# Design of Galvanic Anode Cathodic Protection

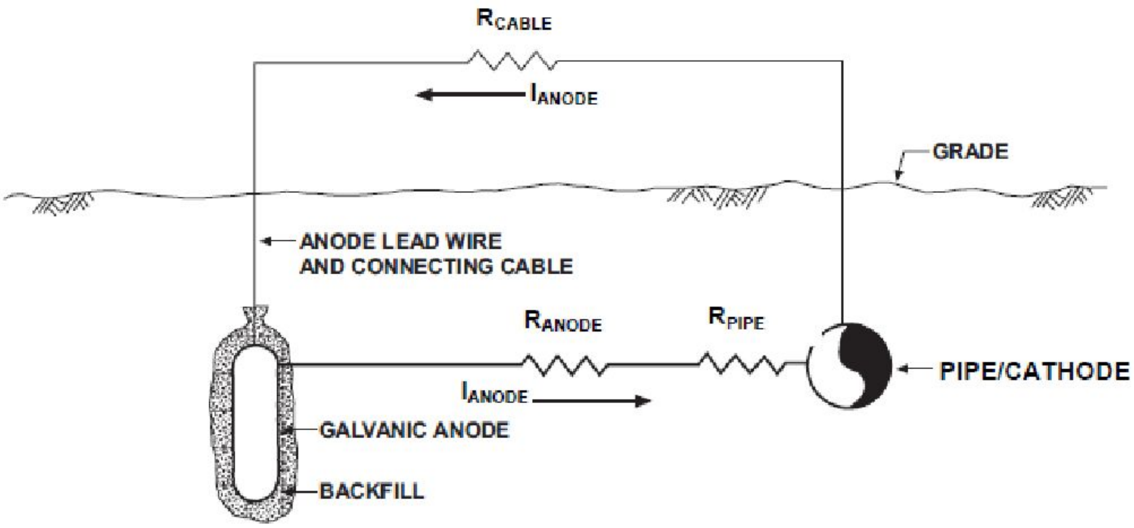
Bob Donlan, Argus Consulting

AUCSC

Appalachian Underground Corrosion Short Course

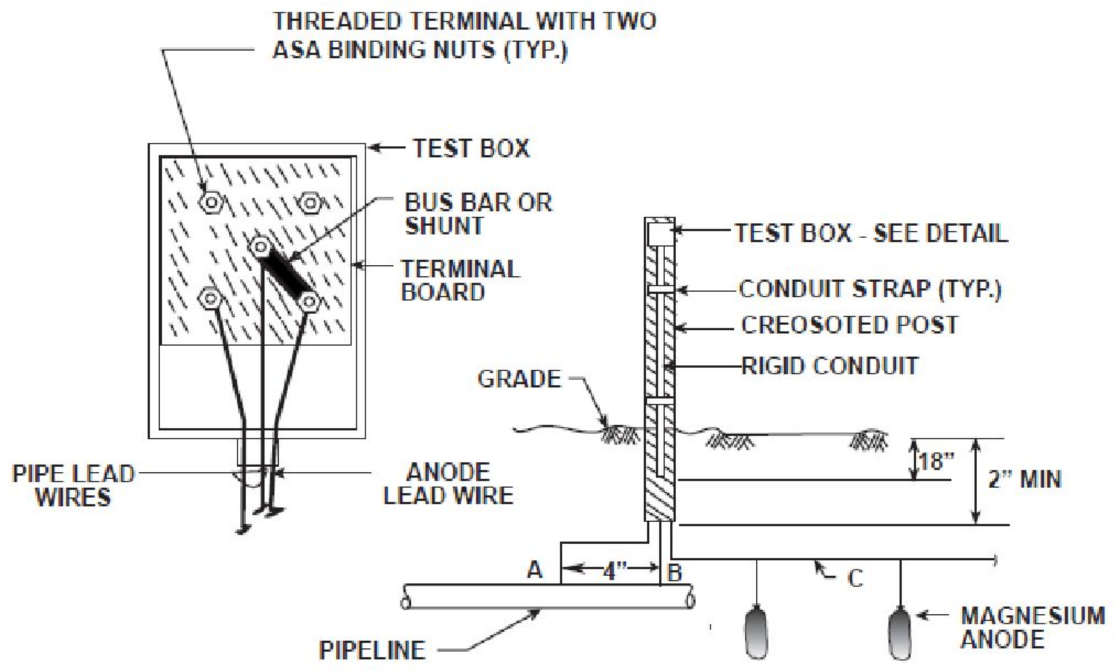
# Galvanic Anode Cathodic Protection

- The system makes use of metals which are more active than the structure metal
- These more reactive materials are placed in the earth near the pipe and are electrically connected to the pipe with a small (#12 AWG typical) copper lead wire
- Since the soil contains moisture, a corrosion cell is completed between the active metal and the pipe wherein the active metal becomes the anode and the pipe becomes the cathode
- The active metal anode corrodes "sacrificing" itself to provide corrosion protection for the pipe or underground structure




