-electrolyte resistance in ohms

The anode-to-electrolyte resistance of a single vertical anode, R_V , is given by the Dwight Equation.

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

where -

- R_V = resistance of one vertical anode to the electrolyte in ohms
- ρ = resistivity of the electrolyte in ohm-cm
- L = length of the anode in centimeters
- d = diameter of the anode in centimeters

Number of Galvanic Anodes Required

The number of galvanic anodes required is calculated by dividing the total current requirement by the current output of a single galvanic anode as shown in the following equation:

$$N = I/I_A$$

where -

- N = the number of anodes
- I = the total current required to protect the structure
- I_A = the current output of a single anode

Galvanic Anode Life

The life of a galvanic anode can be estimated if its weight and current output are known. The expected life of a galvanic anode is given by the following formula:

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

where -

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

Example

Given the following engineering data, we will calculate the current output, number, and life of galvanic anodes required to protect the interior of a water storage tank.

Current required: 3.6 amperes

Structure-to-electrolyte resistance: 0.042 ohms

Lead wire resistance: 0.024 ohms

Water resistivity: 15 ohm-cm

Anode: Hydral 2B

Anode dimensions: 22 cm dia. x 22 cm

Anode actual consumption: 4.11 kg/A-yr

Anode weight: 22 kg

Anode solution potential: -1.05 V versus Ag-AgCl

Required structure-to-electrolyte potential: -0.90 V versus Ag-AgCl

Current Output Per Anode

The current output of a single anode is given by the following formula:

$$I = E_D / R_C = (E_A - E_S) / (R_S + R_{LW} + R_V)$$

If we calculate R_V by using the Dwight Equation and insert the known values for E_A , R_S , and R_{LW} , we can determine the anode current output of a single anode as a function of the structure's potential as follows.

$$R_V = \frac{0.159\rho}{L} \left(\ln \frac{8L}{d} - 1 \right) = \frac{0.159(15)}{22} \left(\ln \frac{8(22)}{22} - 1 \right) = 0.12 \text{ ohm}$$

$$I = (1.05 - E_S) / (0.042 + 0.024 + 0.12) = (1.05 - E_S) / 0.186$$

At a negative structure potential of 0.90 volt, the anode's current output is

$$I = (1.05 - 0.90) / 0.186 = 0.81 \text{ A.}$$

Number of Galvanic Anodes Required

The number of anodes required is 3.6 A/0.81 amperes per anode, or at least 5 anodes.

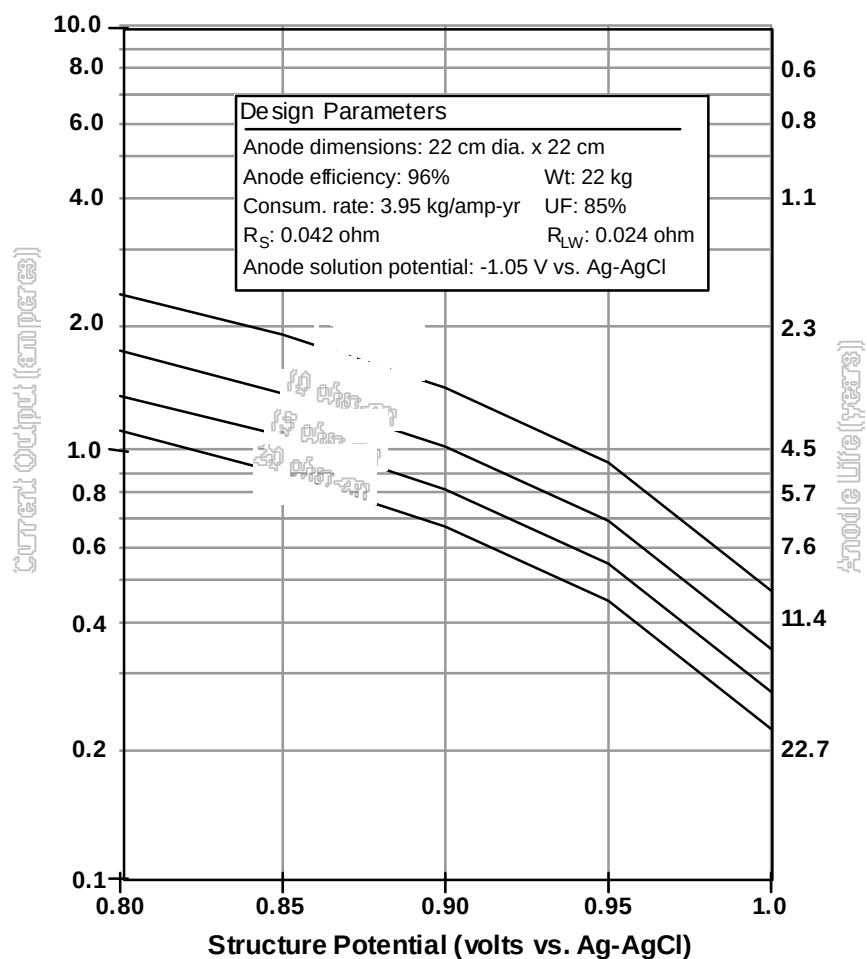
Galvanic Anode Life

$$Y = \left(\frac{W \times UF}{C \times I_A} \right) = \left(\frac{22 \text{ kg} \times 0.85}{4.11 \text{ kg / A - yr} \times 0.81 \text{ A}} \right) = 5.6 \text{ years}$$

We can develop similar “performance data” for this particular Hydral 2B anode in electrolytes with different resistivities. For example, the current output of the Hydral 2B anode in a 10 ohm-cm electrolyte is calculated as follows.

$$I = (1.05 - E_s) / \left(0.042 + 0.024 + \frac{10}{15} (0.12) \right) = (1.05 - E_s) / 0.15$$

By plotting the formulas at water resistivities of 5, 10, 15 and 20 ohm-cm, we obtain the performance chart shown in Figure 17. The anode life is shown on the right side of the performance chart.



Performance Chart of a Hydral 2B Anode
Figure 17

The formulas and procedure used to design galvanic anode systems for vessel and tank interiors are provided in Work Aid 3A.

Impressed Current System Design for Vessel and Tank Interiors

The design of impressed current systems for vessel and tank interiors includes determining the following:

- the number of impressed current anodes required
- the circuit resistance

After describing these calculations, an example, which demonstrates the design of an impressed current system for a tank interior, is provided.

Number of Impressed Current Anodes Required

The number of anodes can be calculated based on the anode's maximum current output in the electrolyte or the anode's consumption rate. It is best to use the method that gives the more conservative value; that is, the method that results in the greatest number of anodes.

To calculate the minimum number of anodes based on the anode's maximum current density, the following formula is used:

$$N = I / (\pi d L \times \gamma_A)$$

where -

- | | | |
|------------|---|---|
| N | = | number of impressed current anodes |
| I | = | total current required in milliamperes* |
| d | = | anode diameter in centimeters |
| L | = | anode length in centimeters |
| γ_A | = | anode maximum current density in mA/cm ² |

To calculate the minimum number of anodes based on the anode's consumption rate, the following formula is used:

$$N = \left(\frac{Y \times I \times C}{W} \right)$$

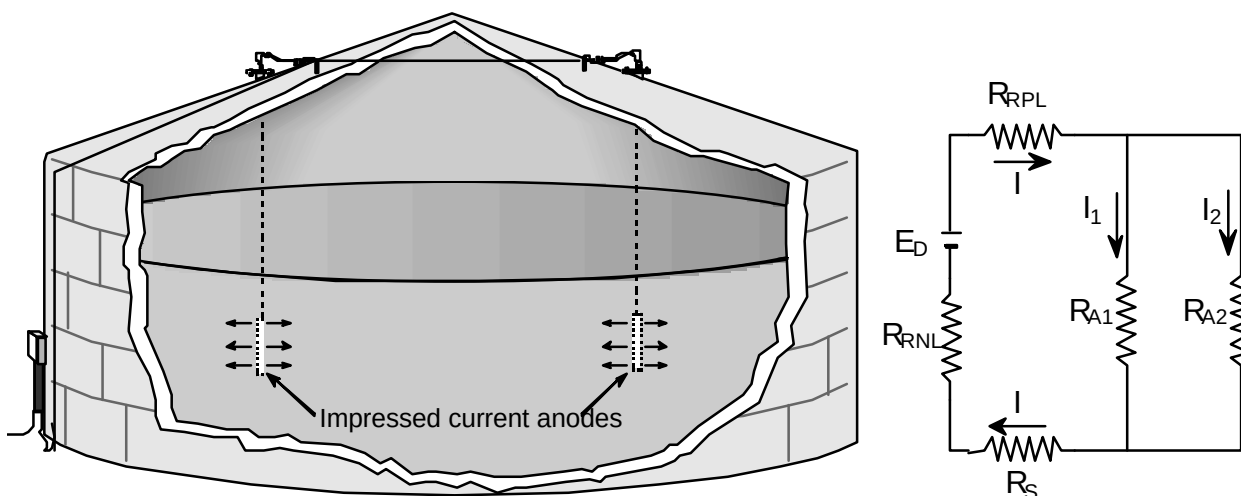
where -

- | | | |
|---|---|---|
| N | = | number of impressed current anodes |
| Y | = | the impressed current system design life in years |
| I | = | total current required in amperes* |
| C | = | anode consumption rate in kg/A-yr |
| W | = | weight of a single anode |

* The total current required is usually multiplied by 120%.

Circuit Resistance

Impressed current anodes in vessels or tanks are connected in parallel as shown in Figure 18. The circuit resistance includes the anode resistances in parallel and the resistances in the negative and positive lead wires of the rectifier.



Tank Impressed Current System and Equivalent Electrical Circuit

Figure 18

The equivalent resistance of N resistances in parallel is obtained from the following formula:

$$\frac{1}{R_{eq}} = \frac{1}{R_{A1}} + \frac{1}{R_{A2}} + \dots + \frac{1}{R_{AN}}$$

If the resistances are equal, the equivalent resistance is given by the following formula:

$$\frac{1}{R_{eq}} = \frac{1}{R_{A1}} + \frac{1}{R_{A2}} + \dots + \frac{1}{R_{AN}} = \frac{N}{R_A} \quad \therefore R_{eq} = \frac{R_A}{N}$$

Therefore, the circuit resistance is given by the formula shown below

$$R_C = R_{RPL} + \frac{R_A}{N} + R_S + R_{RNL}$$

where -

- R_C = the circuit resistance of the entire impressed current system in ohms
- R_{RPL} = the resistance in the positive lead wire from the rectifier to the junction box
- N = the number of impressed current anodes
- R_A = the resistance of a single impressed current anode
- R_S = structure-to-electrolyte resistance
- R_{RNL} = the resistance in the negative lead wire from the structure to the rectifier

The circuit resistance, R_C , must be less than the maximum allowable circuit resistance given by the formula:

$$R_{\max} = E_D/I$$

where -

E_D = the rated voltage of the dc power source
 I = the current output rating of the dc power source

Example

We will design an impressed current system to protect a large, coated storage tank by using the following information:

Current required: 4.95 amperes
Structure-to-electrolyte resistance: 0.06 ohms
Anode lead wire resistance: 0.038 ohms
Rectifier negative lead resistance: 0.04 ohm
Rectifier positive lead resistance: 0.05 ohm
Water resistivity: 15 ohm-cm
Anode material: High silicon chromium cast iron
Anode dimensions: 5.08 cm dia. x 152.4 cm (2" dia. x 60")
Anode weight: 27.3 kg
Anode maximum current density: 0.5 mA/cm²
Anode consumption rate: 1 kg/A-yr
Required structure-to-electrolyte potential: -0.90 V versus Ag-AgCl
Rectifier output rating: 50 V, 50 A

Number of Impressed Current Anodes

First, we will calculate the surface area of a single anode as follows:

$$\text{Anode surface area} = \pi dL = (3.14)(5.08)(152.4) = 2431 \text{ cm}^2$$

The maximum current output for one anode is

$$I_A = (0.5 \text{ mA/cm}^2)(2,431 \text{ cm}^2) = 1,215.5 \text{ mA} = 1.22 \text{ amperes per anode.}$$

Therefore, the number of anodes required is

$$N = 4.95 \text{ amperes} / 1.22 \text{ amperes per anode} = 5 \text{ anodes.}$$

Circuit Resistance

The resistance of the 5 anodes in parallel is given by the following formula:

$$\frac{R_A}{N} = \frac{R_{LW} + R_V}{N}$$

We can solve for R_V by using the Dwight Equation for a single anode as follows.

$$R_V = \frac{0.159\rho}{L} \left(\ln \frac{8L}{d} - 1 \right) = \frac{0.159(15)}{152.4} \left(\ln \frac{8(152.4)}{5.08} - 1 \right) = 0.07 \text{ ohm}$$

Substituting all resistance values into the circuit resistance formula we obtain the following circuit resistance:

$$R_C = R_{RNL} + \frac{R_{LW} + R_V}{N} + R_S + R_{RPL}$$

$$R_C = 0.04 + \frac{0.038 + 0.07}{5} + 0.06 + 0.05$$

$$R_C = 0.17 \text{ ohm}$$

The calculated circuit resistance is less than the maximum allowable circuit resistance, which is

$$R_{\max} = 50 \text{ V} / 50 \text{ A} = 1.0 \text{ ohm}.$$

The formulas and procedure used to design an impressed current system to protect the interior of a vessel or tank are provided in Work Aid 3B.

