Corrosion and Corrosion Control for Solar Arrays

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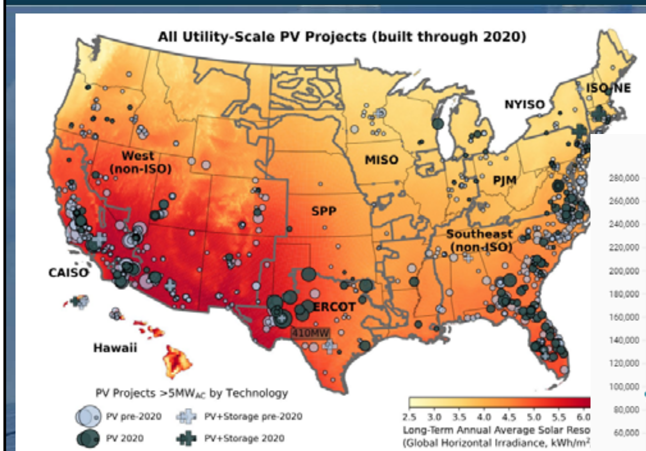
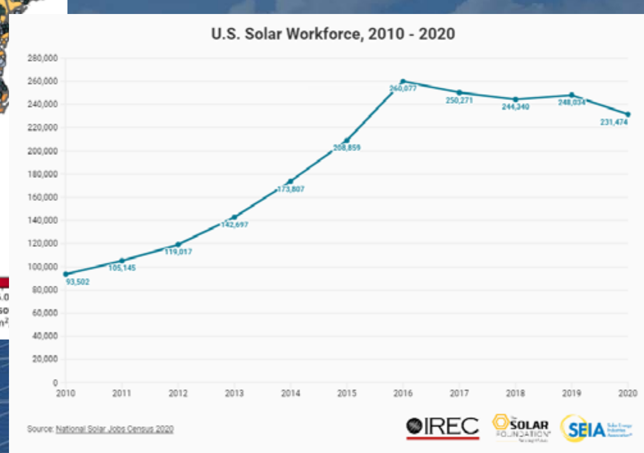
Solar Industry





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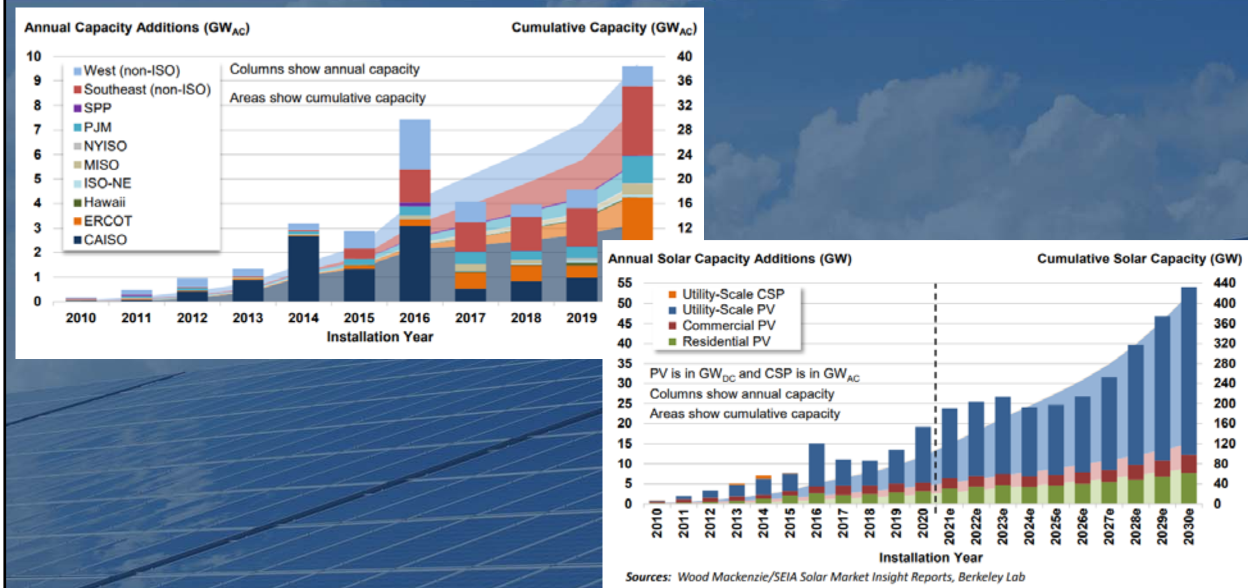
Solar Capacity



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Anatomy of a Pile Supported Solar Array