GALVANIC ANODE SYSTEM
ELECTRICAL CIRCUIT

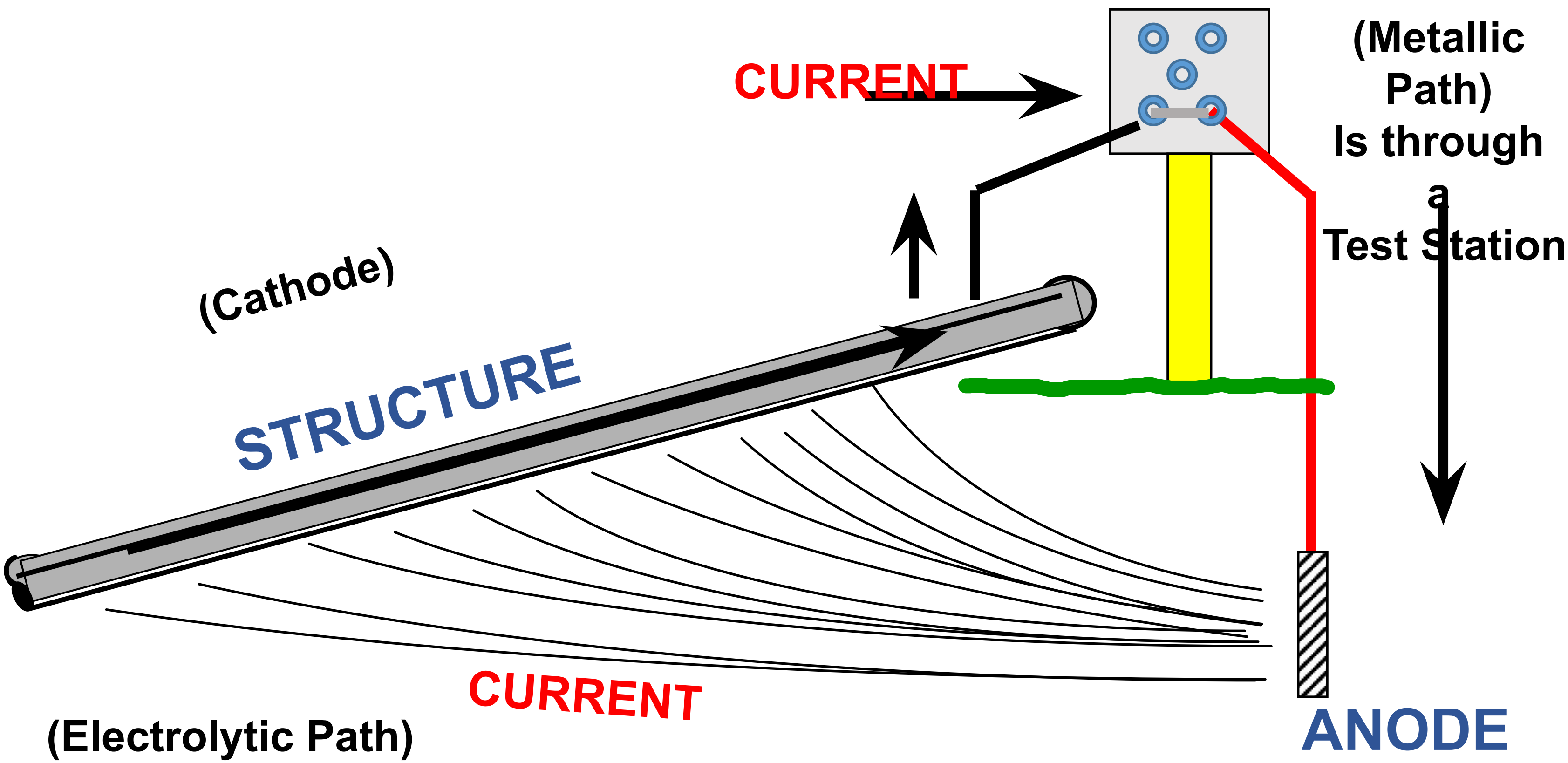
FIGURE 6-1




**TYPICAL GALVANIC ANODE SYSTEM INSTALLATION**

**FIGURE 6-2**

# Galvanic Anode Cathodic Protection System
# (Current flow from positive to negative)



# Specific Uses for Galvanic Anodes

- Protect Well Coated or Small Structures
- Where no AC Power is available
- Discharge Stray Currents
- Hot Spot Protection
- Supplement ICCP protection at select locations
- Temporary CP
- AC Mitigation

