# Galvanic Anode
# Cathodic Protection System Design

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*Portions of the following were excerpted from the Appalachian Underground Corrosion Short Course "Advanced Corrosion Course" text that was edited and revised for applicability to this course*

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Galvanic anodes are an important and useful means for cathodic protection of underground storage tank systems, pipelines and other buried or submerged metallic structures. The application of cathodic protection utilizing galvanic anodes is nothing more than the intentional creation of a galvanic electrochemical cell in which two dissimilar metals are electrically connected while immersed in a common, electrically conductive electrolyte. In the "dissimilar metal" cell, the metal higher in the electromotive series (or more "active") becomes anodic to the less active metal and is consumed during the electrochemical reaction. The less active metal receives some degree of cathodic protection at its surface due to the current arriving from the anodic metal. The design of a galvanic cathodic protection system involves consideration of all factors affecting the proper selection of a suitable anode material and its physical dimensions, placement, and method of installation.

## ADVANTAGES AND LIMITATIONS

There are several important advantages to using galvanic anodes:

- No power source is required – Due to the fact that the protective current is generated by the electrochemical reaction between the metals, no externally supplied power is required.
- Installation and maintenance cost is reduced – Normally, galvanic anodes have the advantage of not requiring additional right-of-way purchase since the anodes are usually installed close to the protected structure. Once installed, very little maintenance is required for the life of the anode. The anode of a galvanic anode system is not subject to the same degree of electrical or mechanical malfunction as that of an impressed current system.
- Efficient and non-interfering – The relatively low, and normally well distributed, current output of the galvanic system can result in a more constant current density at the protected structure. This minimizes over protection and wasted current. The low current output reduces the possibility of interference to a minimum. The advantages mentioned enable the galvanic cathodic protection system to be utilized efficiently in a variety of applications, such as:

  a. For well-coated underground storage tanks and piping
  b. In rural areas and offshore where power is not available
  c. For supplemental protection, such as at pipeline crossings
  d. In isolated corrosive areas ("hot spots")
  e. In highly congested, urban areas where current distribution and interference present problems
  f. On electrically discontinuous structures
  g. Well coated pipelines

However, the galvanic anode system is not without limitations. The difference in the potential of the anode and cathode (protected structure) that causes the protective current to flow is normally quite small. The small potential difference, or "driving potential," results in very limited current outputs, especially in high soil resistivity areas. This fact severely limits the economic use of galvanic systems on:

- Large structures
- Poorly-coated structures

## AVAILABLE ANODE MATERIALS

The most commonly used materials for galvanic anodes on buried structures are alloys of magnesium and zinc.

When the anode alloy is placed in the electrolyte for the protection of a structure, a certain amount of the current is generated due to the self-corrosion of the anode. The current efficiency is a measure of the actual current available for cathodic protection of the primary structure expressed as a percentage of the total current generated.

Because the anode corrosion rate is directly proportional to the current output delivered, the efficiency is an important consideration in the selection of anode material. The higher the efficiency is, the more useable energy per pound of material purchased.

| Characteristic | H-1 Alloy (AZ-63) Mag. Alloy | Hi-Potential Mag. Alloy | Hi-Purity Zinc |
|---|---|---|---|
| Solution potential to Cu-$CuS0_4$ ref. cell | -1.55 | -1.80 | -1.10 |
| Faradaic Consumption Rate | 8.8 | 8.8 | 23.5 |
| Current efficiency (%) | 25-50 | 50 | 90+ |
| Actual amps-hrs/lb | 250-500 | 500 | 360 |
| Actual lb/amp/year | 35-17.5 | 17.5 | 26.0 |

The efficiency is dependent upon the alloy; therefore, it is important that once the proper alloy has been selected, the material purchased meets the alloy specifications. The next two tables list some typical alloy specifications in common usage.

The following elements, most commonly present in magnesium, affect the efficiency of magnesium anodes used for cathodic protection in soils:

- Aluminum – Significant effects outside ranges shown
- Manganese – Controls to some degree the negative impact of iron by surrounding the iron particles during casting solidification
- Nickel – Detrimental to efficiency
- Copper – Detrimental to efficiency
- Iron – Detrimental to efficiency, but can be controlled to some degree by larger amounts of manganese
- Silicon – Detrimental above 0.1 percent
- Zinc – Only slightly detrimental in higher amounts
- Other (lead, tin, beryllium) – Minor impurities that do not significantly affect anode efficiency in amounts commonly found, but can be detrimental above these limits

The following two tables provide industry standard alloy elements for both magnesium and zinc anodes commonly used in cathodic protection applications. Deviation from these alloy specifications can result in anodes that suffer from pacification, intergranular corrosion deterioration and excessive consumption rates.