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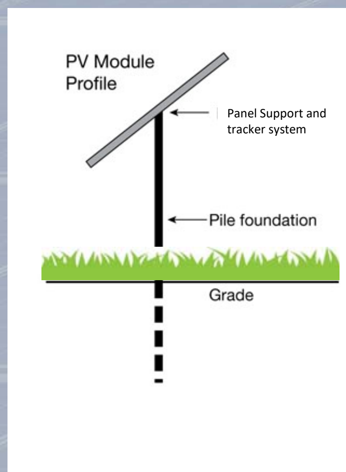
Solar Array Zones



Above Grade – Atmospheric Zone

Below Grade – Soil Zone

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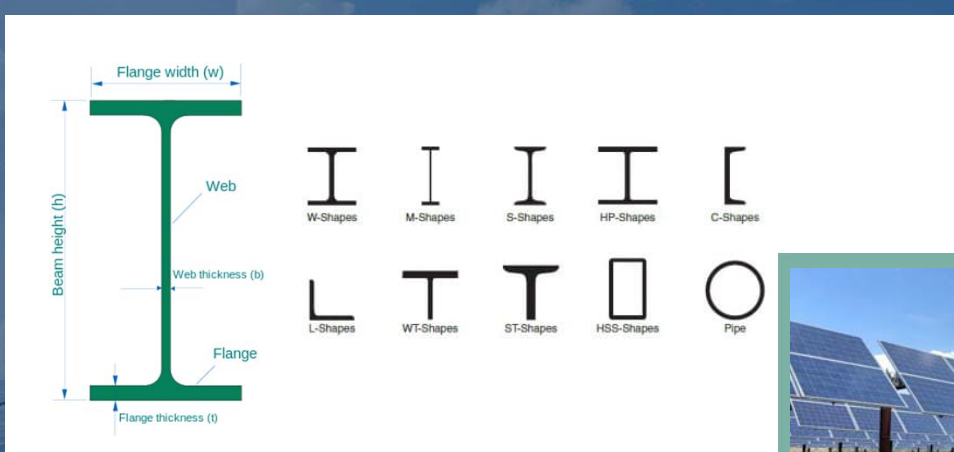
Pile Shapes



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Types of Solar Farm Corrosion

- Above Grade
  - Atmospheric Corrosion
  - Galvanic Couplings
- Below Grade
  - Soil Corrosivity
  - Galvanic Couplings

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Atmospheric Corrosion

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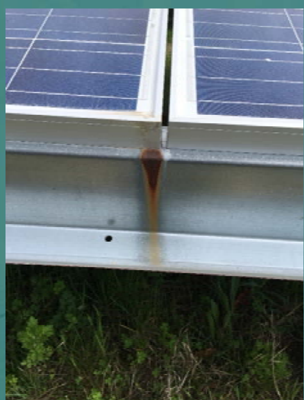
Atmospheric Corrosion



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Atmospheric Corrosion

Grease for Bearings and Dampeners

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Atmospheric Corrosion

Time of Wetness and Pollutants

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ISO 9223 – Atmospheric Corrosivity Categories

Corrosivity category	Corrosivity	Typical environments – Examples from ISO 9223	
		Indoor	**Outdoor**
C1	Very low	Heated spaces with low relative humidity and insignificant pollution, e.g. offices, schools, museums	Dry or cold zone, atmospheric environment with very low pollution and time of wetness, e.g. certain deserts, Central Arctic/Antarctica
C2	Low	Unheated spaces with varying temperature and relative humidity. Low frequency of condensation and low pollution, e.g. storage, sport halls	Temperate zone, atmospheric environment with low pollution (SO_2 < 5 µg/m^3), e.g. rural areas, small towns Dry or cold zone, atmospheric environment with short time of wetness, e.g. deserts, subarctic areas
C3	Medium	Spaces with moderate frequency of condensation and moderate pollution from production process, e.g. food-processing plants, laundries, breweries, dairies	Temperate zone, atmospheric environment with medium pollution (SO_2: 5 µg/m^3 to 30 µg/m^3) or some effect of chlorides, e.g. urban areas, coastal areas with low deposition of chlorides Subtropical and tropical zone, atmosphere with low pollution
C4	High	Spaces with high frequency of condensation and high pollution from production process, e.g. industrial processing plants, swimming pools	Temperate zone, atmospheric environment with high pollution (SO_2: 30 µg/m^3 to 90 µg/m^3) or substantial effect of chlorides, e.g. polluted urban areas, industrial areas, coastal areas without spray of salt water or, exposure to strong effect of de-icing salts Subtropical and tropical zone, atmosphere with medium pollution
C5	Very high	Spaces with very high frequency of condensation and/or with high pollution from production process, e.g. mines, caverns for industrial purposes, unventilated sheds in subtropical and tropical zones	Temperate and subtropical zone, atmospheric environment with very high pollution (SO_2: 90 µg/m^3 to 250 µg/m^3) and/or significant effect of chlorides, e.g. industrial areas, coastal areas, sheltered positions on coastline
CX	Extreme	Spaces with almost permanent condensation or extensive periods of exposure to extreme humidity effects and/or with high pollution from production process, e.g. unventilated sheds in humid tropical zones with penetration of outdoor pollution including airborne chlorides and corrosion-stimulating particulate matter	Subtropical and tropical zone (very high time of wetness), atmospheric environment with very high SO_2 pollution (higher than 250 µg/m^3) including accompanying and production factors and/or strong effect of chlorides, e.g. extreme industrial areas, coastal and offshore areas, occasional contact with salt spray