# Fundamental Characteristics of Galvanic and Impressed Current Systems

- Impressed Current
  - Adjustable Voltage
  - Small or Large Voltage
  - Adjustable Current
  - Large $/Unit Cost
  - Small $/Sq. Ft. Protected
  - Higher Maintenance Cost
  - Causes Stray Currents
- Galvanic
  - Fixed Voltage
  - Small Voltage
  - Fixed, Small Current
  - Small $/Unit Cost
  - Large $/Sq. Ft. Protected
  - Low Maintenance Cost
  - No Stray Currents

# Galvanic Anode CP – Design Parameters

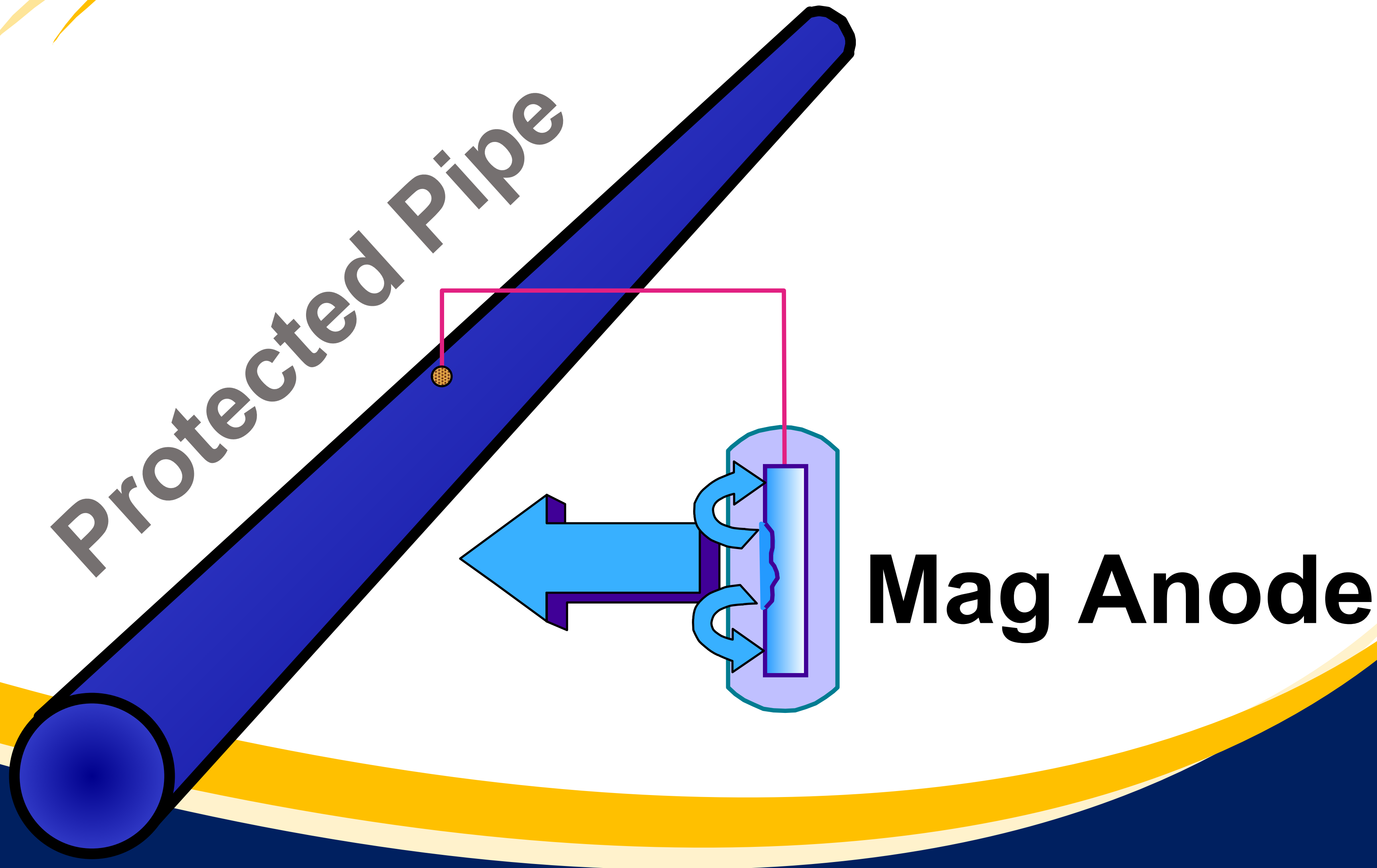
**Consider the following to determine the most economical anode material to use:**