Designing Cathodic Protection Systems For In-Plant Facilities

There are a particular set of problems involved when cathodically protecting structures within a plant area. Hydrocarbon lines, firewater piping, buried valves, and tank bottoms are examples of critical systems, which require cathodic protection in plant areas. Some external corrosion problems are caused by the buried copper grounding grid, which is designed to protect personnel in case of an electrical ground fault. Without cathodic protection, buried steel piping corrodes faster because it becomes anodic to the copper grid.

Tank bottoms in contact with the earth are susceptible to corrosion due to moisture in the soil. Saudi Aramco often bonds tanks and buried structures together and cathodically protects them as a single unit. Cathodic protection current is supplied by surface distributed impressed current or galvanic anode systems near tanks or between parallel pipes. This installation ensures uniform current distribution and prevents shielding.

Previous sections of this module have addressed the design of CP systems for piping and vessel and tank interiors; therefore, this section focuses on CP system design for external tank bottoms. Saudi Aramco protects above-ground storage tanks with close, or distributed, impressed current systems. This type of design is applicable in congested areas such as plants because (1) remote anode beds are electrically shielded by other buried structures, and (2) some buried metal in the plant does not require cathodic protection (e.g., a bare copper grounding grid or rebar in foundations).

The design of impressed current systems that protect external tank bottoms involve determination of the following:

- design requirements using Saudi Aramco standards and drawings
- the current required to shift the potential of the earth under the tank bottom
- the number of impressed current anodes required

After the following information about Saudi Aramco's standards and drawings is presented, a method and example are given to demonstrate the design of impressed current systems to protect tank bottoms.

Saudi Aramco Engineering Standards and Drawings

The design of cathodic protection systems for in-plant facilities is governed by Saudi Aramco Engineering Standard SAES-X-600. Structures which are cathodically protected include the following:

- pressurized steel hydrocarbon pipelines
- bottoms or soil side of above ground storage tanks
- buried tanks containing hydrocarbons
- sea walls and associated anchors
- buried steel bodied valves

SAES-X-600 also states the following:

- The design life of impressed current anode systems shall be 20 years.
- Anode beds shall be sized to discharge 100% of the rated current capacity of the d-c power source.
- The maximum system operating voltage shall be 100 volts with a maximum circuit resistance of 1 ohm or less.
- Designs for systems connected to plant ground, rebar in concrete, and other underground structures shall provide distributed anodes.

The minimum structure-to-soil potentials of in-plant structures are listed in Figure 19.

Structure	Required Potential
Current On	
Buried plant piping	-0.85 volt or more negative versus CuSO ₄ electrode
Tank bottom external	-1.00 volt or more negative versus CuSO ₄ at periphery -0.85 volt or more negative versus permanent CuSO ₄ +0.20 volt or less positive versus permanent Zn -0.35 volt change in structure potential vs CuSO ₄
Sea walls (water side)	-0.90 volt or more negative versus AgCl electrode
Sea walls (soil side)	-0.85 volt or more negative versus CuSO ₄ electrode

Minimum Required Potentials of In-Plant Structures

Figure 19

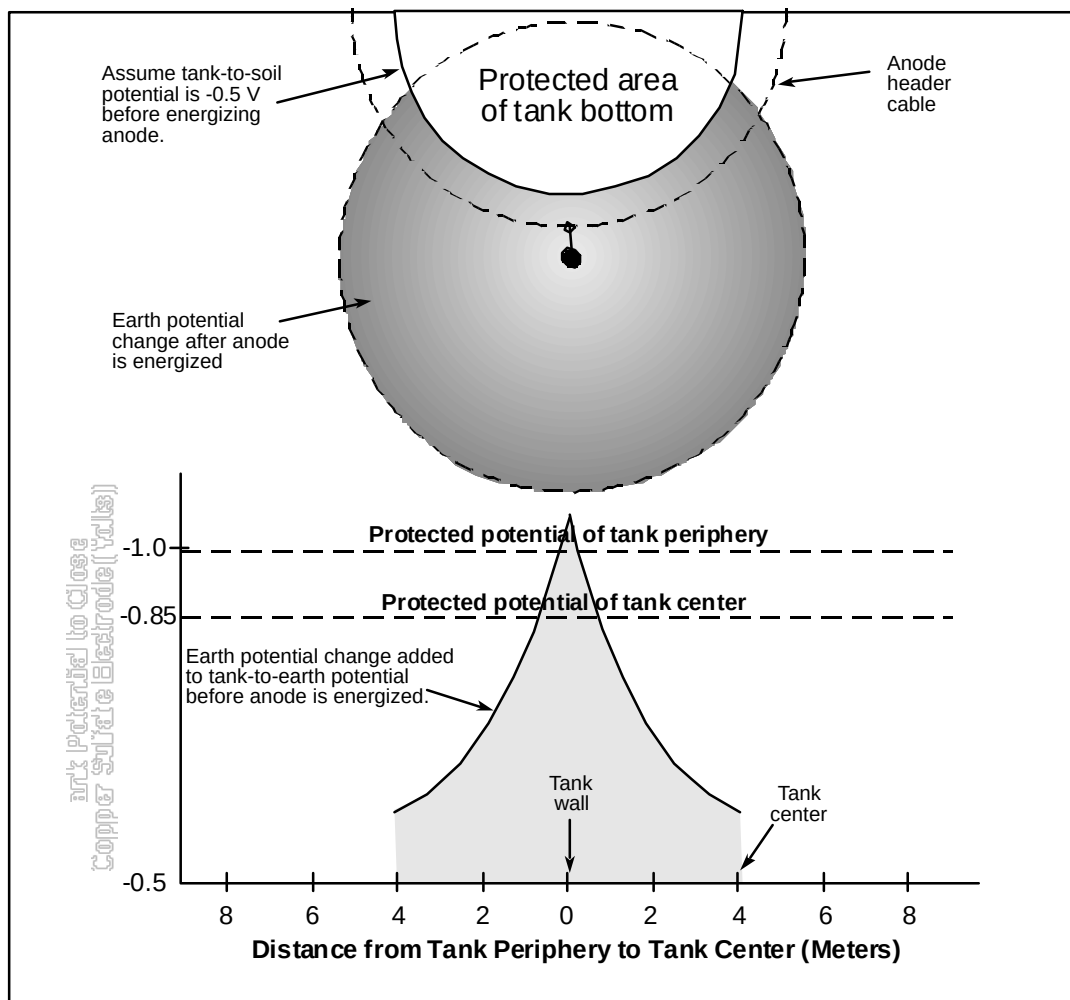
Cathodic protection designs for tanks are based on construction standards set in Standard Drawing AA-036355-Tank Bottom Impressed Current Details. AA-036355 requires a distance between the anodes and the tank of about one-quarter of the tank's radius. The minimum distance is 3 meters and the maximum distance is 10 meters. Also, the maximum separation between distributed anodes is 20 meters. Some diagrams from AA-036355 are shown in Figure 20.



Diagrams from Standard Drawing AA-036355, Tank Bottom Impressed Current Details
Figure 20

Number and Placement of Anodes in Distributed Anode Beds

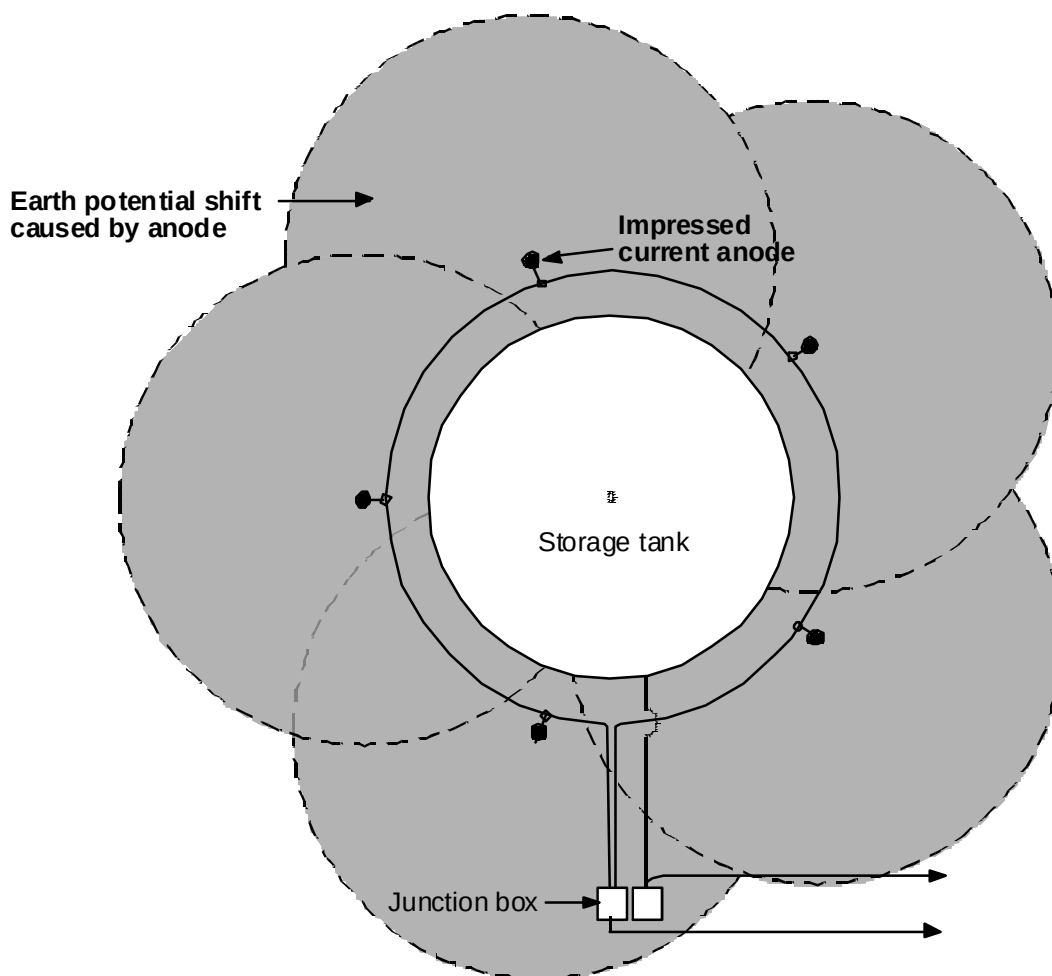
Saudi Aramco uses distributed anode beds in congested areas where electrical shielding prevents the use of remote anode bed installations. Normally, high silicon chromium cast iron anodes are used. Distributed anode systems are designed so that the structure to be protected is within the area of influence that surrounds each anode (Figure 21). The idea of this type of design is to change the potential of the earth around the structure. The earth within the area of influence of each current-discharging anode will be positive with respect to remote earth. There is a limited area of the tank bottom where the net potential difference between the tank bottom and adjacent soil will be sufficient to attain cathodic protection. Note in the figure that although a single anode may cathodically protect the tank periphery closest to it, the anode cannot adequately protect the rest of the tank.



Area of Influence of a Distributed Anode

Figure 21

It must be remembered that the earth potential change is additive for all the anodes that cause a change (see Figure 22). Hence, the earth potential shift at a given point on the tank bottom must include the potential shift caused by neighboring anodes. For example, if the earth potential shift at a given point is 0.2 volt from one anode and 0.1 volt from a neighboring anode, then the total earth potential change would be 0.3 volt.



Additive Effect of Distributed Anodes

Figure 22

To determine the spacing between anodes, there will be some geometry involved to be sure that an adequate potential shift is achieved at all points along the protected structure. Since the separation between anodes cannot exceed 20 meters, divide the circumference of the distributed anode system by 20 meters to determine the total number of anodes. Round up to the nearest number of anodes.