Corrosivity category	Comparative corrosion rates for steel and zinc from ISO 9223 r_{corr}		
	Unit	**Carbon steel**	**Zinc**
C1	g/(m^2·a)	$r_{corr} \leq 10$	$r_{corr} \leq 0.7$
	µm/a	$r_{corr} \leq 1.3$	$r_{corr} \leq 0.1$
C2	g/(m^2·a)	$10 < r_{corr} \leq 200$	$0.7 < r_{corr} \leq 5$
	µm/a	$1.3 < r_{corr} \leq 25$	$0.1 < r_{corr} \leq 0.7$
C3	g/(m^2·a)	$200 < r_{corr} \leq 400$	$5 < r_{corr} \leq 15$
	µm/a	$25 < r_{corr} \leq 50$	$0.7 < r_{corr} \leq 2.1$
C4	g/(m^2·a)	$400 < r_{corr} \leq 650$	$15 < r_{corr} \leq 30$
	µm/a	$50 < r_{corr} \leq 80$	$2.1 < r_{corr} \leq 4.2$
C5	g/(m^2·a)	$650 < r_{corr} \leq 1,500$	$30 < r_{corr} \leq 60$
	µm/a	$80 < r_{corr} \leq 200$	$4.2 < r_{corr} \leq 8.4$
CX	g/(m^2·a)	$1,500 < r_{corr} \leq 5,500$	$60 < r_{corr} \leq 180$
	µm/a	$200 < r_{corr} \leq 700$	$8.4 < r_{corr} \leq 25$

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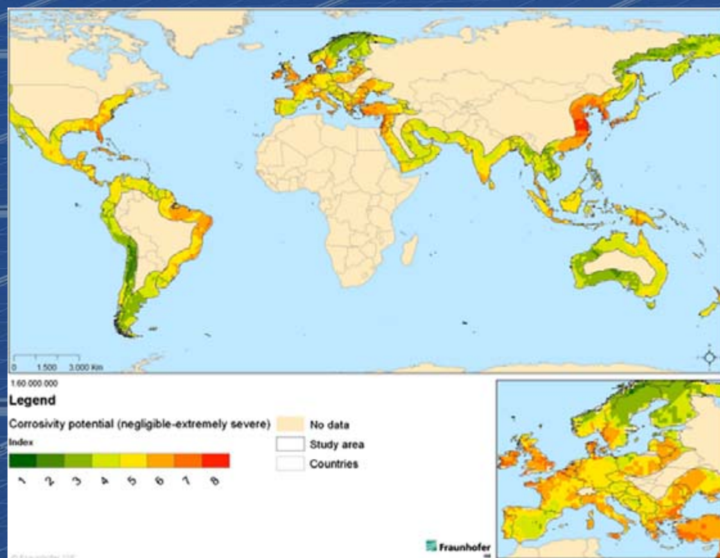
Atmospheric Corrosion Potential Global Map



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Dose Functions

- *For Carbon Steel:*
- $r_{corr}=1{,}77\cdot P_d^{0{,}52}\cdot \exp(0{,}020\cdot RH+f_{St})+0{,}102\cdot S_d^{0{,}62}\cdot \exp(0{,}033\cdot RH+0{,}040\cdot T)$

Table 3 — Parameters used in the derivation of dose-response functions, including symbol, description, interval and unit

Symbol	Description	Interval	Unit
T	Temperature	−17,1 to 28,7	°C
RH	Relative humidity	34 to 93	%
P_d	SO_2 deposition	0,7 to 150,4	mg/(m²·d)
S_d	Cl^- deposition	0,4 to 760,5	mg/(m²·d)

The sulfur dioxide (SO_2) values determined by the deposition method, P_d, and volumetric method, P_c, are equivalent for the purposes of this International Standard. The relationship between measurements using both methods may be approximately expressed as $P_d = 0{,}8\,P_c$ [P_d in mg/(m²·d), P_c in µg/m³].

NOTE All parameters are expressed as annual averages.