1. Required amount of protective current
2. Total weight of each anode
3. Anode Life calculations
4. Desired life of the installation
5. Efficiency of anode types
6. Theoretical anode consumption rate
7. Driving potential
8. Soil or water resistivity
9. Cost of the anode material
10. Shipping costs
11. Degree of skill required for installing the anode system
12. Overall cost of the anode installation

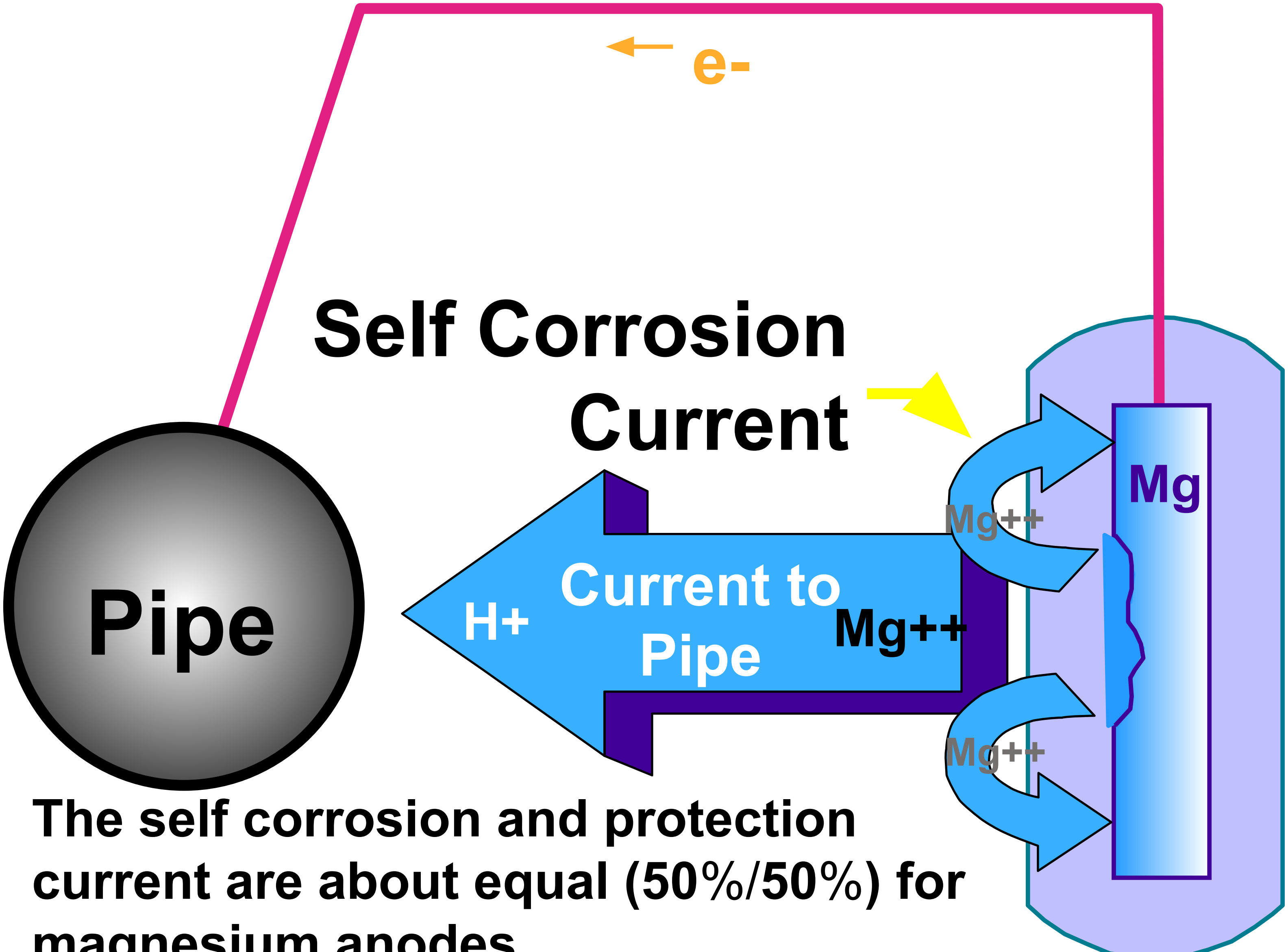
# Anode Current Efficiency

- Anode current efficiency is a measure of the percentage of the total anode current output which is available in a CP circuit
- The remaining current is dissipated in self corrosion of the anode material.
- See Table 6-1