The amount of earth potential change depends on (1) the size and shape of each anode, (2) the anode's position relative to the structure to be protected, (3) the current flow, and (4) the soil resistivity. According to SADP-X-100, Section 18.3.7, the earth potential shift is given by the following formulas:

(1) For a single vertical anode

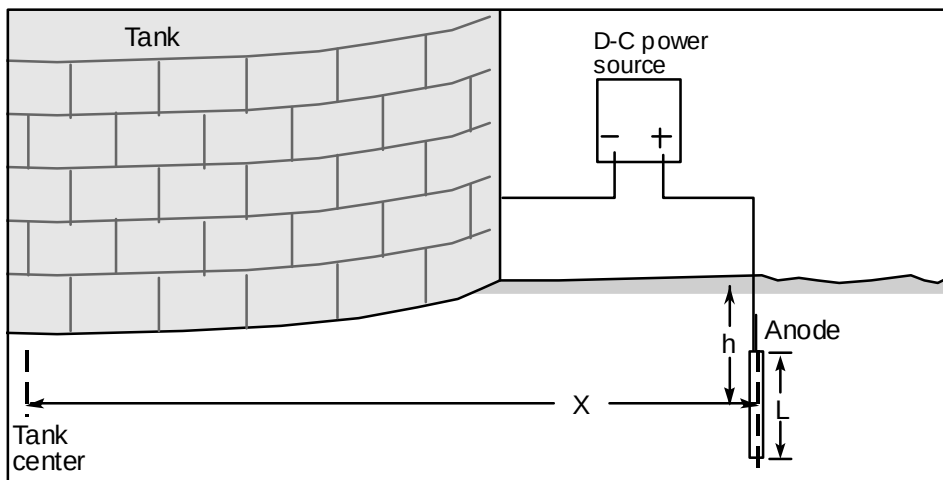
$$V_x = \frac{0.5 \times I \times \rho}{\pi \times L} \left[\ln \frac{\sqrt{L^2 + X^2} + L}{X} \right], \text{ (see Figure 23).}$$

(2) For a single horizontal anode

$$V_x = \frac{I \times \rho}{\pi \times L} \left[\ln \frac{\sqrt{(0.5L)^2 + X^2 + h^2} + 0.5L}{\sqrt{X^2 + h^2}} \right]$$

where -

- V_x = earth potential change at the center of the tank in volts
- I = current flow in amperes
- ρ = soil resistivity in ohm-cm
- L = anode length in cm
- X = horizontal distance from the anode to the center of the tank in cm (Figure 23)
- h = depth of burial to centerline of anode in cm

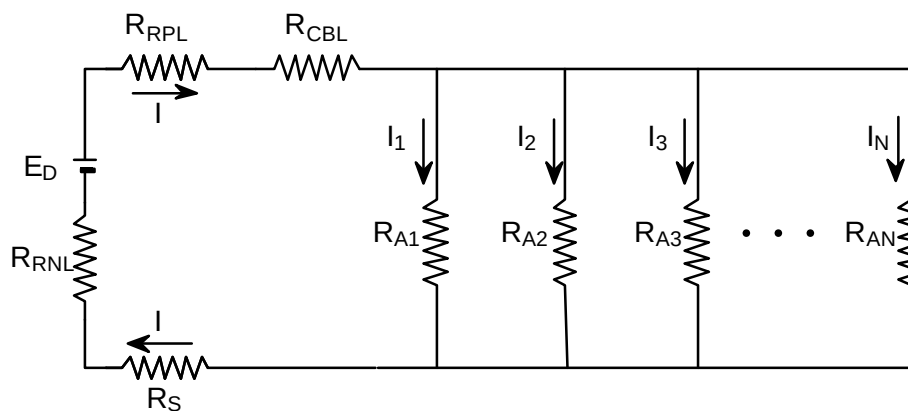
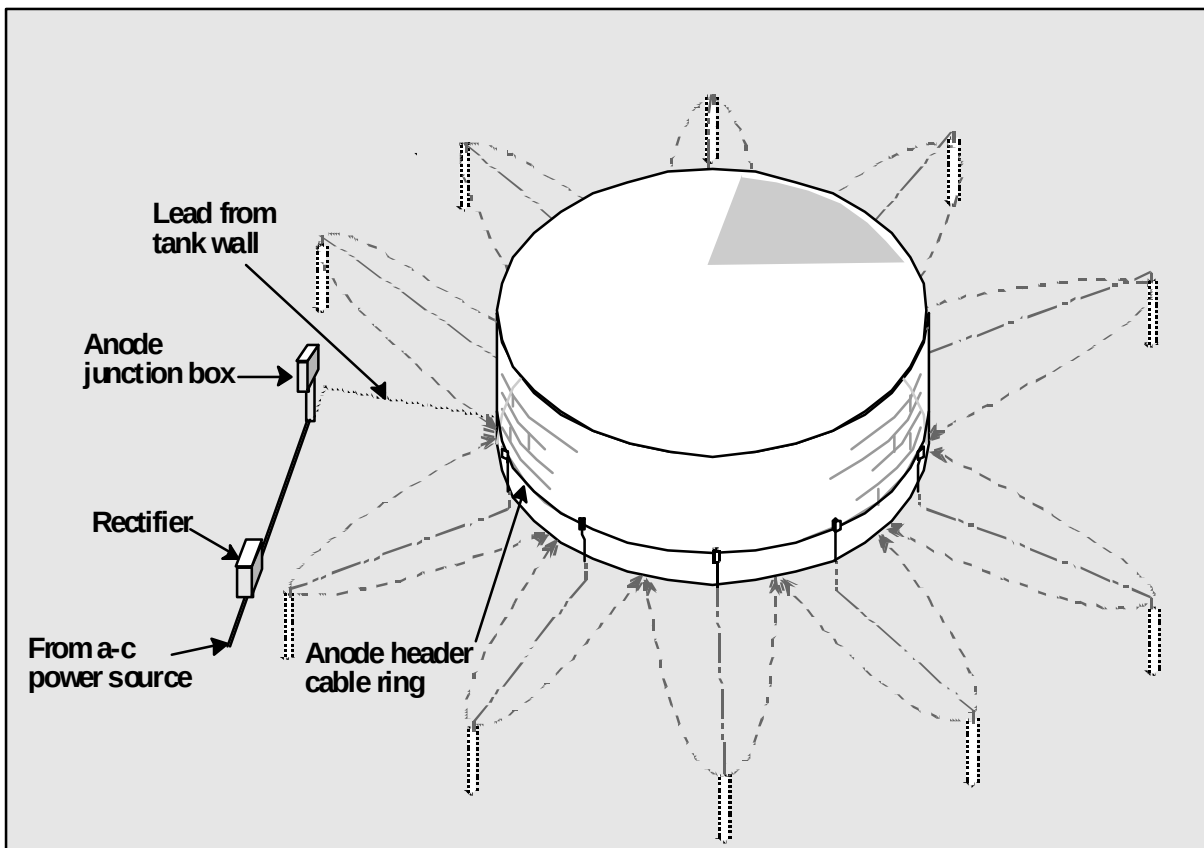


Placement of Distributed Anode

Figure 23

Circuit Resistance

Impressed current anodes around a tank are connected in parallel as shown in Figure 24. Saudi Aramco normally uses high silicon chromium cast iron anodes.



External Tank Bottom Impressed Current System and Equivalent Circuit
Figure 24

The circuit resistance of the impressed current system is given by the following formula:

$$R_C = R_{RPL} + R_{CBL} + \frac{R_A}{N} + R_S + R_{RNL}$$

where -

- R_C = the circuit resistance of the entire impressed current system
- R_{RPL} = the resistance in the positive lead wire from the rectifier to the junction box
- R_{CBL} = the resistance in the header cable
- N = the number of impressed current anodes
- R_A = the resistance of a single impressed current anode
- R_S = structure-to-electrolyte resistance
- R_{RNL} = the resistance in the negative lead wire from the structure to the rectifier

The resistance, R_A , is given by the following formula:

$$R_A = R_{LW} + R_V,$$

where -

- R_{LW} = the anode lead wire resistance in ohms
- R_V = the anode-to-electrolyte resistance in ohms

The anode lead wire resistance, R_{LW} , is very small and can be ignored. Therefore, R_A is equal to the anode-to-electrolyte resistance of a single vertical anode, which is given by the Dwight Equation.

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

where -

- R_V = resistance of one vertical anode to the electrolyte in ohms
- ρ = resistivity of the electrolyte in ohm-cm
- L = length of the backfill in centimeters
- d = diameter of the backfill in centimeters

For high resistivity soils like those found in Saudi Arabia, R_V is much greater than the sum of the other resistances. Therefore, R_{RPL} , R_{RNL} , R_{CBL} , and R_S can be ignored.

Example

Given the following engineering data, we will design an impressed current system to protect a bare tank bottom.

Anode material: High silicon chromium cast iron

Anode dimensions: 7.6 cm dia. x 152 cm (backfill, 20 cm dia. x 180 cm)

Tank dimensions: 30 m diameter

Tank native potential: -0.5 V vs. CuSO₄ electrode

Soil resistivity: 2,000 ohm-cm

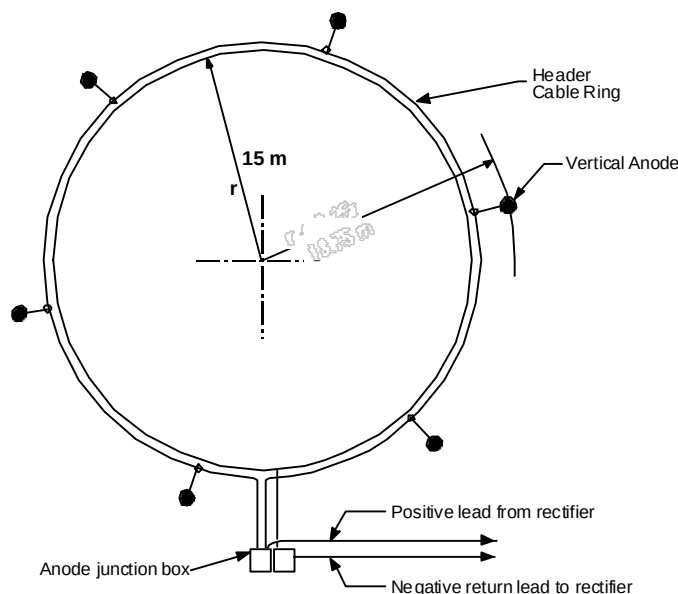
Rectifier output rating: 50 V, 35 A

Number and Placement of Impressed Current Anodes

According to Standard Drawing AA-036355, the distance from the anodes to the tank wall should be approximately one-quarter of the tank radius. In the case of a 30 m dia. tank (15 m radius), the anodes will be placed at a distance of 0.25×15 or 3.75 meters from the tank wall (see Figure 25). The radius of the system is, therefore, $15 + 3.75$ or 18.75 m. The circumference of the circle at which the anodes will be located can be calculated as follows:

$$C = 2\pi r = 2\pi(18.75) = 118 \text{ m}$$

Allowing a maximum separation of 20 m between each anode, we will need $118/20 = 5.9$ or 6 anodes as a minimum number of anodes.



Placement of Impressed Current Anodes

Figure 25

Using the equation for earth potential shift for a single vertical anode, calculate the current needed to give a total of shift of 0.35 volts at the center of the tank from all six anodes.

$$V_x = 0.35 \text{ V} = \frac{0.5 \times I \times 2000}{\pi \times 180} \left[\ln \frac{\sqrt{180^2 + 1875^2} + 180}{1875} \right]$$

$$0.35 \text{ V} = \frac{1000 \times I}{180} \left[\ln \frac{2064}{1875} \right] = I(1.768)(\ln 1.107)$$

$$0.35 \text{ V} = I(1.768)(0.1014) \therefore I = 1.95 \text{ amperes}$$

This is the current that will shift the potential by 0.35 volts at the center of the tank. The formulas and procedure that are used to calculate current required to shift earth potential are provided in Work Aid 4.

To complete the design, it is necessary to determine the total current requirement for the tank bottom and use sufficient anodes to assure a 20 year design life.

Current needed for tank bottom:

$$I = \frac{\pi d^2}{4} \times 0.02 \text{ A / m}^2 = \frac{\pi(30)^2}{4} \times 0.02 = 14.1 \text{ amperes}$$

SAES-X-600 requires sufficient anodes to discharge the rectifier amperage rating without exceeding the maximum anode current density. The current output for a single anode should not exceed:

$$I = \pi dL \times 1 \text{ mA/cm}^2 = \pi(7.6)(152) \times 1.0$$

$$I = 3629 \text{ mA or } 3.6 \text{ amperes}$$

The rectifier output is 35 amperes. Therefore, the minimum number of anodes needed is $35 \div 3.6 = 9.7$ anodes. Use 10 anodes.

