Advanced Galvanic Cathodic Protection

AMPP ROCKY MOUNTAIN SHORT COURSE 2024

TOM TAYLOR, PE, CS, CPS
TOM@TOMTAYLOR.CC // +1 (720) 589-0816

TOM TAYLOR CORROSION CONSULTING
COVERING YOUR ASSETS

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Disclaimer

I am not your corrosion engineer.

Retain the services of a **qualified** and **professionally licensed** corrosion engineer prior to implementing any of the content discussed and ensure they have properly evaluated the implications of this content for your application.

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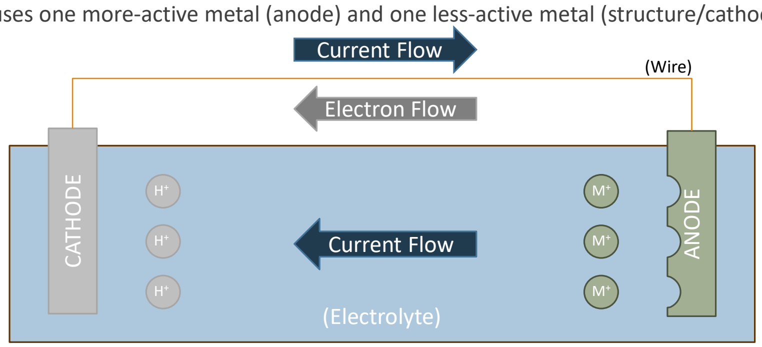
What is Galvanic Cathodic Protection?

Galvanic Cathodic Protection is the use of dissimilar metals to intentionally form a corrosion cell with the goal of protecting a structure.

- Also known as sacrificial anode cathodic protection
- Typically, uses one more-active metal (anode) and one less-active metal (structure/cathode)



The Galvanic Series

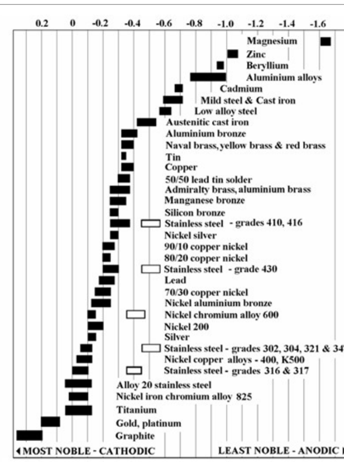
The Galvanic Series is a table of potentials for given materials in an electrolyte – typically seawater.

Nobility is the resistance of a material to reaction.

Nobler metals are often found in their metallic form, while less noble metals are found only in their ores.

The energy required to refine a metal is directly related to the nobility and activity of that metal.

- Sodium, Lithium, Potassium, and Calcium would probably make good galvanic anodes if they didn't burst into flame in water.



CP: Galvanic vs Impressed Current

GALVANIC

Pros:
- Lower material and installation costs
- Lower complexity vs ICCP
- 'Tougher' – operate with little/no maintenance
- Distributed systems allow redundancy

Cons:
- Limited current output
- More sensitive to soil conditions
- Shorter system lifespans

IMPRESSED CURRENT

Pros:
- High current output in differing soil conditions
- Longer 'throw' in pipeline applications
- Centralized control for adjustments and surveys

Cons:
- Higher material and installation costs
- Higher risk of interference with nearby structures
- Require external power source
- Multiple failure points

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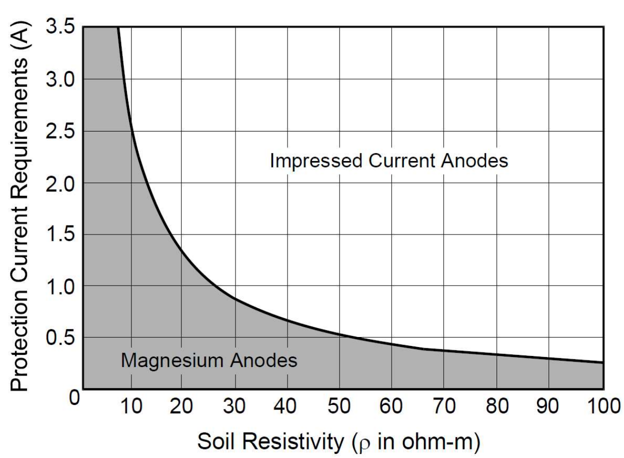
How to Choose Galvanic vs. ICCP

Deciding between GACP and ICCP:
- Consider current required,
- Soil types and seasonal variations,
- Power availability,
- Budgetary considerations,
- Monitoring requirements.