# CP Current vs. Self Corrosion Current



# CP Current vs. Self Corrosion Current




**The self corrosion and protection current are about equal (50%/50%) for magnesium anodes**

# Table 6-1
## Typical Operating Characteristics of Galvanic Anodes

| Galvanic Anode Material | Theoretical Capacity (amp-hr/lb) | Actual Capacity* (amp-hr/lb) | Consumption Rates (lb/amp-yr) | Current Efficiency | Negative Potential to CSE (Volts) |
|---|---|---|---|---|---|
| Zinc (Mil-A-18001 U) | 370 | 370 | 23.7 | 90% | 1.10 |
| Magnesium (H-1 Alloy) | 1000 | 250 - 580 | 15 - 35 | 25 - 58% | 1.40 - 1.60 |
| Magnesium (High Potential) | 1000 | 450 - 540 | 16 - 19 | 45 - 54% | 1.70 - 1.80 |

* Based on shown current efficiencies

# Current Requirements

- Determine the amount of current required to protect a structure.
- Very Important in overall design
- This is accomplished by conducting current requirement tests.  Putting a known current on the line and determining the change in potential
- This can also be accomplished through calculations

# Electrolyte Resistivity

- The selection of the anode material is primarily dependent on the resistivity of the soil.  - VERY IMPORTANT
- Galvanic anodes have low driving potentials
- Zinc – Less than 1,500 ohm-cm.
- Magnesium – Generally 1,000 – 10,000 ohm-cm.
- It’s important to place the galvanic anode bed in the areas of lowest soil resistivity.
- A soil resistivity survey, of some sort, is critical to the design.

# Total Circuit Resistance

- Total Circuit resistance is dependent on the following 3 Items:

1. Anode Bed Resistance
2. Resistance of interconnecting cables
3. Resistance to earth of the cathode (structure)

# Basic Dwight's Equation

$$Rv = .00521p/L(Ln8L/d-1)$$

- where:

  Rv = Resistance to earth of single vertically installed anode

  p = Soil Resistivity at anode depth in ohm-cm

  L = Anode Length in Feet

  d = Anode Diameter in Feet

## Calculating the Resistance-to-Earth of a Galvanic Anode Bed - Example

Calculate the resistance of a galvanic anode bed consisting of six prepackaged 60 lb zinc anodes (5" x 66" long) spaced 15' apart, center-to-center, average soil resistivity in the area is 1,500 ohm-cm.

$$R\text{- Anode} = \frac{0.00521 \cdot \rho}{N \cdot L} \cdot \left( \ln \frac{8 \cdot L}{d} - 1 + \frac{2 \cdot L}{S} \cdot \ln 0.656 \cdot N \right)$$

Where:

R-Anode = resistance-to-earth of the vertical anodes in parallel (ohms)

$\rho$ = electrolyte resistivity (ohm-cm) L

= length of anode (feet)

d = anode diameter in feet

N = number of anodes in parallel

S = spacing between anodes in feet

$$R\text{ - Anode} = \frac{0.00521 \cdot 1500}{5.5 \cdot 6} \cdot \left( \ln \frac{8 \cdot 5.5}{0.417} - 1 + \frac{2 \cdot 5.5}{15} \cdot \ln 0.656 \cdot 6 \right)$$

R - Anode = 1.10 ohms

# Resistance of Interconnecting Cables - R-Cable

The resistance of the interconnecting cables (R-Cable) is normally negligible in the design of galvanic anode cathodic protection systems. The voltage drops in the cables are usually insignificant because of the low current output of this type of installation. When the resistance of the interconnecting cables is to be included in the overall system resistance, R- Cable can be calculated for all practical purposes, using the following formula:

R-Cable = Resistance per ft of cable (from Table 6-2) x Length of cable

# Table 6-2
## Resistance of Concentric Stranded Copper Single Conductors

| Size AWG | Max. DC Resistance @ 20°C (Ohm/1000 ft) |
|---|---|
| 14 | 2.5800 |
| 12 | 1.6200 |
| 10 | 1.0100 |
| 8 | 0.6400 |
| 6 | 0.4030 |
| 4 | 0.2540 |
| 3 | 0.2010 |
| 2 | 0.1590 |
| 1 | 0.1260 |
| 1/0 | 0.1000 |
| 2/0 | 0.0795 |
| 3/0 | 0.0631 |
| 4/0 | 0.0500 |
| 250 MCM | 0.0423 |

# Pipe Resistance-to-Earth - R-Pipe

The pipe resistance-to-earth is the resistance between the pipe and the electrolyte.