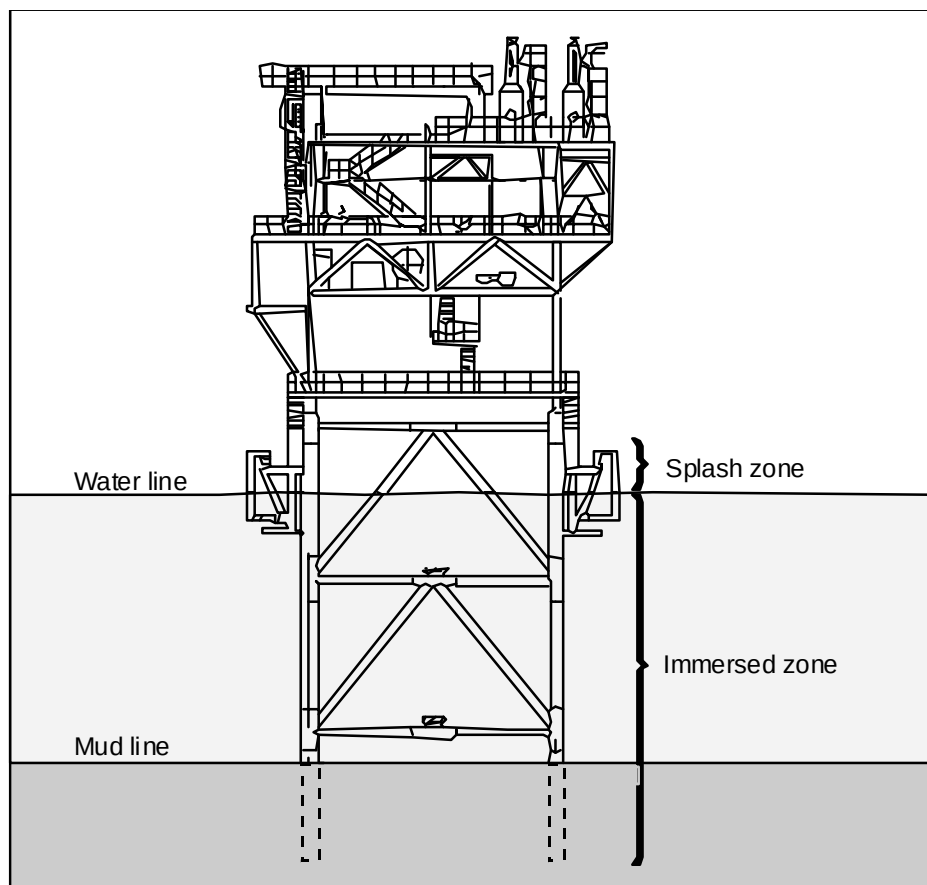
Final anode spacing around tank:

$$C = 118 \text{ meters} \div 10 = 11.8 \text{ meters}$$

Designing Cathodic Protection Systems For Marine Structures

Saudi Aramco cathodically protects the entire submerged surface area of marine structures (see Figure 26). This submerged surface area extends from the base of the structure to the Indian Spring Mean High Tide Level. To calculate the current required to protect the structure, you must know the following:

- the area of steel which is immersed in sea water
- the area of steel which is immersed below the mud line
- the actual or anticipated number of well casings
- any insulated or unprotected foreign structures
- and the required current density for the specific environment



Offshore Platform

Figure 26

The immersed surface areas can be calculated from drawings and specifications of the structure or obtained from the structure designer.

This section is divided into two parts. The first part covers galvanic anode system designs for marine structures. Saudi Aramco cathodically protects all marine structures and pipelines with galvanic anodes. The second part covers impressed current systems. Impressed current systems are used when ac power is available. When used with a galvanic anode system, an impressed current system is intended as the primary system. The galvanic anode system is used as a backup for the following two reasons:

- 1) To protect the structure until the impressed current system is energized.
- 2) To protect the structure when electrical power is interrupted. Power can be interrupted during break downs or during scheduled shutdowns.

The designs for both types of CP systems involve determination of design requirements by using Saudi Aramco Engineering Standards and Drawings. Therefore, after the following information about Saudi Aramco's standards and drawings, methods and examples for designing galvanic and impressed current systems are described separately.

Saudi Aramco Engineering Standards and Drawings

The design of cathodic protection systems for marine structures is governed by SAES-X-300. SAES-X-300 states the following:

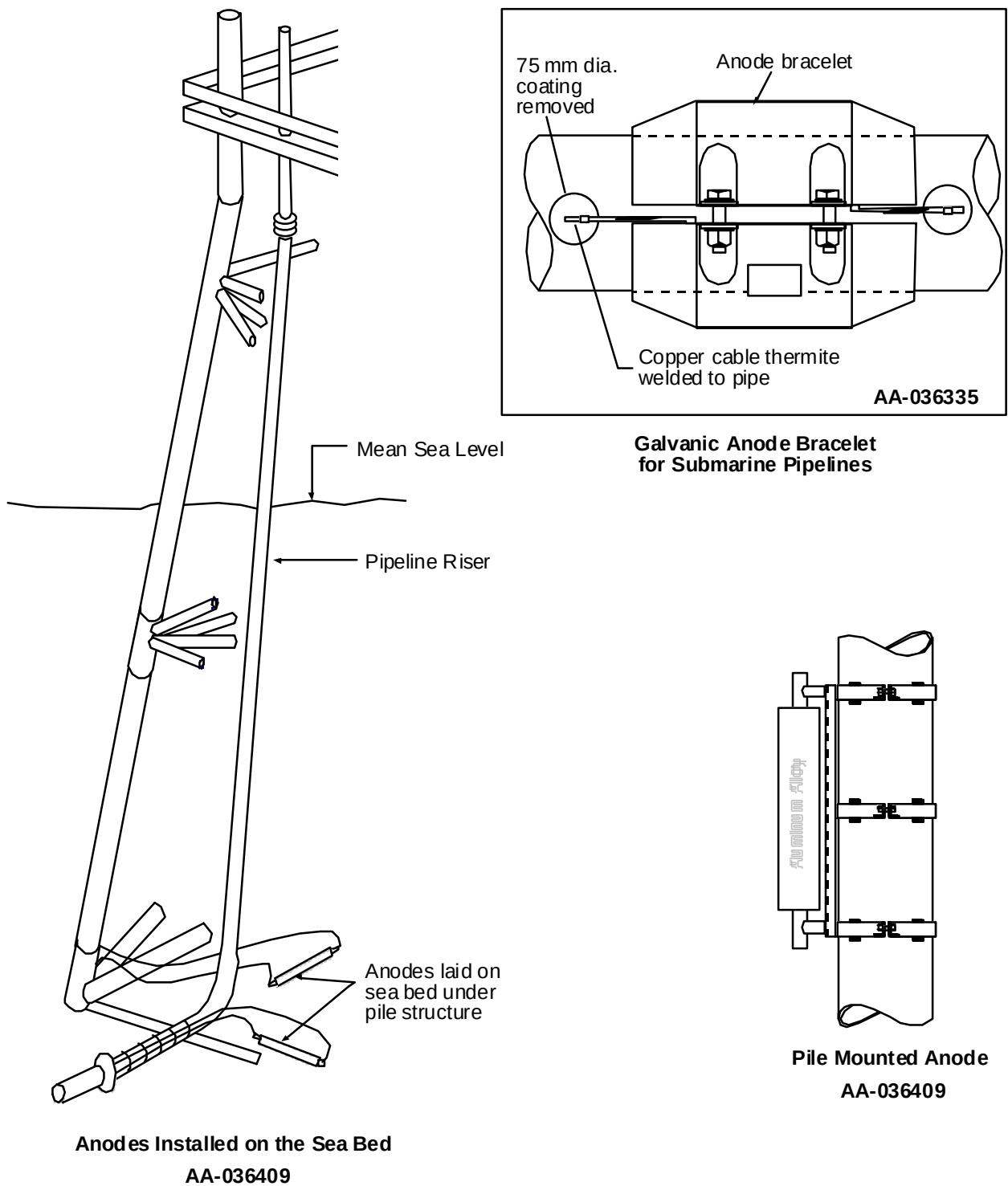
- Galvanic anode systems, when used alone, shall have a design life of 25 years.
- Galvanic anode systems accompanied by impressed current systems shall have a design life of 10 years and the impressed current system shall have a design life of 15 years.
- The cathodic protection system shall achieve a minimum structure-to-electrolyte potential of -0.90 volt versus Ag-AgCl over the entire structure.

Saudi Aramco requires the following current densities in the immersed surface areas.

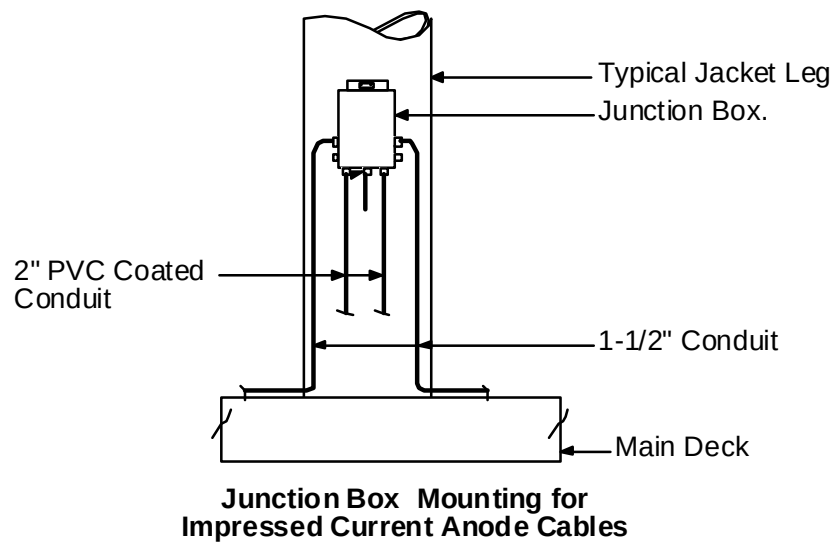
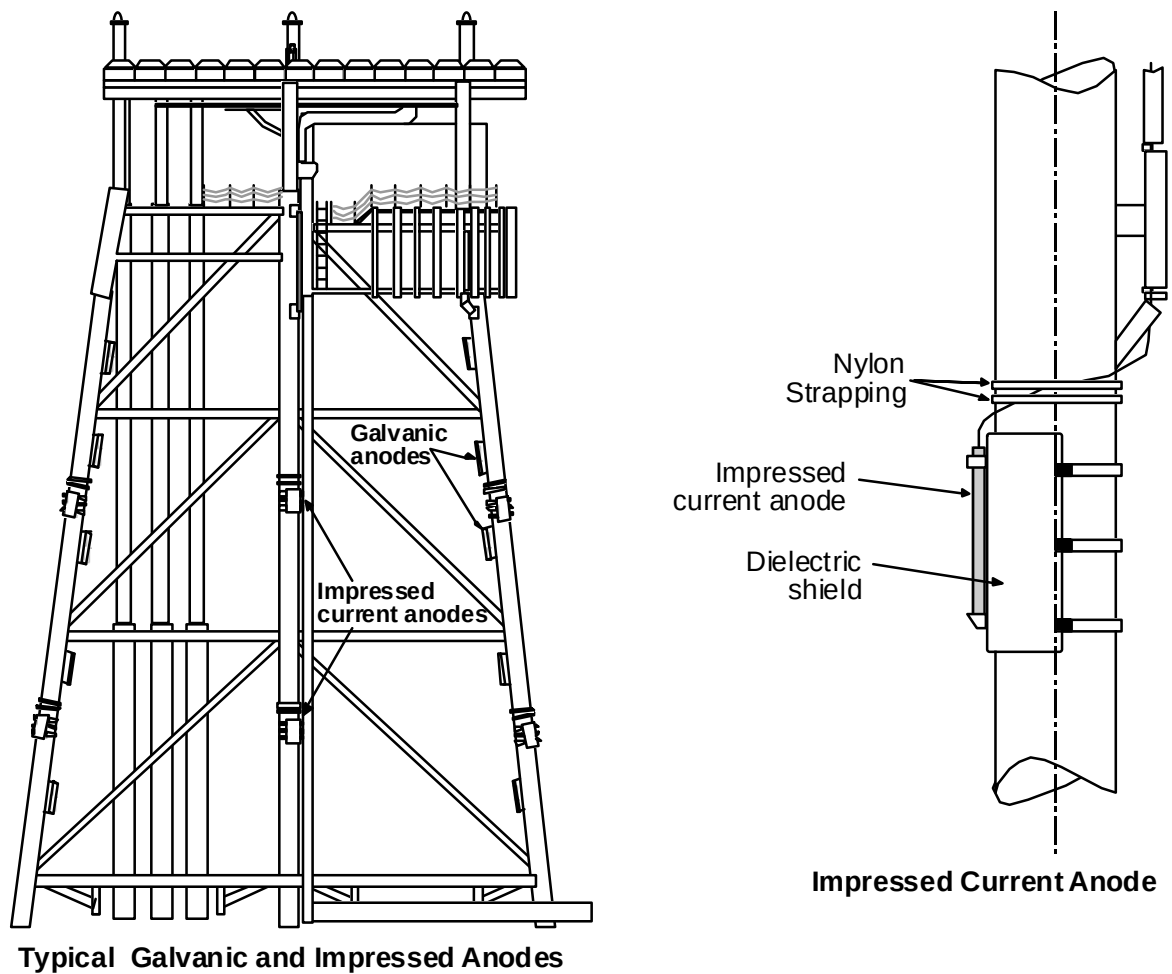
	Current Density (mA/m ²)	
	<u>Coated</u>	<u>Uncoated</u>
Seawater structures	10.0*	50.0*
Structures in mud or soil	10.0	20.0
Marine pipelines (coated)	2.5	--

* Higher current density may be required depending on turbulence and/or velocity.