**Common alloy specifications - Magnesium**

| Element | Hi-Pot. Mg (%) | Grade "A" Mg (%) | Grade "B" Mg (%) | Grade "C" Mg (%) |
|---|---|---|---|---|
| Al | 0.010 max | 5.0 - 7.0 | 5.3 - 6.7 | 5.3 - 6.7 |
| Mn | 0.50 - 1.30 | 0.15 min | 0.15 min | 0.15 min |
| Zn | 0 | 2.5 - 3.5 | 2.5 - 3.5 | 2.O - 4.0 |
| Si | 0 | 0.10% max | 0.30% max | 0.10% max |
| Cu | 0.02 | 0.02 | 0.05 | 0.10 |
| Ni | 0.001 | 0.002 | 0.003 | 0.003 |
| Fe | 0.03 | 0.003 | 0.003 | 0.003 |
| Other | 0.05% each or 0.03% max tot. | 0.30% max | 0.30% max | 0.30% max |
| Mg | Balance | Balance | Balance | Balance |

**Common alloy specifications - Zinc**

| Element | Hi-Amp Zinc (Mil-A 18001) for Seawater Use Only (Percent %) | Hi-Purity Zinc (ASTM B418-67 Type II) Primarily for Underground Use Percent (%) |
|---|---|---|
| Al | 0.1 - 0.3 | 0.005 max |
| Cd | 0.025 - 0.06 | 0.003 max |
| Fe | 0.005 max | 0.0014 max |
| Pb | 0.003 max | 0.003 max |
| Zn | Remainder | Remainder |

## SHAPES, SIZES, AND BACKFILL

Galvanic anodes are offered in a wide variety of standard shapes and sizes, and may also be ordered in custom sizes.

The use of a prepared anode backfill accomplishes the following effects:

- Stabilizes anode potential
- Prevents anode polarization, enhancing current maintenance
- Lowers anode-to-earth resistance, increasing current output
- Reduces self-corrosion of the anode by promoting a uniform corrosion attack, thereby improving efficiency

The most commonly used anode backfill mixture is 75 percent gypsum, 20 percent Bentonite clay, and 5 percent sodium sulfate. This mixture is selected because, over the wide range of soils likely to be encountered, it has shown the best success in achieving the desired characteristics. Due to the solubility of backfill components, the backfill tends to "condition" the adjacent soil for several feet.

## ANODE SELECTION

After considering the available materials, one must make a suitable selection. The criterion for selection is, as one would expect, an analysis of performance versus cost. The performance of an anode is measured by the following criteria:

- Anode life – Life is a function of three factors: weight, current output, and efficiency. Longer life is achieved through heavier weight, lower current output, and high efficiency.
- Current output – Current output is governed by electrolyte resistivity, anode resistance to electrolyte, and alloy potential. Higher current output is achieved through lower resistivity, lower resistance to electrolyte, and higher alloy potential.

The costs involved with the installation and operation of galvanic anodes can be categorized as follows:

- Material costs--This is based on alloy, backfill, and anode size. Generally, the heavier the anode, the lower the cost per pound of material. More efficient anode material results in a lower cost per ampere hour of current delivered.
- Installation costs--The installation cost would not be expected to vary greatly

on a per anode basis regardless of the alloy or size of anode selected. Therefore, consideration of installation costs normally involves an investigation of the number of anodes required.

- Maintenance costs--The cost of maintenance normally involves only the periodic testing of the cathodic protection system, which would not be substantially affected by the type of anode selected. This cost is usually neglected in the selection process.

## PRE-DESIGN CONSIDERATIONS

The primary consideration in the design of the galvanic system is the efficient distribution of sufficient current to achieve cathodic protection. Due to the limited range of voltages available the problem of achieving the desired current becomes one of regulating the resistance of the electrical circuit.

The most important (and least controllable) factor affecting the circuit resistance of underground galvanic cathodic protection systems is soil resistivity. For a small structure, such as an isolated, very well coated buried tank, it is often more economical to overdesign rather than perform field testing. On the other hand, it is imperative that testing be conducted for a poorly coated tank structure. The number of test points to be considered will vary from structure to structure and will depend on the variation of the resistivity measurements and the physical characteristics of the structure. Areas of predominantly uniform resistivity will require less frequent measurements than areas of varying resistivity.