Consider company standards and existing data before deciding on a design type.

The graph on the right should be seen as advice, not a hard division.



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Common Galvanic Anode Materials

	Magnesium	Zinc	Aluminum
Installation Environment			
Soil	Yes (≤ 10,000 Ω-cm)	Sometimes (≤ 1,500 Ω-cm)	No
Fresh Water	Yes	No	No
Salt Water	No	Yes	Yes
Bulk Properties			
Potential ($-V_{CSE}$)	1.5 Standard 1.8 High Potential	1.1	1.1
Efficiency (typ.)	50%	90%	95%
Theoretical Use Rate (lb/A-yr)	8.7	23.5	3.3
Density (lb/ft^3)	106	445	169

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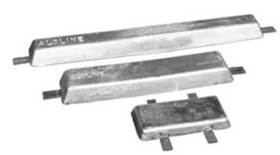
Common Types of Galvanic Anodes

Anode Ingot [Mg, Zn]

Anode Ribbon [Mg, Zn]



Weld/Bolt-On Hull [Al, Zn]

Prepackaged Anode [Mg, Zn]

Heater-Treater [Al, Mg, Zn]

Clip-On [Zn]

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Galvanic CP Design Process

Current Requirement
- Historical Data
- Estimated Demand
- Current Testing

Anode Selection
- Electrolyte Data
- Anode Type
- Installation Process

Design
- Anode Size
- Anode Quantity
- Anode Spacing
- Cable Lengths

Build
- Testing
- Maintenance
- Improvement

Let's do an example for a potable water tank!

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Estimating Current Requirement

Current Requirement Testing
- Use a temporary point anode to determine how much current is required to polarize the structure within a given time
- Requires a power supply and dataloggers

Similar Structure Comparison
- Assess the current needed for an existing similar structure and scale it for the new structure surface area

Dead-reckoning
- Use previous designs or suggested values to determine expected current demand
- Usual values for fresh water and soil: 1 mA/ft^2 to 0.1 mA/ft^2 of bare surface area

Current Requirement Testing Workflow

$V_{native} := -693\ mV$ $\quad V_{target} := -900\ mV$

$I_{test} := 61\ mA$ $\quad V_{test} := -945\ mV$

$$R_{Pol} := \frac{V_{native} - V_{test}}{I_{test}} = 4.131\ \Omega$$

$$I_{ReqCP} := \frac{V_{native} - V_{target}}{R_{Pol}} = 50\ mA$$

Dead-Reckoning Workflow

$D_{Tank} := 43\ ft$ $\quad i_{CD} := 1\ \frac{mA}{ft^2}$

$H_{Tank} := 30\ ft$ $\quad Q_{Coat} := 99\%$

$$SA_{wet} := \pi \cdot \left(\frac{D_{Tank}}{2}\right)^2 + \pi \cdot D_{Tank} \cdot H_{Tank} = 5505\ ft^2$$

$$SA_{bare} := SA_{wet} \cdot (1 - Q_{Coat}) = 55.049\ ft^2$$

$$I_{CP} := i_{CD} \cdot SA_{bare} = 55\ mA$$

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Anode Selection

Looking back at our previous chart:
- High Potential Magnesium is most appropriate
- Extruded 2” diameter rods available

Vertical anode hanging from roof for ease of maintenance/replacement

How much mass?
- Magnesium efficiency at best is 50%
  - For anode surface current density ≥ 30 mA/ft^2
  - For normal temperature ranges (60°F - 80 °F)
- Theoretical efficiency: 8.7 lb/A-yr
- Let’s make it a 20-year design

Unit Mass for Rod Anodes

$d_{mag} := 106 \, \frac{lb}{ft^3}$ $\quad OD_{rod} := 2.024 \, in$

$$m_{mag} := d_{mag} \cdot \pi \cdot \left(\frac{OD_{rod}}{2}\right)^2 = 2.4 \, \frac{lb}{ft}$$