This value can be measured directly or it can be calculated from the average coating resistance (ACR) and then using the following formula:

R-Pipe =

ACR/SA Where:

| | |
|---|---|
| R-Pipe | = Resistance-to-earth of pipeline (ohms) |
| ACR | = Average Coating Resistance (ohm-$ft^2$) |
| SA | = Surface Area of pipeline ($ft^2$) |

# Calculating Pipe Resistance-to-Earth from Average Coating Resistance - Example

If a 10-mile section of 36" diameter pipe has an average coating resistance (ACR) of 50,000 ohms-ft², the pipe resistance-to-earth (R-Pipe) can be calculated as follows:

**Step No. 1** - **Calculate surface area of pipeline:**

SA = π x pipe diameter (ft) x length of pipe (ft)

SA = 3.14 x (36/12) x (10 x 5280)

SA = 497,376 ft²

**Step No. 2 -** Calculate pipe resistance-to-earth :

R-Pipe = ACR/SA = 50,000 ohm-ft²/497,376 ft² = 0.10 ohm

# Anode Life

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:

$$\text{Years Life} = \frac{CAP \times A \times E \times UF}{Hr \times I}$$

Where:

CAP = Theoretical capacity (amp-hours/lb)

A = Anode weight (lbs)

E = Current Efficiency expressed as a decimal

UF = Utilization Factor - typically 85% expressed as a decimal (0.85)

Hr = Hours per year

I = Current (amps)

# Utilization Factor

The utilization factor accounts for a reduction in output as the surface area of the anode decreases with time, limiting the anode output. This is the point at which the anode should be replaced even though the anode metal may not be entirely consumed. This factor is usually assumed to be **0.85.**

1. For magnesium:

$$\text{Years Life} = \frac{0.114\,^{*} \times A \times E \times}{I}$$

UF

2. For zinc:

$$\text{Years Life} = \frac{0.0424\,^{*} \times A \times E \times}{I}$$

UF

* These constants are derived by dividing the theoretical capacity by the number of hours in a year.

# Calculating Anode Life - Example

Let's compare the life expectancy of ten pound anodes of magnesium and zinc, each discharging 0.1 amp. Assume **90%** current efficiency for **zinc** and **50%** for **magnesium**. Each anode is assumed to require replacement when it is **85% consumed**.

Using the formulas above, the life expectancies work out as follows:

1. For magnesium:

$$\text{Years Life} = \frac{0.114 \times 10 \times 0.50 \times 0.85}{0.10} = 4.8 \text{ years}$$

2. For zinc:

$$\text{Years Life} = \frac{0.0424 \times 10 \times 0.90 \times 0.85}{0.10} = 3.2 \text{ years}$$

The calculated life figures reflect the effect of different rates of consumption of the two metals as well as the effect of current efficiency.

# Designing a Galvanic Anode CP System Using Formulas - Example

**Let’s design a galvanic anode cathodic protection system for a well-coated pipeline that is 36" OD and 2500 ft long. The average soil resistivity in the area is 1000 ohm-cm. The desired system life expectancy is 20 years.**

**Step No. 1** - Choose the anode material. Based on the fact that magnesium has a higher capacity (amp-hr/lb) and a lower consumption rate (lb/amp-yr) than zinc (see Table 6-1) magnesium is selected.

**Step No. 2** - Calculate the surface area (SA) to be protected:

SA = π x pipe outside diameter (ft) x length of pipe (ft)

SA = 3.14 x (**36/12**) x (2500)

SA = 23,550 $ft^2$

**Step No. 3** - Calculate current requirements. The anode bed should be designed to achieve a satisfactory amount of polarization. After polarization, galvanic anodes tend to self-regulate and the current output at the anode bed will decline while protection is maintained. **As a rule of thumb, the amount of current required to polarize the pipe is four times the amount of current required to maintain protection.**

a. Current required to maintain protection (I-Req) on the pipe can be calculated as follows, assuming a current requirement of 0.003 mA/ft$^2$, typical for a well coated, electrically isolated pipe. This is based on 1.5 mA/ft$^2$ of exposed metal and on 0.2% coating damage.

I-Req = 0.003 mA/ft$^2$ x SA

I-Req = 0.003 mA/ft$^2$ x 23,550 ft$^2$

I-Req = 71 mA = 0.071 Amperes

b. **The current required to polarize (I-Polar) the pipe, by rule of thumb, is based on a current requirement of 0.012 mA/ft$^2$ (4 times the current required for protection).** This also approximated the current required should coating deteriorate to a total of 0.8% damage from the initial value of 0.2%.