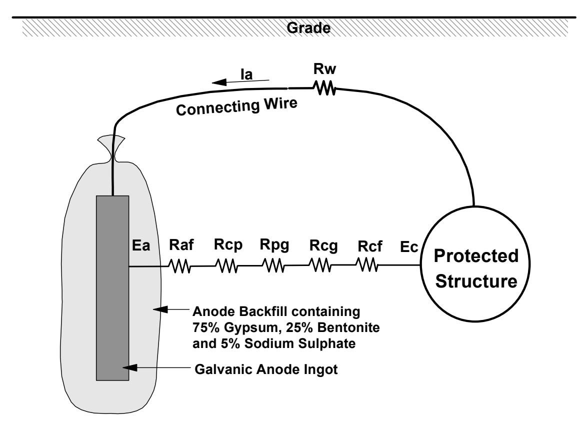
If the tank structure for which the galvanic anode design is intended exists, current requirement tests should be performed in order to more accurately determine the actual amount of current required. Current testing can be performed utilizing temporary "ground bed" of one or more driven metallic rods energized by a test rectifier or storage battery.

The temporary ground bed is energized and its effect upon the structure is measured. Utilizing proper measurement techniques, the current output is adjusted until the selected criterion for protection is achieved with the least amount of current. One or more such temporary ground beds may be required to analyze sections of the structure, especially if the physical characteristics of the structure vary significantly. One must remember that the resistance to ground of the driven rods is likely to be much higher than permanent buried anodes; therefore, the driving voltage required in the test is not indicative of the actual driving voltage requirement.

## DESIGN CALCULATIONS

The electrical circuit that governs the current output of a galvanic anode is depicted in the next figure.

**Galvanic Anode Electrical Circuit Components**




where:

Ea = potential of anode

Ec = potential of cathode

Ia = anode current

Raf = anode film resistance

Rap = backfill resistance

Rcf = cathode film resistance

Rcg = cathode-to-earth resistance

Rpg = backfill-to-earth resistance

Rw = resistance of connecting wire

Rcf is usually negligible in value, compared with the other resistive components, whereas Raf and Rap are constant for a given anode in a given backfill. Rcg, the cathode-to-electrolyte resistance, is heavily dependent on the quality of the structure coating, being nearly negligible for bare structures. Therefore, Rpg, Rcg, and Rw are the significant and variable components which must be considered.

$R_{TAV}$, the total resistance of a vertically installed anode in the electrolyte can be approximated by H. B. Dwight's equation:

$$R_{TAV} = \frac{0.00521}{L} p\left[\ln\left(\frac{8L}{d}\right) - 1\right]$$

where:

$R_{TAV}$ = Resistance of vertical, rod shaped anode

$p$ = resistivity of electrolyte,

$L$ = length of anode rod

$d$ = diameter of packaged anode

Once the total anode resistance has been calculated, the current output of the anode can be calculated in accordance with Ohms Law:

$$I_A = \frac{E_A - E_P}{R_{AF} + R_{AP} + R_{PG} + R_{CF} + R_W} = amperes$$

Since $R_{AF} + R_{AP} + R_{PG}$ is equal to $R_{TAV}$ calculated above and since $R_{CG} + R_{EF} + R_W$ is generally considered to be relatively small when compared to $R_{TAV}$, the above formula is often reduced to the following simplified form:

$$I_A = \frac{E_A - E_P}{R_{TAV}}$$

This theoretical expression will normally result in a conservative value of current for anodes in backfill that are installed in the soil. In addition, it is time-consuming to calculate the various resistive factors, and often certain. assumptions must be made that result in an approximate current calculation. The output of magnesium and zinc anodes has been fairly well documented under varying conditions, and many graphs, charts, and tables have been prepared based on actual outputs. These references provide a simplified and reasonably accurate determination of anode output under conditions normally encountered in the design of cathodic protection systems for pipelines, buried tanks, etc. One of the widely used references has been prepared by D. A. Tefankjian. He developed a set of equations for the output of an anode at a polarized structure potential of -0.85 volts versus a Cu-$CuSO_4$ reference electrode.