Total Mass Required

$t_{life} := 20 \, yr$

$Q_{mag} := 8.7 \, \frac{lb}{A \cdot yr}$ $\quad eff_{mag} := 50\%$

$$m_{anodeReq} := \frac{Q_{mag}}{eff_{mag}} \cdot t_{life} \cdot I_{CP} = 19.157 \, lb$$

$$l_{magReq} := \frac{m_{anodeReq}}{m_{mag}} = 8.089 \, ft$$

Anode Current Output

We need at least 8.1 ft of 2” HiPot Mag Rod

For redundancy, let’s round that up to 10 ft

Also, let’s split it into 2x 5 ft lengths

Electrolyte Resistivity: 5,400 Ω-cm (tested)

Let’s ignore crowding factors (for now)

Vertical Anode Resistance

$l_{anode} := 5 \, ft$ $\quad d_{anode} := 2 \, in$

$\rho := 5400 \, \Omega \cdot cm$

$$R_{anode} := \frac{\rho}{2 \, \pi \cdot l_{anode}} \cdot \ln\left(\frac{2 \cdot l_{anode}}{d_{anode}}\right) = 23.089 \, \Omega$$

$V_{magHP} := -1800 \, mV$ $\quad V_{magPol} := 100 \, mV$

$$I_{single} := \frac{V_{target} - V_{magHP} - V_{magPol}}{R_{anode}} = 35 \, mA$$

$$I_{2Anodes} := \frac{V_{target} - V_{magHP} - V_{magPol}}{\frac{R_{anode}}{2}} = 69 \, mA$$

Anode Current Output Checks

We've got to make sure that what we've designed will last our time as these anodes will put out more current than we need

We also want to see what our anode current density is – are we close to 30 mA/ft^2?

No! We can expect decreased efficiency from our anodes.

Easiest course of action: Double up on anodes to account for less efficiency.

Harder course: Rework the problem. A lot.

New Mass & Output Check

$$m_{2anodes} := 10\ ft \cdot m_{mag} = 24\ lb$$

$$t_{2anodes} := \frac{m_{2anodes} \cdot eff_{mag}}{Q_{mag} \cdot I_{2Anodes}} = 20\ yr$$

Current Density Check

$$CD_{anodes} := \frac{I_{single}}{\pi \cdot d_{anode} \cdot l_{anode}} = 13\ \frac{mA}{ft^2}$$

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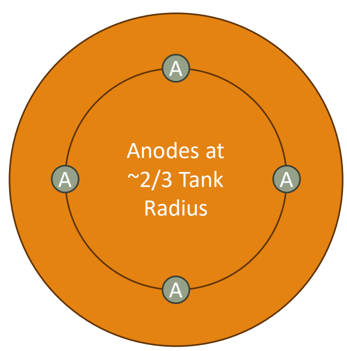
Cable Voltage Drop & Anode Placement

In higher output systems, cable voltage drop is significant. Here, with an anode resistance of 23 Ω, we can ignore it. We'll come back to the topic later.

Regarding anode placement, for well coated tanks, common sense is more pragmatic than calculating the surface area centroids, but feel free to do it.

Keep your anodes away from ladders and drains if possible, and make sure they're still wetted between the high and low levels.



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Special Considerations for GACP Systems

Crowding Factor
- The distance between multiple anodes can significantly change the output characteristics.

Cable Voltage Drop
- With limited driving voltage, even small resistive voltage drop on cables can have impacts.

Anode Depth
- Anode depth and local water or soil conditions can have big effects for better or worse.

Anode-to-Structure Coupling
- Close-coupled current distribution issues
- Internal vessel anode applications

Survey Considerations
- Interrupting distributed GACP systems

Special Applications
- Offshore

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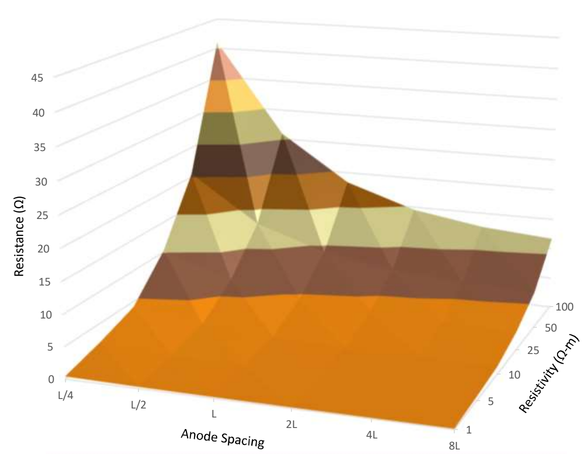
Crowding Factor