I-Polar = 0.012 mA/ft$^2$ x SA
I-Polar = 0.012 mA/ft$^2$ x 23,550 ft$^2$

I-Polar = 283 mA = 0.283 Amperes

**Step No. 4** - Determine the minimum amount of anode material (W) required to provide an anode bed life of 20 years, based on the current required to polarize the pipe.

$$\text{Years Life} = \frac{0.114 \times W \times E \times UF}{I_{POLAR}}$$

$$20 = \frac{0.114 \times W \times 0.50 \times 0.85}{0.283}$$

Solving for W, W = 117 lbs of magnesium.

**Based on the weight of anode material calculated above, it appears that 7 - 17 lb anodes (4" x 4" x 17"), with backfill outer dimensions of 7.5" x 24", will provide sufficient anode material for the desired life.**

**Step No. 5 -** Calculate the anode bed resistance-to-earth (R-Anode Bed) for the anode bed assuming center-to-center anode spacing of 15 feet.

$$R\text{-}Anode = \frac{0.00521 \cdot \rho}{N \cdot L} \cdot \left( \ln \frac{8 \cdot L}{d} - 1 + \frac{2 \cdot L}{S} \cdot \ln 0.656 \cdot N \right)$$

$$R\text{-}Anode = \frac{0.00521 \cdot 1000}{7 \cdot 2} \cdot \left( \ln \frac{8 \cdot 2}{0.625} - 1 + \frac{2 \cdot 2}{15} \cdot \ln 0.656 \cdot 7 \right)$$

R-Anode = 0.99 ohm

**Step No. 6** - Calculate the pipe resistance-to-earth (R-Pipe) assuming an average coating resistance (ACR) of 15,000 ohm-$ft^2$.

R-Pipe = ACR/SA
R-Pipe = 15,000 ohm-$ft^2$/23,550

$ft^2$ R-Pipe = 0.64 ohm

**Step No. 7** - Calculate the connecting cable resistance (R-Cable) assuming the use of approximately 105 ft of No. 6 AWG wire.
R-Cable = Resistance of wire x length

R-Cable = 0.403 ohm/1000 ft x 105 ft

R-Cable = 0.042 ohm

**Step No. 8** - Calculate anode bed current output (I-Anode). Assume the anode potential to be
-1.55 volts and you want to polarize the pipe to -1.0 volt.

$$I\text{ - Anode} = \frac{\text{Anode Potential} - \text{Cathode Potential}}{R\text{ - Anode} + R\text{ - Pipe} + R\text{ - Cable}}$$

$$I\text{ - Anode} = \frac{1.55 - 1.0}{0.991 + 0.64 + 0.042} = 0.329 \text{ Ampere}$$

The anode bed current output (I-Anode) calculated above exceeds the previously calculated current values required to polarize and protect the structure, therefore the design will be effective in providing cathodic protection. Once the pipe polarizes (usually within a few months), the anode current will drop to the protective level of about 0.071 amperes, thus further extending anode life. Also, using the polarizing current in these calculations allows for coating deterioration over time.

## Simplified Calculations - D. A. Tefankjian

The following equations can be used to determine the current output for magnesium or zinc anodes, utilizing correction factors provided in Tables 6-3 and 6-4.

Bare or Poor Coating: Good coating:

$$I\text{-}Mag = \frac{150000 \cdot F \cdot Y}{\rho} \qquad I\text{-}Mag = \frac{120000 \cdot F \cdot Y}{\rho}$$

$$I\text{-}Zn = \frac{50000 \cdot F \cdot Y}{\rho} \qquad I\text{-}Zn = \frac{40000 \cdot F \cdot Y}{\rho}$$

Where:

I-Mag = current output for magnesium anode in milliamperes

I-Zn = current output for zinc anode in milliamperes

$\rho$ = soil resistivity in ohm-cm

F = anode shape factor from Table 6-3

Y = driving voltage factor from Table 6-4

# Table 6-3
# Anode Shape Factors (F)

| Anode Weight (lbs) | Anode | Factor (F) |
|---|---|---|
| **Standard Anodes** | | |
| 3 | (Packaged) | 0.53 |
| 5 | (Packaged) | 0.60 |
| 9 | (Packaged) | 0.71 |
| 17 | (Packaged) | 1.00 |
| 32 | (Packaged) | 1.06 |
| 50 | (Packaged - anode dimension 8" dia x 16") | 1.09 |
| 50 | (Packaged - anode dimension 5" x 5" x 31") | 1.29 |
| **Long Anodes** | | |
| 9 | 2.75" x 2.75" x 26" backfill 6" x 31" | 1.01 |
| 10 | 1.50" x 4.50" x 72" backfill 4" x 78" | 1.71 |
| 18 | 2.00" x 2.00" x 72" backfill 5" x 78" | 1.81 |
| 20 | 2.50" x 2.50" x 60" backfill 5" x 66" | 1.60 |
| 40 | 3.75" x 3.75" x 60" backfill 6.5" x 66" | 1.72 |
| 42 | 3.00" x 3.00" x 72" backfill 6" x 78" | 1.90 |
| **Extra-Long Anodes** | | |
| 15 | 1.6" dia x 10' backfilled to 6" dia | 2.61 |
| 20 | 1.3" dia x 20' backfilled to 6" dia | 4.28 |
| 23 | 2.0" dia x 10' backfilled to 8" dia | 2.81 |