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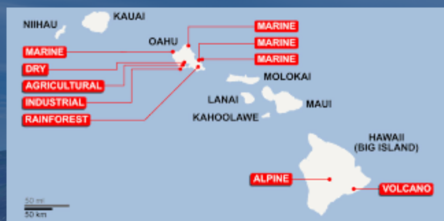
Atmospheric Corrosion Monitoring Stations



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Field Atmospheric Corrosion Testing - Coupons

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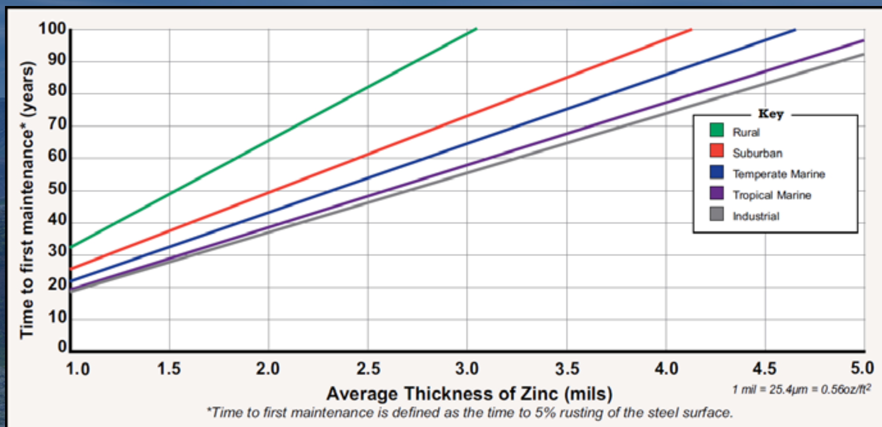
Atmospheric Corrosion Rates



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Once you know your corrosion rate

- Select Materials which are less susceptible to atmospheric corrosion
- Galvanization

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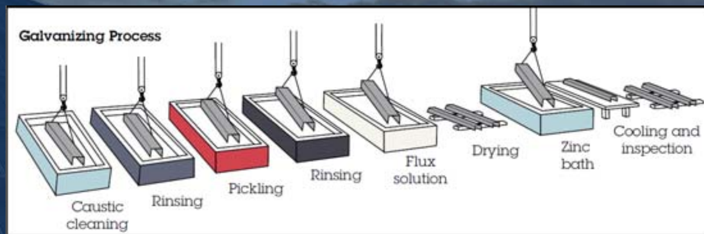
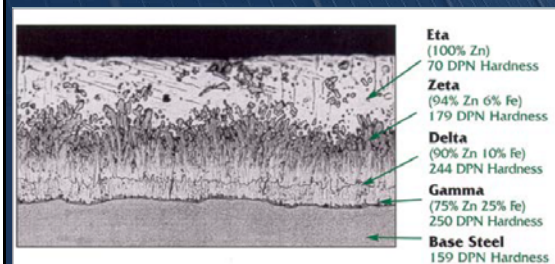
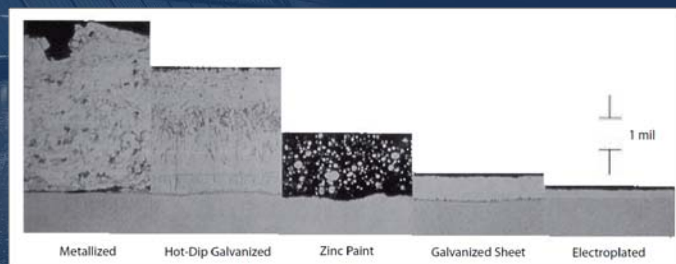
Galvanization







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Types of Galvanizing

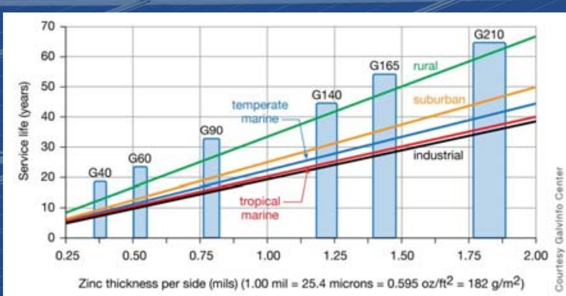

Figure 1 The service life for hot-dip galvanized finishes depends on the environmental conditions of its installation.

Continuous Sheet Galvanizing				
Coating Grade	Total Both Sides	Per Side		
	oz/ft²	oz/ft²	mils	µm
G360	3.60	1.80	3.24	82.3
G300	3.00	1.50	2.70	68.6
G235	2.35	1.18	2.12	53.7
G210	2.10	1.05	1.89	48.0
G185	1.85	0.93	1.67	42.3
G165	1.65	0.83	1.49	37.7
G140	1.40	0.70	1.26	32.0
G115	1.15	0.58	1.04	26.3
G90	0.90	0.45	0.81	20.6
G60	0.60	0.30	0.54	13.7
G40	0.40	0.20	0.36	9.1
G30	0.30	0.15	0.27	6.9
G01	no minimum			

Continuous Sheet Galvanizing: The number following the 'G' coating grade designation correlates to the total thickness of zinc applied to both sides of the steel sheet.