Anodes are susceptible to crowding factor when placed too close to one another:
- Essentially, current from each anode is competing for the same current path to the structure,
- Biggest concern in for closely-spaced side-by-side anodes in vertical or horizontal configurations

$$R_V = \frac{\rho}{2\pi N L}\left\{\left(ln\frac{8L}{d}\right) - 1 + \frac{2L}{s} ln(0.656N)\right\}$$

R_V [Ω]: Resistance of multiple vertical anodes to remote earth
ρ [Ω-m]: Soil resistivity
L [m]: Length of single anode
d [m]: Diameter of single anode
s [m]: Anode spacing
N: Number of anodes



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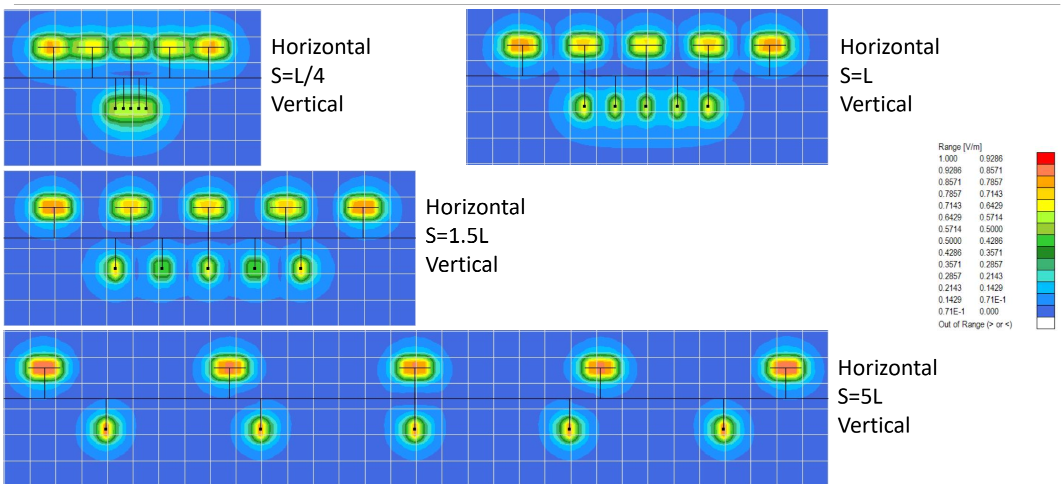
Crowding Factors Illustrated



Crowding Factor – Scale Modeling

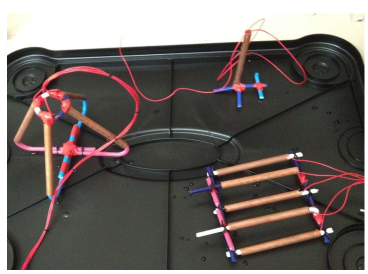
Scale modeling is a recognized and valid form of modeling the behavior of complex CP systems.

Model accuracy will depend on simplifications:
- Material selection,
- Geometric,
- Electrolytic,
- Electronic, Etc.

Easier to do now with 3D printers and electroplating:
- Ship hulls, complex skids, Etc.,
- Anode diameter less important than arrangement and length.

For more details, see:

- Lucas, K E, Thomas, E D, Kaznoff, A I, and Hogan, E A. 1999. "Design of impressed current cathodic protection (ICCP) systems for U.S. Navy hulls". United States.
- V.G. DeGiorgi, E.D. Thomas III, K.E. Lucas. 1998. "Scale effects and verification of modeling of ship cathodic protection systems". United States.



Individual Anode Skid Design Models

Skid Crowding Model

Cable Voltage Drop

All conductors have resistance:
- Copper has a very low resistivity but can still become significant,
- Resistance will change with temperature,
- Solid wire has slightly more cross-sectional area, thus a lower resistance.

Check your expected load and your design calculations:
- Often, an iterative process is easiest.
- Select your cable size and length, then discount the cable voltage drop.

Topology matters:
- "Star" layout is easiest,
- Daisy-chained or spliced becomes harder.