Cathodic protection designs for offshore structures are based on construction standards set in the following Standard Drawings: AA-036348 (Galvanic and Impressed Current Anodes on Offshore Structures), AA-036409 (Replacement of Galvanic Anodes on Offshore Structures and Risers), and AA-036335 (Half Shell Bracelet Type Anode for Pipe Sizes 4" Through 60"). Standard Drawing AA-036335 states that the maximum spacing for all sizes of anode bracelets shall be 150 meters. Some diagrams from AA-036348, AA-036409, and AA-036335 are shown in Figures 27 and 28.



Diagrams from Standard Drawings AA-036409 and AA-036335
Figure 27



AA-036348

Diagrams from Standard Drawing AA-036348
Figure 28

Galvanic Anode System Design for Marine Structures

Saudi Aramco uses indium-doped aluminum alloy or zinc-tin-doped aluminum alloy galvanic anodes to protect marine structures. Galvanic anodes are usually installed at least 30 cm (1 ft.) from the structure. A calcareous build-up forms on the structure as it polarizes. This build-up increases the current distribution of the anodes. Galvanic anode bracelets are used to protect marine pipelines.

The design of galvanic anode systems for marine structures (such as platforms, mooring buoys, etc.) involves determining the following:

- the number of galvanic anodes required
- galvanic anode life

The design of galvanic anode systems for marine pipelines involves determining the following:

- the number of galvanic anode bracelets required
- the spacing of the bracelets

After describing these calculations, an example, which demonstrates the design of a galvanic anode system for a marine platform and pipeline, is provided.

Number of Galvanic Anodes Required

The number of anodes needed to protect a marine structure depends on the total current required and the current output per anode. In Module 107.01, we calculated the total current requirement by multiplying the required current density from SAES-X-300 by the immersed surface area of the marine structure. The total number of anodes is calculated by using the following equation:

$$N = I/I_A$$

where -

- N = the number of anodes
- I = the total current required to protect the structure
- I_A = the current output of a single anode

According to SADP-X-100, Eqn. 20, the current output from a single anode, I_A , can be found using the following equation:

$$I_A = E_D / R_C,$$

where -

- I_A = anode current output in amperes
- E_D = the anode driving potential in volts versus Ag-AgCl
- R_C = the circuit resistance in ohms

Circuit Resistance

The circuit resistance, R_C , is given by the following equation:

$$R_C = R_S + R_V$$

where -

- R_S = the structure-to-electrolyte resistance (for offshore structures, this is negligible)
- R_V = the anode-to-electrolyte resistance

For galvanic anodes on marine structures, the Dwight Equation is used to calculate R_V .

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

where -

- ρ = the electrolyte (seawater) resistivity in ohm-cm
- L = the length of the anode in centimeters
- d = the diameter of the anode in centimeters or the circumference divided by π for non-cylindrical shapes

Galvanic Anode Life

The anodes must last over the design life of the system. The anode life is given by the following equation.

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

where -

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

Number and Spacing of Galvanic Anode Bracelets

The number of anode bracelets required to protect a marine pipeline is calculated as follows.

$$N = L/150 \text{ m}$$

where -

- N = the number of anode bracelets
- L = length of the pipeline

The anode bracelets must last over the design life of the pipeline. The anode life is given by the following equation.

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

where -

- Y = anode life in years
- W = net weight of one anode bracelet in kg
- UF = utilization factor
- C = actual consumption rate in kg/A-yr
- I_A = current output of one anode in amperes

The net weight per bracelet, W, can be obtained from Standard Drawing AA-036335 (see also Work Aid 5A). The current requirement for one anode bracelet, I_A, can be calculated by dividing the total current requirement by the number of anode bracelets.

An alternative method involves calculating the current output of a single anode bracelet by dividing the driving potential of the galvanic anode material by the circuit resistance. As shown previously, the circuit resistance is equivalent to the anode-to-electrolyte resistance because the structure-to-electrolyte resistance is negligible. For bracelet type anodes, the following equation from Design Practice SADP-X-100 (Eqn. 22, p. 33) is used to calculate the anode-to-electrolyte resistance.

$$R_A = \frac{0.315\rho}{\sqrt{A}}$$

where -

- R_A = the anode-to-electrolyte resistance for bracelet type anodes
- ρ = the electrolyte resistivity in ohm-cm
- A = the exposed surface area of the anode in cm²

Then, the number of anodes can be calculated by dividing the total current requirement by the current output of a single anode bracelet.

Example

We will calculate the number of Galvalum III anodes needed to protect an offshore platform and a coated marine pipeline. Assume that an impressed current system will also be installed to protect the platform. We will use the following information to design the platform's galvanic anode system.

Current required: 250 amperes

Galvalum III solution potential: -1.09 V versus Ag-AgCl

Galvalum III anode dimensions: 28 cm x 28 cm x 304.8 cm (11" x 11" x 120")

Galvalum III anode weight: 566 kg (1,245 lbs.)

Galvalum III consumption rate: 3.46 kg/A-yr

Water resistivity: 15 ohm-cm

Required structure potential: -0.90 V versus Ag-AgCl

Number of Anodes

The current output of each anode is given by the equation $I = E_D/R_A$. The driving potential of the Galvalum III anode is

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

To calculate the anode-to-electrolyte resistance of the anode, we must insert its dimensions and the water resistivity into the Dwight Equation. The effective diameter of the anode is

$$d = (28+28+28+28)/\pi = 35.7 \text{ cm.}$$

Therefore, the anode-to-electrolyte resistance is

$$R_V = \frac{0.159\rho}{L} \left(\ln \frac{8L}{d} - 1 \right) = \frac{0.159(15)}{304.8} \left(\ln \frac{8(304.8)}{35.7} - 1 \right) = 0.025 \text{ ohm}$$

and the current output of a single Galvalum III anode on the platform is

$$I = E_D/R_V = 0.19 \text{ V}/0.025 \text{ ohm} = 7.6 \text{ A.}$$

The number of anodes required to produce the required current is

$$N = 250 \text{ amperes}/7.6 \text{ amperes per anode} = 33 \text{ anodes.}$$

Galvanic Anode Life

The lifetime of one anode is

$$Y = \frac{W \times UF}{C \times I_A} = \frac{(566 \text{ kg})(.85)}{(3.46 \text{ kg/amp-yr})(7.6 \text{ amp})} = 18 \text{ years}$$

This is greater than the design lifetime of 10 years.

Now, using the following information, we will calculate the current requirement and number of Galvalum III anodes needed to protect the coated marine pipeline:

Length of pipeline: 4.5 km

Pipe diameter: 45.7 cm

Current required: 14 amperes

Galvalum III consumption rate: 3.46 kg/A-yr

Number and Spacing of Galvanic Anode Bracelets

The number of anode bracelets required is

$$N = 4500 \text{ m} / 150 \text{ m} = 30 \text{ bracelets.}$$

Now we will make sure that the anodes will last over the design lifetime of 10 years. According to Standard Drawing AA-036335 (see table in Work Aid 5A), the net anode material weight of a bracelet for a 45.7 cm diameter pipeline is 61 kg. Therefore, the lifetime of one anode bracelet is calculated as follows:

$$Y = \left(\frac{W \times UF}{C \times I} \right) = \frac{(61 \text{ kg})(0.85)}{(3.46 \text{ kg/amp-yr})(14 \text{ amps}/30 \text{ bracelets})} = 32 \text{ years}$$

The formulas and procedure used to design galvanic anode systems for marine structures and offshore pipelines are provided in Work Aid 5A.

Impressed Current System Design for Marine Structures

The driving potentials of impressed current anodes are much greater than galvanic anodes. Therefore, fewer impressed current anodes are required to provide the same amount of current. However, their placement is more critical to achieve adequate current distribution. An impressed current anode will tend to over-protect areas close to it and under-protect more remote areas. To improve the current distribution of impressed current anodes, the following methods are sometimes used:

- An insulating shield is installed on the structure near impressed current anodes.
- Impressed current anodes are separated from the structure by at least 1.5 m.

The design of impressed current systems for marine structures involves determining:

- the corrected current required
- the number of impressed current anodes required
- the rectifier voltage requirement

After describing these calculations, an example, which demonstrates the design of an impressed current system to protect a marine platform, is provided.

Corrected Current Requirement

Impressed current anodes are considered 67-80% as effective as galvanic anodes. In the Arabian Gulf, 75% effectiveness is used in most design calculations. Therefore, we must modify the current requirement as follows:

$$I_{\text{Corr}} = I(1 + (100\% - \% \text{Efficiency})/100)$$

where -

- I_{Corr} = corrected total current requirement for an impressed current system
- I = total current requirement for galvanic anode systems
- Efficiency = efficiency of the impressed current anodes

Number of Impressed Current Anodes Required

The number of impressed current anodes is calculated based on the maximum anode current output as follows:

$$N = I_{\text{Corr}}/I_A$$

where -

- I_{Corr} = corrected total current requirement for an impressed current system
- I_A = the maximum current output of one impressed current anode

The maximum current output is the maximum current density of the anode material multiplied by the anode surface area.

Rectifier Voltage Requirement

Saudi Aramco sizes the rectifier to meet the total current requirement of the anodes based on a rectifier efficiency of 67%. The rectifier output voltage is given by the following formula:

$$E = I_{\text{Corr}} R_C / \text{Efficiency}$$

The total circuit resistance, R_C , is given by the following formula:

$$R_C = R_{RPL} + R_{RNL} + \frac{R_V + R_{LW}}{N}$$

where -

R_C	=	the circuit resistance of the entire impressed current system
R_{RPL}	=	the resistance in the positive lead wire from the rectifier to the junction box
R_{RNL}	=	the resistance in the negative lead wire from the structure to the rectifier
N	=	the number of impressed current anodes
R_V	=	the resistance of a single impressed current anode (Dwight Equation)
R_{LW}	=	anode lead wire resistance

Note that the structure-to-electrolyte resistance, R_S , is omitted from the formula for R_C . This is because R_S is negligible in seawater.

Example

We will design an impressed current system to protect the previous offshore platform for which we designed a galvanic anode system. However, assume that the platform is also electrically bonded to four conductor pipes.