Correction factors are then applied to adjust the result for various shapes and structure potentials:

$$I_{mb} = 150{,}000\ FY/p$$

$$I_{zb} = 50{,}000\ FY/p$$

$$I_{mc} = 120{,}000\ FY/p$$

$$I_{zc} = 40{,}000\ FY/p$$

where:

$I_{mb}$ = current output for magnesium anode on bare structure in milli-amperes

$I_{zb}$ = current output for zinc anode on bare structure in milli-amperes

$I_{mc}$ = current output for magnesium anode on coated structure in milli-amperes

$I_{zc}$ = current output for zinc anode on coated structure in milli-amperes

P = soil resistivity in ohm-centimeters

F = factor from anode shape table

Y = factor from driving voltage table

**Anode shape correction - Table (f)**

| Alloy | Weight (lbs.) | Packaged Dimensions | Anode Factor (F) |
|---|---|---|---|
| Mg | 3 | 3" x 3" x 4.5" | .53 |
| Mg | 5 | 3" x 3" x 7.5" | 0.60 |
| Mg | 9 | 3" x 3" x 13.5" | 0.71 |
| Mg | 9 | 2.75" x 2.75" x 26" | 1.01 |
| Mg | 10 | 1.5" x 1.5" x 72" ingot, 4" x 78" Package | 1.71 |
| Mg | 15 | 1.6" dia. x 10' extrusion, 6” x 10’ Backfill | 2.61 |
| Mg | 17 | 4" x 4"x 17" | 1.00 |
| Mg | 18 | 2" x 2" x 72" ingot, 5" x 78" Package | 1.81 |
| Mg | 20 | 2.5" x 2.5" x 60" ingot, 5" x 66" Package | 1.60 |
| Mg | 20 | 1.3" dia. x 20' extrusion, 6” x 20’ Backfill | 4.28 |
| Mg | 25 | 2" dia. x 10' extrusion, 8” x 10’ Backfill | 2.81 |
| Mg | 32 | 5" x 5" x 21" | 1.06 |
| Mg | 40 | 3.75" x 3.75" x 60" ingot, 6.5" x 66" Package | 1.72 |
| Mg | 42 | 3" x 3" x 72 ingot, 6" x 78" Package | 1.90 |
| Mg | 50 | 8" dia. x 16" | 1.09 |
| Mg | 50 | 5" x 5" x 31" | 1.29 |
| Zn | 18 | 1.4” x 1.4” x 36” ingot, 5” x 42” Package | 1.68 |
| Zn | 30 | 2” x 2” x 30” ingot, 5” x 36” Package | 1.44 |
| Zn | 36 | 1.4” x 1.4” x 72” ingot, 5” x 78” Package | 1.81 |
| Zn | 60 | 2” x 2” x 60” ingot, 6.5” x 66” Package | 1.72 |

*Note:* Anodes are installed vertically.

**Driving voltage correction - Table (y)**

| Structure Potential (vs. Cu-$CuSO_4$) | Std. Mag. | Hi-Pot Mag | Zinc |
|---|---|---|---|
| -0.70 | 1.21 | 2.14 | 1.60 |
| -0.80 | 1.07 | 1.36 | 1.20 |
| -0.85 | 1.00 | 1.29 | 1.00 |
| -0.90 | 0.93 | 1.21 | 0.80 |
| -1.00 | 0.79 | 1.07 | 0.40 |
| -1.10 | 0.64 | 0.93 | n/a |
| -1.20 | 0.50 | 0.79 | n/a |

The equation assumes a minimum resistivity of 500 ohm-centimeters and a distance between anode and structure of 10 feet. It can be seen immediately from the tables that increasing the surface area of the anode (especially length) or use of a high potential alloy has the effect of increasing resultant current output, assuming other factors are equal.

For example, compare the current output of 17-pound standard alloy, high-potential alloy, and 20-pound (2" dia. x 60") magnesium anodes. Assume a well coated structure, a soil resistivity of 3000 ohm-centimeters, and an anticipated structure-to-soil potential of 0.85 volt.

**Standard 17# H-1 Alloy Magnesium Anode**

$$I_{MC} = \frac{120{,}000(1.0)(1.0)}{3000} = 40mA$$

**Standard 17# High Pot. Magnesium Anode**

$$I_{MC} = \frac{120{,}000(1.0)(1.29)}{3000} = 51.6mA$$

**Long 20# H-1 Alloy Magnesium Anode**

$$I_{MC} = \frac{120{,}000(1.60)(1.0)}{3000} = 64mA$$

Anodes may be connected in parallel, in order to achieve a higher total current output at a given location. Unfortunately, the output of two anodes in parallel which are buried less than 30 feet apart (center to center spacing) is not quite equal to the sum of the current from two separate anodes of the same size.