# Table 6-4
# Driving Voltage Correction Factors (Y)

| P/S | Standard Magnesium | High-Potential Magnesium | 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 | -- |
| -1.20 | 0.50 | 0.79 | -- |

## Designing a Galvanic Anode CP System Using Simplified Calculations - Example

Let's calculate the number of anodes required to protect 10,000 feet of well coated, electrically isolated 16" OD pipe at a pipe-to-soil potential of 0.85 volts in a soil of 2500 ohm- cm. Assume a current requirement of 1.5 mA/exposed square foot of metal and coating damage of 1%. Use 32 lb pre-packaged standard alloy magnesium anodes and design for a 20 year anode life.

**Step 1** - Calculate the surface area (SA) to be protected.

Total SA = $\pi$ x pipe outside diameter (ft) x length of pipe (ft)

Total SA = $\pi$ x (16/12) x 10000 = 41,888 $ft^2$

**Exposed SA to be protected = 41,888 x 1% = 419 $ft^2$**

**Step 2** - Calculate the current required: 419 $ft^2$ x 1.5 $mA/ft^2$ = **629 mA**

**Step 3 -** Calculate the anode current output (I-Mag):

$$I\text{-}Mag = \frac{120000 \cdot F \cdot Y}{\rho} \Rightarrow I\text{-}Mag = \frac{120000 \cdot 1.06 \cdot 1.00}{2500}$$

**I-Mag = 50.9 mA = 0.0509 amps**

**Step 4** - Calculate the number of anodes required:

$$\text{Number} = \frac{\text{current requirement}}{\text{anode output}}$$

$$\text{Number} = \frac{629 \text{ mA}}{50.9 \text{ mA / Anode}}$$

$$\text{Number} = 12.4 \quad \text{or} \quad 13 \text{ anodes}$$

Anodes could be spaced evenly along the line at intervals of 10,000/13 or about every 769 ft.

**Step 5** - Calculate anode life:

$$\text{Life} = \frac{0.114 \times W \times E \times UF}{\text{Current (amps)}}$$

$$\text{Life} = \frac{0.114 \times 32 \times 0.50 \times 0.85}{0.0509}$$

Life = 30.5 years

The twenty year design life is satisfied.

# Calculating the Current Output of Multiple Anodes in Parallel - Example

The current output (I-Anode) of six 32-lb pre-packaged standard alloy magnesium anodes connected in parallel can be calculated as follows, based on a current output of 50.88 mA for an individual anode. Assume an anode spacing of 10 feet.

I-Anode = 50.88 mA x Adjusting Factor (from Table 6-5)

I-Anode = 50.88 mA x 4.902

I-Anode = 249.41 mA

# Table 6-5
# Multiple Anode Adjustment Factors

| No of Anodes in parallel | Adjustment Factors (anode spacing in feet) | | | |
|---|---|---|---|---|
| | **5'** | **10'** | **15'** | **20'** |
| 2 | 1.839 | 1.920 | 1.946 | 1.965 |
| 3 | 2.455 | 2.705 | 2.795 | 2.848 |
| 4 | 3.036 | 3.455 | 3.625 | 3.714 |
| 5 | 3.589 | 4.188 | 4.429 | 4.563 |
| 6 | 4.125 | **4.902** | 5.223 | 5.411 |
| 7 | 4.652 | 5.598 | 6.000 | 6.232 |
| 8 | 5.152 | 6.277 | 6.768 | 7.035 |
| 9 | 5.670 | 6.964 | 7.536 | 7.876 |
| 10 | 6.161 | 7.643 | 8.304 | 8.679 |

# Specification and Maintenance Galvanic Anode Installations

- Maintenance of Galvanic Anode CP systems consists of:
  - Routine surveys
  - Repair and/or replacement when necessary
  - Utilize current measurements during annual surveys

# Conclusions

- Galvanic anode cathodic protection systems are important in providing CP to pipelines and other buried systems, provided that various factors are considered in the overall design. These factors include:
    1. Soil Resistivity
    2. Current requirements
    3. Anode material selection
    4. Life expectancy
    5. Cost factors

# Questions?