Courtesy of American Galvanizers Association

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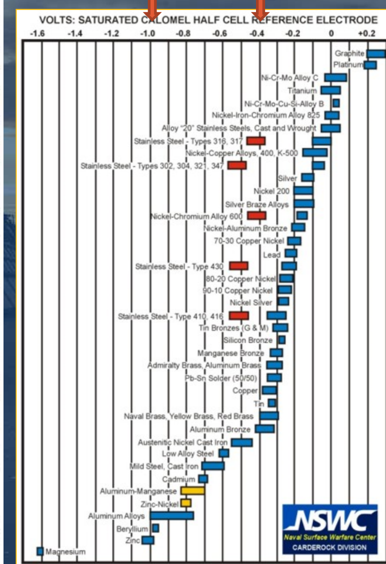
Galvanic Corrosion

Galvanic corrosion between the stainless steel bolts and the aluminum panel

Galvanic Series

Metal	
Magnesium	Active (Anode)
Zinc	
Galvanized Steel	
Aluminum	
Mild Steel	
Cast Iron	
Lead	
Brass	
Copper	
Bronze	
Monel	
Nickel (passive)	
Stainless Steel 304 (passive)	
Stainless Steel 316 (passive)	
Silver	
Titanium	
Gold	
Graphite	
Platinum	Noble (Cathode)

Table 1 The similarity of metals is indicated by their relative position in the galvanic series. The more dissimilar the metals, the greater the corrosion potential in a galvanic circuit.



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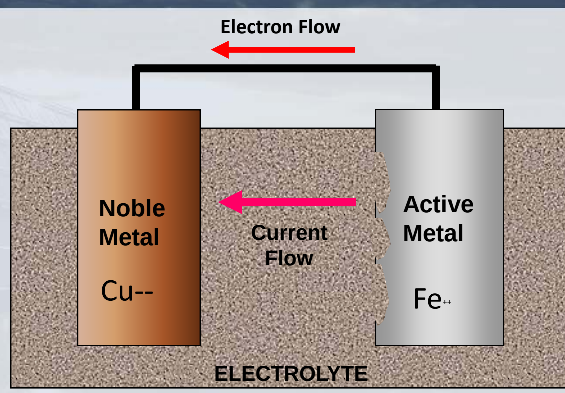
Bi-metallic or Galvanic Corrosion Cells

Dissimilar metals or galvanic corrosion is a very common form of corrosion created when two dissimilar metals are electrically coupled in a common electrolyte.



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Galvanic Corrosion Above Grade

Galvanic Corrosion between fayed surfaces. In this case between the aluminum panel and a stainless steel bolt


UL 2703

STANDARD FOR SAFETY

Mounting Systems, Mounting Devices, Clamping/ Retention Devices, and Ground Lugs for Use with Flat-Plate Photovoltaic Modules and Panels

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Atmospheric Corrosion Remedies

- Eliminate bi-metallic coupling when possible
  - UL 2703 Standard Mounting Systems for Photovoltaic Modules and Panels
- Increase Galvanization if needed

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Soil Corrosion

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Soil Corrosion Evaluation Benefits

Addresses Corrosion Concerns Early:

- Client/developer is better informed and has time to evaluate design options for steel supports.

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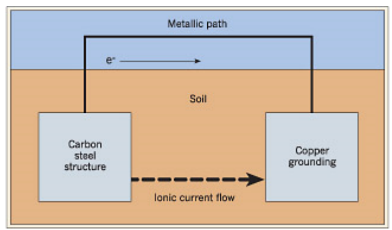
Galvanic Corrosion on Steel Piles

Galvanic corrosion occurs between the steel support piles and the copper grounding system



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Examples of Soil Corrosion on Steel Piles

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Preliminary Site Corrosivity Evaluations

Two principal facets to a site corrosivity survey

1. In-situ Phase - soil resistivity survey
2. Laboratory Phase - soil sampling & chemical analysis

In-situ soil resistivity surveys should be conducted to a depth of 15 ft. and at various locations throughout the project site. In-situ resistivities should be measured at depths of 2.5', 5', 7.5', 10' and 15'. Barnes layer calculations should be used to layer the resistivity data.

Soil samples should be collected from various locations and at various depths throughout the project site. Soil samples should be sent to a qualified laboratory for chemical analysis.