Current required for platform: 251 amperes

Anode material: Platinized niobium

Anode dimensions: 7.6 dia x 76.2 cm (3" dia. x 30")

Anode max. current output density: 40 mA/cm²

Water resistivity: 15 ohm-cm

Anode lead wire: No. 2 AWG, 50 meters long

Lead wire resistance: 0.531 x 10⁻³ ohm/m

Total resistance in both rectifier lead wires: 0.02 ohm

Current requirement for conductor pipes: 3 amperes each

Corrected Current Requirement

The total current requirement for the platform and conductor pipes is

$$I = 251 \text{ A} + (4)(3 \text{ A}) = 263 \text{ A}.$$

The corrected current required for an impressed current system is calculated as follows:

$$I_{\text{Corr}} = (263 \text{ A})(1 + (100\% - 75\%)/100) = 329 \text{ A}$$

Number of Anodes Required

The current output of a single platinized niobium anode is

$$I_A = \pi(7.6 \text{ cm})(76.2 \text{ cm})(40 \text{ mA/cm}^2) = 72,774 \text{ mA} = 73 \text{ A}.$$

The number of anodes required is

$$N = I_{\text{Corr}}/I_A = 329 \text{ A}/73 \text{ A} = 4.5 \text{ anodes} = 5 \text{ anodes}.$$

Rectifier Voltage Requirement

The output voltage is given by the equation $E = I_{\text{Corr}}R_C$. The total circuit resistance, R_C , is calculated as follows: (Remember, R_S is negligible in seawater)

$$R_C = R_{RPL} + R_{RNL} + \frac{R_V + R_{LW}}{N}$$

The anode-to-electrolyte resistance, R_V , is calculated using the Dwight Equation as follows:

$$R_V = \frac{0.159\rho}{L} \left(\ln \frac{8L}{d} - 1 \right) = \frac{0.159(15)}{76.2} \left(\ln \frac{8(76.2)}{7.6} - 1 \right) = 0.11 \text{ ohm}$$

The anode lead wire resistance is

$$R_{LW} = (50 \text{ m})(0.531 \times 10^{-3} \text{ ohm/m}) = 0.03 \text{ ohm.}$$

The total resistance in the rectifier lead wires, $R_{RPL} + R_{RNL}$, is 0.02 ohm. Therefore, the circuit resistance is

$$R_C = 0.02 + (0.11 + 0.03)/5 = 0.05 \text{ ohm.}$$

Allowing for a rectifier efficiency of 67%, the voltage requirement of the rectifier is

$$E = I_{\text{Corr}}R_C/\text{Eff} = (329 \text{ A})(0.05 \text{ ohms})/0.67 = 25 \text{ volts.}$$

Formulas and procedures used to design impressed current systems for marine structures are provided in Work Aid 5B.

Work Aid 1: Data Base, Formulas, and Procedures to Design Cathodic Protection Systems for Buried Pipelines

This Work Aid provides formulas, and procedures to design galvanic and impressed current systems for buried pipelines.

Work Aid 1A: Data Base, Formulas, and Procedure to Design Galvanic Anode Systems for Road and Camel Crossings

This Work Aid provides requirements from Standard Drawing AA-036352, formulas, and a procedure for determining the number, circuit resistance, current output, and design life of galvanic anodes used to protect buried pipelines.

NUMBER OF 60 lb. GALVANIC ANODES REQUIRED

Pipe Length (meters)	Dia. of Pipe (inches)				
	Up to 6"	Up to 12"	Up to 24"	Up to 36"	Over 36"
15	2	2	2	2	4
30	2	2	4	4	6
45	2	4	4	6	8
60	2	4	6	8	10
75	4	6	8	10	10
90	4	6	10	10	12

NOTES:

1. Minimum number of anodes shall always be 2, regardless of pipe length or diameter.
2. 100 lb. anodes are to be used only in Subkha areas. When substituting 100 lb. anodes for 60 lb. anodes, reduce anode quantity by one-half from that noted in table.
3. One-half of the anodes shall be located on either side of crossing where practical on existing pipelines.

Formulas

Galvanic Anode Current Output

$$I_A = E_D / R_C$$

where -

- I_A = anode current output (amperes)
- E_D = driving potential of the galvanic anode (volts)
- R_C = circuit resistance (ohms)

Circuit Resistance

$$R_C = R_S + \left(\frac{R_{LW} + R_V}{N} \right)$$

where -

- R_C = circuit resistance (ohms)
- R_S = the structure-to-soil resistance (ohms)
- R_{LW} = the lead wire resistance (ohms)
- R_V = the resistance of a single vertical anode to earth (ohms)
- N = the number of anodes

Dwight Equation (for a single vertical anode)

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

where -

- R_V = resistance of vertical anode to earth in ohms
- ρ = resistivity of soil in ohm-cm
- L = length of anode (or backfill column) in centimeters
- d = diameter of anode (or backfill column) in centimeters

Galvanic Anode Life

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

where -

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

Procedure

- 1.0 Determine the number of anodes.
 - 1.1 Obtain the dimensions of buried pipe section.
 - 1.2 If using 60 lb. anodes, find number of anodes for pipe diameter and length in the Table at the beginning of this Work Aid.
- 2.0 Calculate the circuit resistance.
 - 2.1 Obtain the following information:
 - anode dimensions (in centimeters)
 - chemical backfill package dimensions (in centimeters)
 - soil resistivity
 - 2.2 If the anode is bare, determine the working diameter of the galvanic anode.
 - If anode is cylindrical, use its diameter (in centimeters)
 - If anode is not cylindrical, calculate its effective diameter (circumference/3.14).
 - 2.3 Calculate the anode-to-earth resistance by inserting the values for soil resistivity and the backfill dimensions into the Dwight Equation. In Subkha, where no backfill package is used, insert the anode dimensions.
 - 2.4 Divide the sum of the lead wire resistance and anode-to-earth resistance by the number of anodes. Add this resistance to the structure-to-electrolyte resistance to calculate the circuit resistance.
- 3.0 Calculate the anode current output.
 - 3.1 Divide the anode driving potential by the circuit resistance calculated in Step 2.4.
- 4.0 Calculate the galvanic anode life.
 - 4.1 Obtain the following information:
 - anode mass in kg
 - anode utilization factor
 - actual anode consumption rate in kg/A-yr
 - 4.2 Substitute the anode current output from Step 3.1 and the values from Step 4.1 into the Galvanic Anode Life formula and calculate the anode life.

Work Aid 1B: Formulas and Procedure to Design Impressed Current Systems for Buried Pipelines

This Work Aid provides formulas and procedures to calculate the number and spacing of impressed current anodes and the volume of coke breeze needed for the anode bed. This procedure assumes that you have determined the current requirement and allowable anode bed resistance.

Formulas

Minimum Number of Anodes Based on Anode Maximum Current Density

$$N = I/(\pi dL \times \gamma_A)$$

where -

- N = number of impressed current anodes
- I = total current required in milliamperes times 120%
- d = anode diameter in centimeters
- L = anode length in centimeters
- γ_A = anode maximum current density in mA/cm²

Minimum Number of Anodes Based on Anode Consumption Rate

$$N = \left(\frac{Y \times I \times C}{W} \right)$$

where -

- N = number of impressed current anodes
- Y = the impressed current system design life in years
- I = total current required in amperes times 120%
- C = anode consumption rate in kg/A-yr
- W = weight of a single anode in kg

Allowable Anode Bed Resistance

$$R_{agb} = R_{max} - (R_S + R_{LW})$$

where -

- R_{agb} = the allowable anode bed resistance
- R_{max} = the maximum allowable circuit resistance (the rectifier's rated voltage minus 2 volts, divided by its rated current output)
- R_S = structure-to-electrolyte resistance
- R_{LW} = total lead wire cable resistance

Sunde Equation (for multiple vertical anodes in parallel)

$$R = \frac{0.159\rho}{NL} \left[\left(\ln \frac{8L}{d} - 1 \right) + \frac{2L}{S} (\ln 0.656N) \right]$$

where -

- R = resistance, in ohms, of N anodes in parallel and spaced S centimeters apart along a straight line.
- ρ = soil resistivity in ohm-cm
- N = number of anodes
- L = length of anode (or backfill column) in centimeters
- d = diameter of anode (or backfill column) in centimeters
- S = anode spacing in centimeters

Corrected Allowable Anode Bed Resistance (for use with Design Chart A in this Work Aid)

$$R_{5000} = R_{\rho}(5,000/\rho)$$

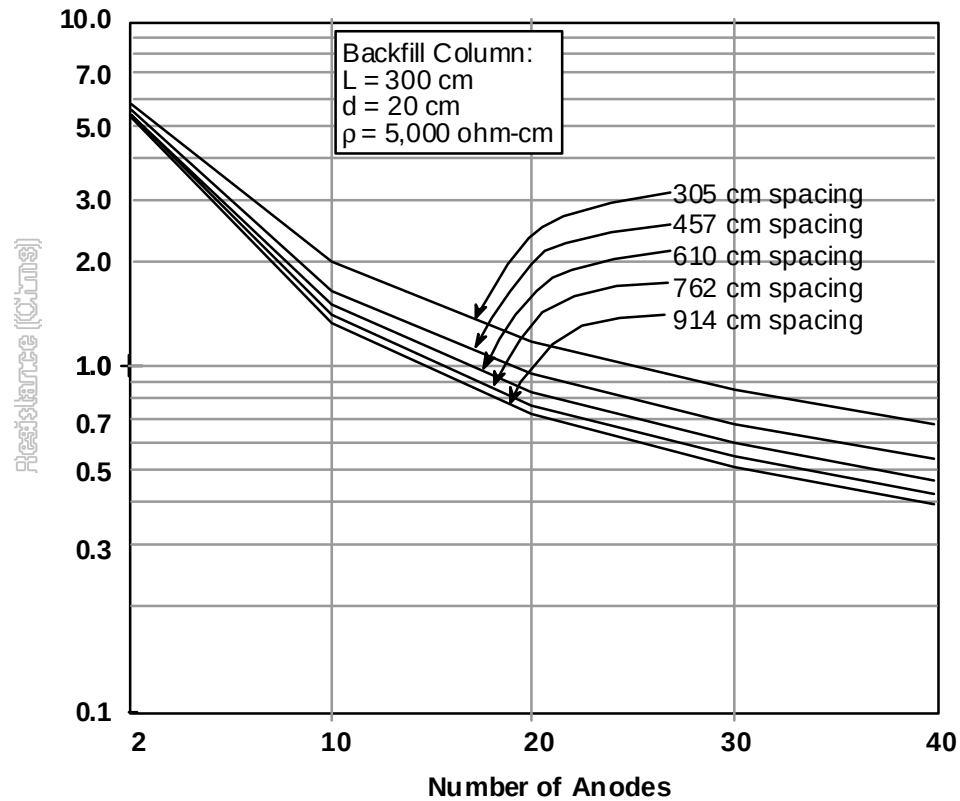
where -

- R_{5000} = allowable anode bed resistance corresponding to 5,000 ohm-cm soil
- R_{ρ} = allowable anode bed resistance of soil with resistivity of ρ ohm-cm
- ρ = soil resistivity in ohm-cm

Procedure

- 1.0 Determine the minimum number of impressed current anodes.
 - 1.1 Obtain the following information:
 - anode material
 - anode weight (in kg)
 - anode consumption rate
 - coke breeze backfill column dimensions (in centimeters)
 - soil resistivity (in ohm-cm)
 - current required
 - allowable anode bed resistance
 - structure-to-electrolyte resistance
 - total lead wire resistance
 - 1.2 Calculate the minimum number of anodes required by using the anode current density formula and anode consumption rate formula. Use the largest number of anodes calculated from the two formulas. Round up to the nearest multiple of 10.
- 2.0 Determine the anode bed resistance.
 - 2.1 If the allowable anode bed resistance (R_{agb}) is not available, calculate R_{agb} by using the Allowable Anode Bed Resistance Formula.
 - 2.2 Correct the allowable anode bed resistance, R_{agb} , for soil with resistivity other than 5000 ohm-cm by using the Corrected Allowable Anode Bed Resistance formula.
 - 2.3 Use Design Chart A in Figure 30 to determine the optimum number and spacing of anodes so that R_{gb} is less than the corrected value of R_{agb} . Ensure that the number of anodes is greater than the minimum number from Step 1.2.
- 3.0 Calculate the weight of coke breeze needed for the anode bed.
 - 3.1 Obtain the following information:
 - anode diameter and length (in centimeters)
 - coke breeze column dimensions
 - coke breeze density
 - 3.2 Subtract the volume of one anode from the volume of the backfill column to obtain the net volume of coke breeze.

- 3.3 Multiply the net volume of coke breeze by 1.2 (for spillage) and by the number of anodes from Step 3.2.
- 3.4 Multiply the total volume of backfill by the density of the coke breeze.



Design Chart A
Figure 30

Work Aid 2: Formulas and Procedure to Design Cathodic Protection Systems for Onshore Well Casings

This Work Aid provides formulas and procedures to design impressed current deep anode beds to protect onshore well casings. This procedure assumes that you have determined the current requirement and allowable anode bed resistance.