Cable Size		DC Ω/1000ft	
AWG#	**Ø (in)**	**Solid**	**Stranded**
14	**0.06**	2.67	2.79
12	**0.08**	1.68	1.72
10	**0.10**	1.02	1.08
8	**0.13**	0.66	0.68
6	**0.16**	0.41	0.43
4	**0.20**	0.26	0.27
2	**0.26**	0.16	0.17
0	**0.32**	0.10	0.11
2/0	**0.36**	0.08	0.08
3/0	**0.41**	0.06	0.07
4/0	**0.46**	0.05	0.05

Example: 5A on 80ft of #6 STR

$$I:=5\ A$$

$$R_C:=0.43\ \frac{\Omega}{1000\ ft}$$

$$L_C:=80\ ft$$

$$\Delta V_{Cable}:=I \cdot R_C \cdot L_C = 172\ mV$$

Example: 500mA on 20ft of #14 SOL

$$I:=500\ mA$$

$$R_C:=2.67\ \frac{\Omega}{1000\ ft}$$

$$L_C:=20\ ft$$

$$\Delta V_{Cable}:=I \cdot R_C \cdot L_C = 26.7\ mV$$

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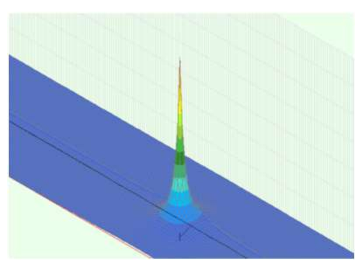
Anode Depth

Anode depth plays a significant role in current output and distribution for pipelines:
- Utah/Wyoming: Watch for very dry surface layers
  - Be wary of high salt concentrations in former lake beds
- Consider 'deep' galvanic anode beds
  - Depending on soil strata, 25'-50' is effective in many areas,
  - Provide means to regulate current output to prevent overprotection,
  - Install using hollow-stem auger or air drill.
- Anode watering systems can also be effective but require regular inspection.
- Example with 2-Layer soil:
  - Top Layer: 6,000 Ω-cm, Surface to -10 ft
  - Bottom Layer: 1,500 Ω-cm, Infinite Depth
  - Pipe: 8" Poorly Coated x 5,000'
  - Anode: 6' x 4" Magnesium, 10' horizontal offset from pipe



Depth:	Pipe	Pipe+5'	Pipe+25'	Pipe+50'
Estimated Shift mV:	-47	-96	-143	-144
Output mA	71	144	213	214

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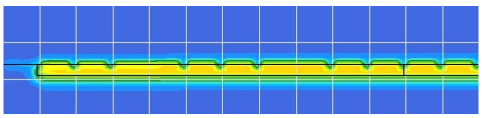
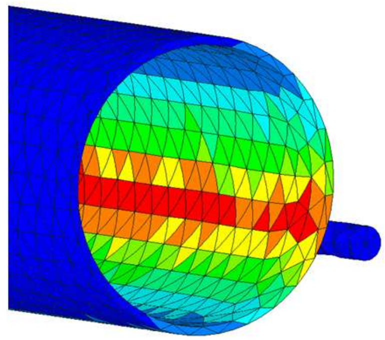
Anode-to-Structure Coupling (External)

Closely coupled anodes can work well in congested areas (i.e. facilities):
- Allow protection of shorted structures
- WARNING: Spacing is critical!
  - Too close: Protect only part of the structure, damage coatings, may cause other issues
  - Too far: Current runs to other structures, not enough protection
  - Spacing will depend on soil type, coating, and many other factors. We could do a whole class just on that.
- Good use for magnesium or zinc ribbon

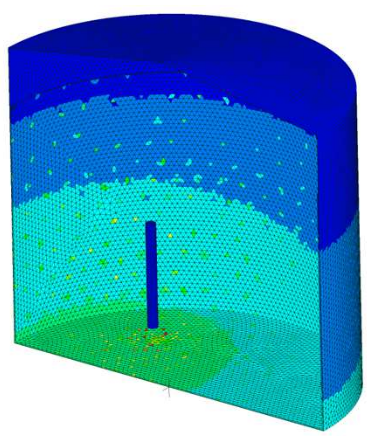


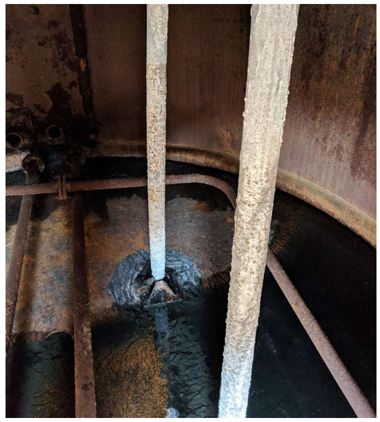


Anode-to-Structure Coupling (Internal)