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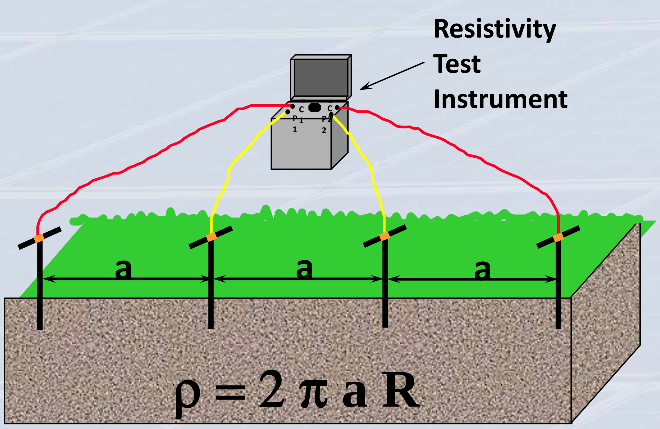
In –situ Phase



Wenner 4-pin Resistivity Measurements

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Laboratory Phase

Chemical Analysis
- Resistivity
- pH
- Chlorides
- Sulfates
- Moisture Content
- Redox

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Corrosivity Classifications

Resistivity (Ohm-cm)	Corrosivity Classification
0 – 500	Severely Corrosive
501 – 2,000	Corrosive
2,001 – 8,000	Moderately Corrosive
8,001 – 32,000	Mildly Corrosive
> 32,000	Progressively Less Corrosive

Courtesy of William J. Ellis

pH	Corrosivity Classification
< 5.5	Corrosive
5.5 – 6.0	Moderately Corrosive
6.0 – 6.5	Mildly Corrosive
6.5 – 9.0	Non-Corrosive

Reference: M. Romanoff, Underground Corrosion, 1957

Chloride (ppm)	Corrosivity Classification
>1,500	Severely Corrosive
300 – 1,500	Corrosive
150 – 300	Moderately Corrosive
100 – 150	Mildly Corrosive
0 – 100	Non-Corrosive

Reference: ACI-318, Building Code Requirements for Reinforced Concrete (American Concrete Institute, 1999)

Sulfate (ppm)	Corrosivity Classification
>15,000	Severely Corrosive
2,000 – 15,000	Corrosive
1,000 – 2,000	Moderately Corrosive
200 – 1,000	Mildly Corrosive
0 – 200	Non-Corrosive

Reference: ACI-318, Building Code Requirements for Reinforced Concrete (American Concrete Institute, 1999)

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Understanding what constitutes pile failure is critical

- *Pitting corrosion is very common for buried steel.*
- *Extremely localized pitting corrosion can cause pipelines and tanks to be compromised, especially if they are under pressure.*
- *Structural load-bearing piles are not significantly affected by pitting corrosion.*
- *Overall loss in weight is the key corrosion concern for piles.*

***Article by Scott Canada in Solar Pro Magazine entitled "Corrosion Impacts on Steel Piles, Issue 5.1, Dec/Jan, 2012**

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Methods of Corrosion Control for Pile Supports

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Corrosion Protection Methods for Buried Steel Piles

1. Corrosion Allowance
2. Galvanizing
3. Dielectric Coatings
4. Concrete Encasement
5. Cathodic Protection

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1 Corrosion Allowance

Added steel thickness to account for corrosion

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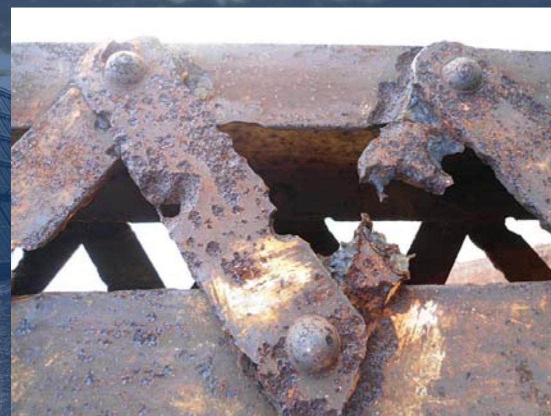
How much steel do you add?

- Federal Highway Administration
- Cal Trans
- American Iron and Steel Institute
- American Galvanizers Association
- British Corrosion Journal
- Romanoff Studies
- Faraday's Law
- Eurocode
- E-Log-I
- LPR Testing
- Australian Corrosion Association
- AASHTO
- AMPP Standard in progress



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Is the site considered corrosive?