The closer together the anodes are spaced, the more the current output is restricted because the current from one anode tends to be opposed by the current output from adjacent anodes. To determine the approximate current output of a multiple anode ground bed, multiply the single anode current previously calculated by the appropriate adjusting factor found in the table below.

The table is calculated for 17-pound packaged anodes installed vertically in parallel. For approximate calculations, it is good for any size anodes.

For a more exact calculation, an adjusting factor may be determined from the following equation (based upon the E.D. Sunde formula for resistance to earth of multiple anodes). This equation is provided immediately following the table developed by Mr. Tefanjian.

$$MA_{ADJ} = \frac{N}{1 + \dfrac{2L(\ln 0.656N)}{S\left[\ln\left(\dfrac{8L}{d}\right) - 1\right]}}$$

Where:

$MA_{ADJ}$ = Multiple Anode Adjusting Factor

$N$ = number of anodes in parallel

$L$ = length of the anode in feet

$d$ = diameter of the anode in feet

$S$ = spacing, center-to-center in feet

**Multiple anode adjusting factors**
**(Vertically Installed Anodes)**

| | **Anode Spacing** (in Feet) | | | | |
|---|---|---|---|---|---|
| **No. of Anodes in Bank** | **5'** | **10'** | **15'** | **20'** | **25'** |
| 2 | 1.84 | 1.92 | 1.95 | 1.97 | 2.03 |
| 3 | 2.46 | 2.71 | 2.80 | 2.85 | 3.02 |
| 4 | 3.04 | 3.46 | 3.63 | 3.71 | 4.01 |
| 5 | 3.59 | 4.19 | 4.43 | 4.56 | 4.98 |
| 6 | 4.13 | 4.90 | 5.22 | 5.41 | 5.96 |
| 7 | 4.65 | 5.60 | 6.00 | 6.23 | 6.91 |
| 8 | 5.15 | 6.28 | 6.77 | 7.04 | 7.85 |
| 9 | 5.67 | 6.96 | 7.54 | 7.88 | 8.82 |
| 10 | 6.16 | 7.64 | 8.30 | 8.68 | 9.75 |
| 11 | 6.76 | 8.41 | 9.14 | 9.56 | 10.75 |
| 12 | 7.30 | 9.12 | 9.93 | 10.40 | 11.71 |
| 13 | 7.83 | 9.83 | 10.72 | 11.23 | 12.68 |
| 14 | 8.37 | 10.54 | 11.51 | 12.07 | 13.64 |
| 15 | 8.91 | 11.25 | 12.30 | 12.91 | 14.61 |
| 16 | 9.44 | 11.96 | 13.09 | 13.75 | 15.57 |
| 17 | 9.98 | 12.68 | 13.89 | 14.58 | 16.54 |
| 18 | 10.51 | 13.39 | 14.68 | 15.45 | 17.50 |
| 19 | 11.05 | 14.10 | 15.47 | 16.26 | 18.47 |
| 20 | 11.59 | 14.81 | 16.26 | 17.10 | 19.43 |

To determine the approximate current output of six 17-pound standard alloy anodes spaced on 10-foot centers in 3000 ohm-centimeter soil with a structure potential of (-)0.85 volts, it was determined earlier that the current output of a single 17 pound anode under these same conditions = 40 milli-amperes.

From the Multiple Anode Adjusting Factor Table, select 4.90 from the 6 anode row and the 10' column.

Therefore the output of the six anodes = (40)(4.90) = 196 ma.

Having arrived at an anode configuration that will produce the required current output is not sufficient in itself. An examination of the estimated life of the anodes must be undertaken in order to determine whether the design will provide protection for a reasonable period of time. The following expression may be used to calculate the estimated life of the anode:

> ***Anode Life*** *= [Faraday Consumption Rate (Ampere Hours/Pound)/No. of Hours per Year] x Anode Weight (lbs) x Anode Efficiency x Utilization Factor/Anode Current in Amperes*

The utilization factor accounts for a reduction in output as the surface area of the anode decreases with time, limiting the anode output. This factor is usually assumed to be 0.85. The equation may then be reduced to simpler form by substituting the constant factors:

For magnesium:

$$L_M = \frac{48.5W}{I}$$

For zinc:

$$L_Z = \frac{32.5W}{I}$$

where:

W = Anode metal weight in pounds
I = Current output in milli-amperes
$L_M$ = magnesium anode life, years
$L_Z$= zinc anode life, years

The expected life of the cathodic protection system should be consistent with the design life, use, and maintenance of the protected structure.