Many internal anode applications are closely-coupled.
- As a rule-of-thumb, if the tank diameter is less than 3x the anode length, you're likely coupled.
- Be wary of continuous bare structures (like ladders) in coated tanks, they tend to draw most of your current.
- You cannot use normal anode resistance equations in these constrained cases!
- Heater tubes can exhibit interesting behavior from both galvanic and thermal standpoints!

If your tank is well coated and large diameter, you can probably get away with hand calculations like we did in the example.





Tank Internal Anodes

CONSIDER WHAT IS MOST PRACTICAL FOR YOUR APPLICATION!

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Special Survey Considerations

Yes, you really need to interrupt all current sources!
- Yes, including magnesium anodes.
- Multiple interrupters recommended.
- Consider coupons!

Permanently attached anodes will cause nightmares later.
- Precludes effective CIS or periodic surveys,
- Creates significant blind spots for DCVG or ACVG external coating assessments,
- You may pay $$$ to have them found and removed.

For tank internal systems, assess your resistivity for magnitude of IR drop.
- If you can get your electrode close to surfaces, you have actually considered and eliminated most of your IR.
- Thinking about it in the shower doesn't count.

Label your test stations if possible and use chainage instead of incremental test point numbers.
- Hard once, simple for every analysis after.
- Make your GIS folks do it.

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Offshore Systems

Offshore or other 'wet' systems have entirely different CP demands:

- Aggressive environment attacks coatings, cables, and everything much faster than onshore,
- Different oxygen and temperature levels create challenges,
- Fish bite is also a concern,
- Calcareous deposits accelerate marine growth on structures.

Gain practical experience before attempting to design or service offshore CP systems, please!

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Offshore System Design

Offshore systems are usually designed to DNV Standards or similar specs:

- DNV-RP-B401 Cathodic Protection Design
- DNV-RP-F103 Cathodic Protection of Submarine Pipelines

Both use some slightly different concepts than we normally see:

- Coating degradation is much faster at sea
- Lifespan Current Output Design Process:
  - Polarization Current: New coating & anodes
  - Maintenance Current: Weathered coating & anodes
  - End-of-Life Current: Very weathered coating & anodes
- Historical data critical if available

Do not be surprised to see 100's of amp current demands.

This can be successfully achieved with galvanic anodes!

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Closing Notes

Galvanic anodes can be great in many situations!
- Proper anode selection, installation location, and monitoring are vital to success
- Material and installation control is vital (Garbage In, Garbage Out)

Regular monitoring is essential for reliable performance

Be wary of proprietary tools, software, and data management
- Vendor goes out of business? Relationship sours? Gets hacked?
- If you need a rental tool or time-limited license, you don't own it!

Be the change you want to see in the industry
- Provide open feedback to peers about successes and failures

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References & Suggested Reading

- Peabody's Control of Pipeline Corrosion
- AMPP Course Manuals: CP-1, CP-2, CP-3, CP-Interference, CP-4
- AMPP/NACE SP0169 "Standard Practice: Control of External Corrosion on Underground or Submerged Metallic Piping Systems"
- DNV RP-F103 "Cathodic Protection of Submarine Pipelines"
- DNV RP-B401 "Cathodic Protection Design"
- US Department of Defense MIL-STD-889D "Standard Practice: Galvanic Compatibility of Electrically Conductive Materials"

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Questions & Discussion

Thank you for attending!

Please feel free to reach out:

Tom Taylor, PE, CS, CPS
Tom@tomtaylor.cc
+1 (720) 589-0816

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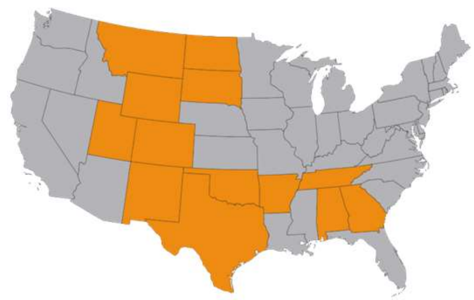

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