Property	Standard	Test Procedures
Resistivity	Ω-cm >3000	AASHTO T-288
pH	>5 <10	AASHTO T-289
Organic Content	1% Max.	AASHTO T-267
Chlorides	< 100 PPM	ASTM D4327
Sulfates	< 200 PPM	ASTM D4327

Zinc corrosion rate first 2 years	0.58 mils/yr (15 μm/yr)
Zinc corrosion to depletion	0.16 mils/yr (4 μm/yr)
Carbon steel rate	0.47 mils/yr (12 μm/yr)

U.S. Department of Transportation
Federal Highway Administration

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Cal Trans

For structural elements, the Department considers a site to be corrosive if one or more of the following conditions exist for the representative soil and/or water samples taken at the site:

Chloride	***≥500 ppm***
Sulfate	***≥1500 ppm***
pH	***≤5.5***

The Department currently uses the following corrosion rates for steel piling exposed to corrosive soil and/or water or marine environments

- ***Soil Embedded Zone*** — ***1 mil per year***
- ***Fill or Disturbed Natural Soils*** — ***1.5 mpy***
- ***Atmospheric Zone (marine)*** — ***2 mpy***
- ***Immersed Zone (marine)*** — ***4 mpy***
- ***Splash Zone (marine)*** — ***6 mpy***

Caltrans

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Romanoff

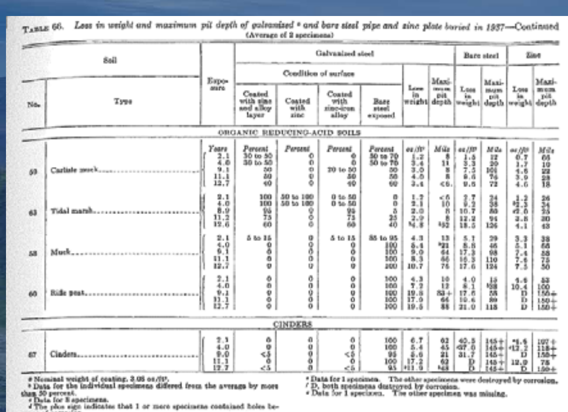
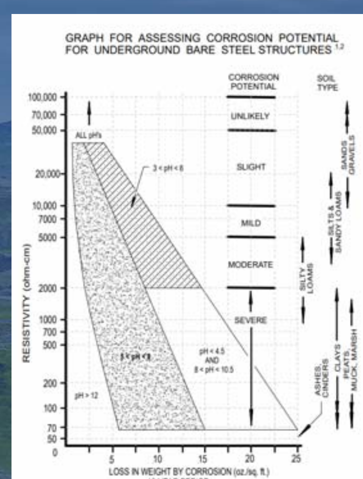


TABLE 66. *Loss in weight and maximum pit depth of galvanized ᵃ and bare steel pipe and zinc plate buried in 1937—Continued*
(Average of 2 specimens)

No.	Soil Type	Exposure	Galvanized steel: Coated with zinc and alloy layer	Coated with zinc	Coated with zinc-iron alloy	Bare steel exposed	Galvanized steel: Loss in weight	Galvanized steel: Maximum pit depth	Bare steel: Loss in weight	Bare steel: Maximum pit depth	Zinc: Loss in weight	Zinc: Maximum pit depth
	ORGANIC REDUCING-ACID SOILS											
		Years	Percent	Percent	Percent	Percent	oz/ft²	Mils	oz/ft²	Mils	oz/ft²	Mils
59	Carlisle muck	2.1	30 to 50	0	0	50 to 70	1.2	8	1.5	12	0.7	66
		4.0	30 to 50	0	0	50 to 70	3.4	11	3.3	20	1.7	10
		9.1	50	0	20 to 50	50	3.0	8	7.5	101	4.6	22
		11.1	50	0	50	50	4.5	8	9.6	76	3.9	28
		12.7	40	0	40	60	3.4	<6	9.6	72	4.6	18
63	Tidal marsh	2.1	100	50 to 100	0 to 50	0	1.7	<6	2.7	24	1.2	26
		4.0	100	50 to 100	0 to 50	0	2.1	10	9.2	38	2.3	34
		8.9	95	0	95	5	2.0	8	10.7	80	2.0	35
		11.2	75	0	75	25	2.9	8	12.2	94	2.8	30
		12.6	60	0	60	40	4.8	52	18.5	126	4.1	43
58	Muck	2.1	5 to 15	0	5 to 15	85 to 95	4.3	13	5.1	29	3.3	38
		4.0	0	0	0	100	5.4	21	8.8	46	5.1	68
		9.1	0	0	0	100	9.0	64	17.3	98	7.4	88
		11.1	0	0	0	100	8.3	66	16.3	110	7.6	75
		12.7	0	0	0	100	10.7	76	17.6	124	7.5	50
60	Rifle peat	2.1	0	0	0	100	4.3	10	4.0	15	4.6	53
		4.0	0	0	0	100	7.2	12	8.1	28	10.4	100
		9.1	0	0	0	100	19.8	53+	17.6	58	D	150+
		11.1	0	0	0	100	17.0	66	19.6	89	D	150+
		12.7	0	0	0	100	19.5	88	21.0	118	D	150+
	CINDERS											
67	Cinders	2.1	0	0	0	100	6.7	62	40.5	145+	1.6	107+
		4.0	0	0	0	100	5.4	45	37.0	145+	12.2	118+
		9.0	<5	0	<5	95	6.6	21	31.7	145+	D	150+
		11.1	0	0	0	100	17.2	62	D	145+	12.9	78
		12.7	<5	0	<5	95	11.9	48	D	145+	D	150+