Formulas

Minimum Number of Anodes Based on Anode Maximum Current Density

$$N = I / (\pi d L \times \gamma_A)$$

where -

- N = number of impressed current anodes
- I = total current required in milliamperes times 120%
- d = anode diameter in centimeters
- L = anode length in centimeters
- γ_A = anode maximum current density in mA/cm²

Minimum Number of Anodes Based on Anode Consumption Rate

$$N = \left(\frac{Y \times I \times C}{W} \right)$$

where -

- N = number of impressed current anodes
- Y = the impressed current system design life in years
- I = total current required in amperes times 120%
- C = anode consumption rate in kg/A-yr
- W = weight of a single anode

Circuit Resistance

$$R_C = R_{RPL} + R_{LW} + R_V + R_S + R_{RNL}$$

where -

- R_C = circuit resistance
- R_{RPL} = the resistance in the positive lead wire from the rectifier to the junction box
- R_{LW} = the equivalent resistance of the anode lead wires (the sum of the individual lead wire resistances divided by the number of lead wires)
- R_V = the resistance of the anode bed as a single vertical anode
- R_S = structure-to-electrolyte resistance
- R_{RNL} = the resistance in the negative lead wire from the well casing to the rectifier

Dwight Equation (for a deep anode bed)

$$R_V = \frac{0.159\rho_{\text{eff}}}{L} \left(\ln \frac{8L}{d} - 1 \right)$$

where -

- R_V = resistance of vertical anode to earth in ohms
 ρ_{eff} = effective soil resistivity of the interval in ohm-cm
 L = length of the coke breeze column in centimeters
 d = diameter of deep anode hole in centimeters

Volume of Coke Breeze Column

$$V_C = \pi(d^2/4)H$$

where -

- d = diameter of the coke breeze column in meters
 H = height of the coke breeze column in meters

Procedure

- 1.0 Determine the length of the coke breeze column.
 - 1.1 Obtain the following information:
 - anode material
 - anode diameter and length (in centimeters) and weight (in kg)
 - anode consumption rate
 - current required
 - anode spacing
 - 1.2 Calculate the minimum number of anodes required by using the anode current density formula and anode consumption rate formula. Use the largest number of anodes calculated from the two formulas.
 - 1.3 Calculate the length of the coke breeze column. Allow at least 6 meters above the top anode and at least 1.5 meters below the bottom anode for the coke breeze backfill.

2.0 Calculate the circuit resistance.

2.1 Obtain the following information:

- effective soil resistivity from Geonics measurement
- length of coke breeze column (from Step 1.3)
- diameter of coke breeze column
- maximum allowable circuit resistance
- structure-to-electrolyte resistance
- length of anode lead wires
- length of rectifier lead wires

2.2 Calculate the deep anode bed resistance by inserting the effective soil resistivity and the dimensions of the coke breeze column into the Dwight Equation.

2.3 Multiply the total length of the rectifier lead wires by both the lead wire resistance (in ohm/m) and 110%.

2.4 Divide the total length of the anode lead wires by the number of lead wires. Multiply this amount by the lead wire resistance (in ohm/m) and 120%.

2.5 Add the resistances from Steps 2.2, 2.3, and 2.4 to the well casing-to-soil resistance. Make sure that this total circuit resistance is less than the maximum allowable circuit resistance, R_{max} . $R_{max} = (\text{rectifier rated voltage} - 2 \text{ volts}) / \text{rectifier rated current output}$.

3.0 Calculate the amount of coke breeze.

3.1 Obtain the following information:

- coke breeze density
- coke breeze column dimensions

3.2 Calculate the volume of coke breeze using the provided formula. Multiply the volume of coke breeze by 120% (for spillage).

3.3 Multiply the volume of coke breeze by the coke breeze density to obtain the weight of coke breeze required.

Work Aid 3: Formulas and Procedures to Design Cathodic Protection Systems for Vessel & Tank Interiors

This Work Aid provides formulas and procedures to design galvanic and impressed current systems for the interior of tanks and vessels.

Work Aid 3A: Formulas and Procedure for the Design of Galvanic Anode Systems for Vessel & Tank Interiors

Formulas

Current Output of a Galvanic Anode in a Vessel or Tank

$$I = E_D \left(\frac{1}{R_C} \right) = E_D \left(\frac{1}{R_S + R_{LW} + R_V} \right)$$

where -

- I = current output of the anode(s)
- E_D = anode driving potential
- R_C = circuit resistance
- R_S = structure-to-electrolyte resistance
- R_{LW} = resistance of a single anode lead wire
- R_V = the anode-to-electrolyte resistance of a single anode

Dwight Equation (for a single vertical anode)

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

where -

- R_V = anode-to-electrolyte resistance of a single anode in ohms
- ρ = electrolyte resistivity
- L = anode length in centimeters
- d = anode diameter in centimeters

Anode Life (galvanic anode)

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

where -

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

Procedure

1.0 Calculate the current output per anode.

- 1.1 If you have the manufacturer's performance chart for the anode, locate the protected potential of the structure on the horizontal or "X" axis. Move vertically up the chart until you intersect the curve for the water resistivity of interest. Move horizontally along the chart and read the value of the anode's current output on the vertical or "Y" axis. Go to Step 2.1.

CAUTION: Performance charts are developed based on specific design parameters. You must be sure that the performance chart you use was developed for your particular situation.

- 1.2 If you do not have the manufacturer's performance chart, obtain the following information:
- total current required to protect the tank or vessel
 - electrolyte resistivity
 - anode material
 - anode diameter and length (in centimeters)
 - maximum allowable circuit resistance
 - structure-to-electrolyte resistance
 - anode lead wire resistance

1.3 Insert the anode dimensions and water resistivity into the Dwight Equation to calculate the anode-to-electrolyte resistance.

- 1.4 Add the structure-to-electrolyte resistance, anode lead wire resistance, and the anode-to-electrolyte resistance from Step 1.3 to calculate the circuit resistance.

- 1.5 Subtract the required potential of the structure from the solution potential of the galvanic anode to calculate the driving potential of the anode.

- 1.6 Divide the driving potential from Step 1.5 by the circuit resistance from Step 1.4 to calculate the current output of a single galvanic anode.

2.0 Determine the number of galvanic anodes.

- 2.1 Divide the total current required by the anode current output from Step 1.6 to calculate the number of anodes required. Round up to the nearest integer.

3.0 Calculate the galvanic anode life.

3.1 Obtain the following information:

- anode mass in kg
- anode utilization factor
- anode actual consumption rate

3.2 Divide the product of the anode mass and utilization factor by the product of the anode consumption rate and anode current output calculated in Step 1.6.

Work Aid 3B: Formulas and Procedure for the Design of Impressed Current Systems for Vessel & Tank Interiors

Formulas

Minimum Number of Anodes Based on Anode Maximum Current Density

$$N = I / (\pi d L \times \gamma_A)$$

where -

- N = number of impressed current anodes
- I = total current required in milliamperes times 120%
- d = anode diameter in centimeters
- L = anode length in centimeters
- γ_A = anode maximum current density in mA/cm²

Minimum Number of Anodes Based on Anode Consumption Rate

$$N = \left(\frac{Y \times I \times C}{W} \right)$$

where -

- N = number of impressed current anodes
- Y = the impressed current system design life in years
- I = total current required in amperes times 120%
- C = anode consumption rate in kg/A-yr
- W = weight of a single anode

Circuit Resistance

$$R_C = R_{RPL} + \frac{R_{LW} + R_V}{N} + R_S + R_{RNL}$$

where -

- R_C = the circuit resistance of the entire impressed current system
- R_{RPL} = the resistance in the positive lead wire from the rectifier to the junction box
- N = the number of impressed current anodes
- R_{LW} = anode lead wire resistance
- R_V = the anode-to-electrolyte resistance of a single anode
- R_S = structure-to-electrolyte resistance
- R_{RNL} = the resistance in the negative lead wire from the structure to the rectifier

Dwight Equation (for a single vertical anode)

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

where -

- R_V = anode-to-electrolyte resistance of a single anode in ohms
- ρ = electrolyte resistivity
- L = anode length in centimeters
- d = anode diameter in centimeters

Procedure

- 1.0 Determine the number of impressed current anodes.
 - 1.1 Obtain the following information:
 - total current required to protect the tank or vessel
 - anode material and dimensions
 - maximum current density of the anode
 - 1.2 Calculate the minimum number of anodes required by using the anode current density formula and anode consumption rate formula. Use the largest number of anodes calculated from the two formulas. Round up to the nearest integer.
- 2.0 Calculate the circuit resistance.
 - 2.1 Obtain the following information:
 - structure-to-electrolyte resistance
 - anode lead wire resistance
 - rectifier to junction box lead wire resistance
 - resistance in the lead wire from the tank or vessel to the rectifier
 - water resistivity
 - rectifier voltage and current output ratings
 - 2.2 Calculate the anode-to-electrolyte resistance of a single anode by inserting the anode dimensions and the water resistivity into the Dwight Equation.
 - 2.3 Divide the sum of the lead wire resistance and the anode-to-electrolyte resistance by the number of anodes calculated in Step 1.2. To this resistance, add the structure-to-electrolyte resistance and the resistances in the positive and negative lead wires of the rectifier. This will give you the total circuit resistance of the impressed current system.
 - 2.4 Divide the rated voltage of the rectifier by its output current rating to calculate the maximum allowable circuit resistance. Ensure that the circuit resistance you calculated in Step 2.3 is less than the maximum allowable circuit resistance.

Work Aid 4: Formulas and Procedure to Design Cathodic Protection Systems for In-Plant Facilities

This Work Aid provides formulas and procedures to design impressed current systems to protect the bottom exterior of storage tanks using the earth potential shift formula.

Formulas

Earth Potential Shift

For a single vertical anode

$$V_x = \frac{0.5 \times I \times \rho}{\pi \times L} \left[\ln \frac{\sqrt{L^2 + X^2} + L}{X} \right]$$

For a single horizontal anode

$$V_x = \frac{I \times \rho}{\pi \times L} \left[\ln \frac{\sqrt{(0.5L)^2 + X^2 + h^2} + 0.5L}{\sqrt{X^2 + h^2}} \right]$$

where -

- V_x = earth potential change at the tank center (volts)
- I = current flow (amperes)
- ρ = soil resistivity (ohm-cm)
- L = anode backfill length (cm)
- X = horizontal distance from the anode to the center of the tank (cm)
- h = depth of burial to centerline of anode (cm)

Procedure

- 1.0 Determine the number and location of impressed current anodes.
 - 1.1 Select the location of the anodes within one-quarter of the tank radius from the tank wall according to Standard Drawing AA-036355.
 - 1.2 Add the distance between one anode and the tank to the tank radius to obtain the radius of the anode header cable. Multiply the header cable radius by 2π to calculate the circumference of the header cable.
 - 1.3 Divide the anode header cable length by 20 m to obtain the minimum number of anodes required.
- 2.0 Calculate the earth potential shift due to each anode.
 - 2.1 Obtain the following information:
 - average tank native potential
 - soil resistivity
 - anode and anode backfill dimensions
 - distance between the anodes and tank center
 - 2.2 Substitute the soil resistivity, anode distance, anode backfill length, and required earth potential shift (0.35 volts according to Saudi Aramco Standards) into the earth potential shift formula for a single vertical anode and solve for the current I , required.
 - 2.3 Divide the current flow by the number of anodes to obtain the estimated current required from each anode.
- 3.0 Calculate the current required to protect the tank based on surface area and required current density.

Work Aid 5: Formulas and Procedures to Design Cathodic Protection Systems for Marine Structures

This Work Aid provides formulas and procedures to design galvanic anode and impressed current systems to protect offshore platforms and submerged pipelines.

Work Aid 5A: Data Base, Formulas, and Procedure for the Design of Galvanic Anode Systems for Marine Structures

This Work Aid provides requirements from Standard Drawing AA-036335, formulas, and a procedure for determining the number, circuit resistance, current output, and design life of galvanic anodes used to protect marine platforms and pipelines.

HALF SHELL ANODE BRACELET TYPE ANODE FOR PIPE SIZES 4" THROUGH 60"

Pipe Size	Net Weight	Nominal Weight
10.2 cm (4") NB	16 kg	24 kg
15.2 cm (6") NB	23 kg	31 kg
20.3 cm (8") NB	30 kg	39 kg
25.4 cm (10") NB	36 kg	46 kg
30.5 cm (12") NB	41 kg	51 kg
35.6 cm (14") OD	50 kg	61 kg
40.6 cm (16") OD	54 kg	66 kg
45.7 cm (18") OD	61 kg	74 kg
50.8 cm (20") OD	68 kg	82 kg
55.9 cm (22") OD	75 kg	89 kg
61.0 cm (24") OD	82 kg	96 kg
66.0 cm (26") OD	86 kg	109 kg
71.1 cm (28") OD	91 kg	116 kg
76.2 cm (30") OD	95 kg	120 kg
81.3 cm (32") OD	100 kg	127 kg
86.4 cm (34") OD	104 kg	132 kg
91.4 cm (36") OD	109 kg	138 kg
106.7 cm (42") OD	129 kg	161 kg
116.8 cm (46") OD	143 kg	177 kg
121.9 cm (48") OD	167 kg	184 kg
132.1 cm (52") OD	161 kg	204 kg
152.4 cm (60") OD	186 kg	230 kg

Formulas

Current Output of a Galvanic Anode

$$I_A = E_D / R_C$$

where -

- I_A = anode current output in amperes
- E_D = the anode driving potential in volts versus Ag-AgCl
- R_C = the circuit resistance in ohms

Circuit Resistance of a Galvanic Anode

$$R_C = R_S + R_A = R_A$$

where -

- R_C = Circuit resistance in ohms
- R_S = the structure-to-electrolyte resistance (approximately zero)
- R_A = the anode-to-electrolyte resistance

Dwight Equation

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

where -

- ρ = the electrolyte resistivity in ohm-cm
- L = the length of the anode in centimeters
- d = the diameter of the anode in centimeters or the circumference divided by π for non-cylindrical shapes

Number of Galvanic Anodes Required

$$N = I / I_A$$

where -

- N = the number of anodes
- I = the total current required to protect the structure
- I_A = the current output of a single anode

Galvanic Anode Lifetime

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

where -

- Y = anode life in years
- W = anode mass in kg
- UF = Utilization factor
- C = actual consumption rate in kg/A-yr
- I_A = current output of one anode in amperes

Procedure

- 1.0 Calculate the required current.
 - 1.1 Obtain the following information:
 - platform surface area in seawater in m^2
 - current density required in seawater in mA/m^2
 - platform surface area below mud line in m^2
 - current density required in mud in mA/m^2
 - 1.2 To calculate the total current requirement, multiply the immersed surface area of the structure in seawater by Saudi Aramco's current density requirement. Multiply the surface area of the structure below the mud line by Saudi Aramco's current density requirement. Add the two current requirements together.
- 2.0 Calculate the number of galvanic anodes for an offshore platform.
 - 2.1 Obtain the following information:
 - anode solution potential in volts versus Ag-AgCl
 - anode dimensions in centimeters
 - anode weight in kg
 - seawater resistivity in ohm-cm
 - anode consumption rate in kg/A-yr
 - anode utilization factor
 - galvanic anode design life in years
 - 2.2 If the anode is not cylindrical, determine its effective diameter by dividing its circumference by π . Calculate the anode-to-electrolyte resistance of the anode by inserting its effective diameter, length, and the electrolyte resistivity into the Dwight Equation.
 - 2.3 Subtract the required potential of the structure from the solution potential of the anode to calculate the anode driving potential. Divide the anode driving potential by the anode-to-electrolyte resistance from Step 2.2 to determine the current output of a single anode.
 - 2.4 Divide the total current required by the anode current output from Step 2.3 to calculate the number of anodes required. Round up to the nearest integer.

-
- 2.5 Insert the weight of a single anode, utilization factor, consumption rate, and current output from Step 2.3 into the Galvanic Anode Lifetime formula. Ensure that the anode life is greater than the required design life. If the anode life is less than the required design life, multiply the number of anodes from Step 2.4 by the ratio of the design lifetime and calculated lifetime. The result is the proper number of anodes required for the design life of the cathodic protection system.
- 3.0 Calculate the number of galvanic anode bracelets for marine pipelines.
- 3.1 Obtain the following information:
- pipeline surface area in seawater in m^2
 - pipeline length in meters
 - pipeline diameter in cm
 - anode consumption rate in kg/A-yr
 - anode utilization factor
 - anode design life in years
- 3.2 To calculate the pipeline's current requirement, multiply its surface area by Saudi Aramco's required current density of $2.5 \text{ mA}/m^2$.
- 3.3 Divide the length of the pipeline by 150 meters to calculate the number of anode bracelets required.
- 3.4 Divide the total current requirement by the number of anode bracelets to calculate the current output per anode bracelet. Locate the net weight anode weight per bracelet in the table provided in this Work Aid.
- 3.5 Verify that the anode bracelet will last over the required design life. Substitute the anode consumption rate, current output, utilization factor, and net weight of anode material into the galvanic anode life formula and solve for Y.
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Work Aid 5B: Formulas and Procedure for the Design of Impressed Current Systems for Marine Structures

Formulas

Current Requirement for Impressed Current Systems

$$I_{\text{Corr}} = I(1 + (100\% - \% \text{Efficiency})/100)$$

where -

- I_{Corr} = corrected total current requirement for an impressed current system
- I = total current requirement (multiply total surface area by Saudi Aramco's current density requirement)
- Efficiency = efficiency of the impressed current anodes

Minimum Number of Anodes Based on Anode Maximum Current Density

$$N = I_{\text{Corr}}/(\pi dL \times \gamma_A)$$

where -

- N = number of impressed current anodes
- I_{Corr} = corrected total current requirement for an impressed current system in mA
- d = anode diameter in centimeters
- L = anode length in centimeters
- γ_A = anode maximum current density in mA/cm²

Circuit Resistance

$$R_C = R_{\text{RPL}} + R_{\text{RNL}} + \frac{R_V + R_{\text{LW}}}{N}$$

where -

- R_C = the circuit resistance of the entire impressed current system
- R_{RPL} = the resistance in the positive lead wire from the rectifier to the junction box
- R_{RNL} = the resistance in the negative lead wire from the structure to the rectifier
- N = the number of impressed current anodes
- R_V = the resistance of a single impressed current anode (Dwight Equation)
- R_{LW} = anode lead resistance

Dwight Equation

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

where -

- R_A = The anode-to-electrolyte resistance
- ρ = the electrolyte resistivity in ohm-cm
- L = the length of the anode in centimeters
- d = the diameter of the anode in centimeters or the circumference divided by π for non-cylindrical shapes

Procedure

- 1.0 Calculate the corrected current requirement.
 - 1.1 Add the current required to protect any conductor pipe and unprotected pipelines to the current required to protect the structure.
 - 1.2 Use the Current Requirement for Impressed Current Systems formula to calculate the corrected current requirement.
- 2.0 Calculate the number of impressed current anodes.
 - 2.1 Obtain the following information:
 - anode dimensions in centimeters
 - anode maximum current density
 - 2.2 Calculate the minimum number of anodes required by using the anode current density formula. Round up to the nearest integer.
- 3.0 Calculate the rectifier voltage requirement.
 - 3.1 Obtain the following information:
 - anode dimensions in centimeters
 - seawater resistivity in ohm-cm
 - anode lead wire resistance
 - rectifier lead wire resistance

- 3.2 Calculate the anode-to-electrolyte resistance of a single anode by inserting the anode dimensions and the seawater resistivity into the Dwight Equation.
- 3.3 Divide the sum of the lead wire resistance and the anode-to-electrolyte resistance by the number of anodes calculated in Step 2.2. To this resistance, add the resistances in the positive and negative lead wires of the rectifier. This will give you the total circuit resistance of the impressed current system.
- 3.4 To calculate the voltage requirement of the rectifier, multiply the corrected current by the circuit resistance. Divide this result by the rectifier efficiency to determine the actual voltage requirement.

GLOSSARY

anode internal resistance	The resistance from the anode to the outer edge of the backfill.
anode-to-earth resistance	The resistance between the anode, or backfill, and the soil.
backfill	A low resistance, moisture-retaining material immediately surrounding a buried impressed current anode for the purpose of increasing the effective area of contact with the soil and thus reducing the resistance to earth. Calcined petroleum coke backfill is commonly used as backfill for deep and surface anode beds in Saudi Aramco.
conductor pipe	Tubular members through which oil or gas wells are drilled and then through which casing and tubing are inserted and often grouted into place.
current density	The direct current per unit area are generally expressed as amperes per square meter or milliamperes per square meter. Current density to achieve cathodic protection varies depending on the environment and metal being protected.
deep anode bed	A type of anode bed that uses a drilled vertical hole to contain impressed current anodes.
insulated flange	A flanged joint used to electrically isolate pipelines and systems. The flange faces and securing bolts are electrically insulated from each other by insulating sleeves, washers, and gaskets.
polarization	The change of potential of a metal surface resulting from the passage of current to or from an electrolyte.
protective potential	A term used in cathodic protection to define the minimum potential required to suppress corrosion. Protective potential depends on the structure metal and the environment.
remote earth	The area(s) in which the structure-to-earth potential change is negligible with change in reference electrode position away from the structure.

shielding	The act of preventing or diverting cathodic protection current from reaching a structure. Shielding may be caused by a non-metallic barrier or by metallic structures that surround the structure to be protected.
structure-to- electrolyte potential	The potential difference between a buried or immersed metallic structure and the electrolyte surrounding it, measured with a reference electrode in contact with the electrolyte.
surface anode bed	A type of anode bed that uses vertically or horizontally placed impressed current or galvanic anodes.
utilization factor	The factor determined by the amount of anode material consumed when the anode can no longer deliver the current required.

APPENDIX 1

Saudi Aramco Engineering Standards

SAES-B-068	Electrical Area Classification
SAES-P-100	Basic Electrical Design Criteria
SAES-P-107	Overhead Power Distribution (SCECO Standard)
SAES-P-111	Grounding
SAES-Q-001	Criteria for Design and Construction of Concrete Structures
SAES-X-300	Cathodic Protection Marine Structures
SAES-X-400	Cathodic Protection of Buried Pipelines
SAES-X-500	Cathodic Protection Vessel and Tank Internals
SAES-X-600	Cathodic Protection In-Plant Facilities
SAES-X-700	Cathodic Protection of Onshore Well Casings
GI 482.002	Commissioning Procedures for Cathodic Protection Installations
SADP-X-100	Saudi Aramco Design Practice

Saudi Aramco Standard Drawings

AB-036008	Lidan anode - Pile Mounted
AA-036069	Galvanic Anodes at Thrust Anchors
AA-036073	Cable Connection to Wellhead
AA-036108	Offshore Negative Terminal Box
AD-036132	Termination Detail Cable Identification
AB-036272	Deep Anode Bed Steel Cased Hole
AB-036274	Junction Box 5-Terminal
AB-036275	Junction Box 12-Terminal
AA-036276	Splice Box; Multi-Purpose Details
AA-036277	Bond Box 5-Terminal
AA-036278	Deep Anode Bed Scrap Steel
AA-036280	Photovoltaic Power System
AA-036304	Pile Mounted Anodes for Offshore
AA-036335	Half Shell Bracelet Type Anode, for Pipe Sizes 4" through 60"
AA-036336	Half Shell Bracelet Type Anode, for Pipe Sizes 26" through 48"
AA-036346	Surface Anode Bed Details Horizontal and Vertical Anodes
AA-036347	Junction Box 20-Terminal
AA-036348	Anode Installation Details Galvanic and Impressed, Offshore Structures
AA-036349	Bond Box 3-Terminal
AA-036350	Bond Box 2-Terminal
AA-036351	Marker Plate Details

AA-036352	Galvanic Anodes for Road and Camel P/L Crossings, P/L Repair Locations, Installations and Details
AA-036353	Water Storage Tanks Impressed Current
AA-036354	Water Storage Tanks Galvanic Anodes
AA-036355	Tank Bottom Impressed Current Details
AA-036356	Deep Anode Bed Details, Aquifer Penetrating
AA-036378	Rectifier Installation Details
AB-036381	Thermite Welding of Cables to Pipelines & Structures
AA-036384	Junction Box, Offshore Anode
AA-036385	Deep Anode Bed Details, Non-Aquifer Penetrating
AA-036409	Replacement Galvanic Anodes for Offshore Structures & P/L's
AB-036478	Magnesium Anode Installation at P/L Repair Locations Layout & Details
AC-036524	Galvanic Anode Details Submarine Pipelines
AB-036540	Mounting Support Details for Junction Boxes
AB-036558	Standard Insulating Assemblies for Ring Joint Flanges with Gask-O-Seal Filler Gaskets
AA-036674	Bonding Methods for Onshore Pipelines and Flow Lines
AA-036675	Direct Buried Electric D-C Cathodic Protection Positive or Negative Cable
AA-036761	Lead Silver Anode Seabed Installation Details
AC-036762	Crude and Product Tank Internal Galvanic Anode Installation
AD-036763	Plidco Sleeve Anode, Offshore
AA-036782	Bond Box, 2-Terminal for Insulating Devices
AE-036785	Symbols for Cathodic Protection
AB-036787	Road Crossings Installation In Plant (Plastic Envelope)
AB-036907	Test Stations For Buried Pipelines, Pipeline Kilometer Markers

Saudi Aramco Material System Specifications

02-AMSS-008	Insulating Spools and Joints
17-AMSS-004	Constant Voltage Rectifiers
17-AMSS-005	Phase Controlled Rectifiers
17-AMSS-006	Galvanic Anodes
17-AMSS-007	Impressed Current Anodes
17-AMSS-008	Cathodic Protection Junction Boxes
17-AMSS-012	Photovoltaic Power Supply
17-AMSS-017	Cathodic Protection Cables