ᵃ Nominal weight of coating, 3.08 oz/ft².
ᵇ Data for the individual specimens differed from the average by more than 50 percent.
ᶜ Data for 3 specimens.
ᵈ The plus sign indicates that 1 or more specimens contained holes because of corrosion.
ᵉ Data for 1 specimen. The other specimens were destroyed by corrosion.
ᶠ D, both specimens destroyed by corrosion.
ᵍ Data for 1 specimen. The other specimen was missing.

National Bureau of Standards



Chance Anchors

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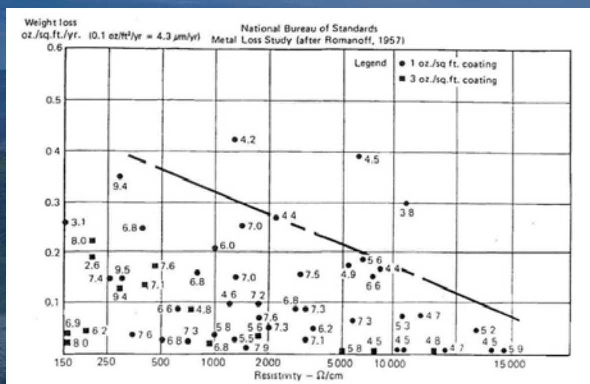
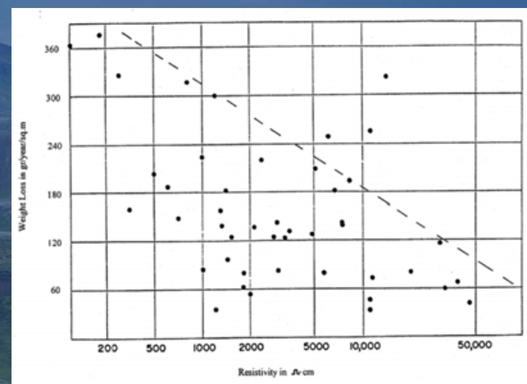
Metal Loss vs. Soil Resistivity



Zinc Loss vs Resistivity



Steel Loss vs Resistivity

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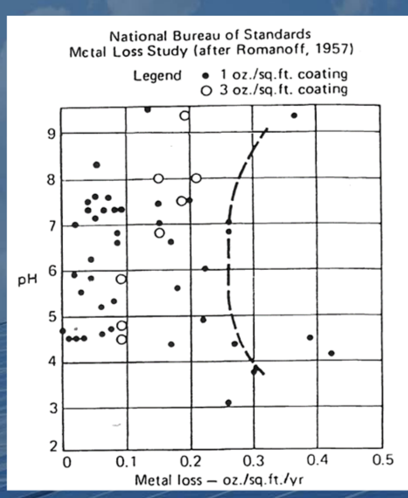
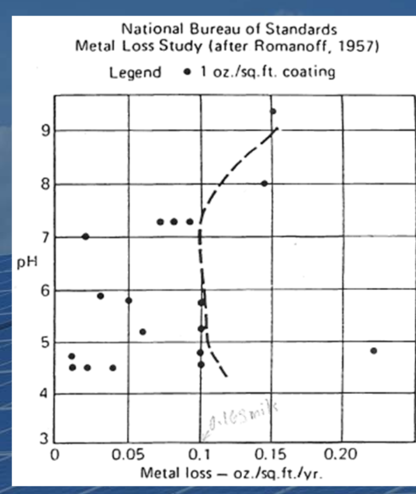
Metal Loss vs. pH





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Eurocode 3: In Soils

Table 4-1: Recommended value for the loss of thickness [mm] due to corrosion for piles and sheet piles in soils, with or without groundwater

Required design working life	5 years	25 years	50 years	75 years	100 years
Undisturbed natural soils (sand, silt, clay, schist, ...)	0,00	0,30	0,60	0,90	1,20
Polluted natural soils and industrial sites	0,15	0,75	1,50	2,25	3,00
Aggressive natural soils (swamp, marsh, peat, ...)	0,20	1,00	1,75	2,50	3,25
Non-compacted and non-aggressive fills (clay, schist, sand, silt, ...)	0,18	0,70	1,20	1,70	2,20
Non-compacted and aggressive fills (ashes, slag, ...)	0,50	2,00	3,25	4,50	5,75

Notes:

1) Corrosion rates in compacted fills are lower than those in non-compacted ones. In compacted fills the figures in the table should be divided by two.

2) The values given for 5 and 25 years are based on measurements, whereas the other values are extrapolated.

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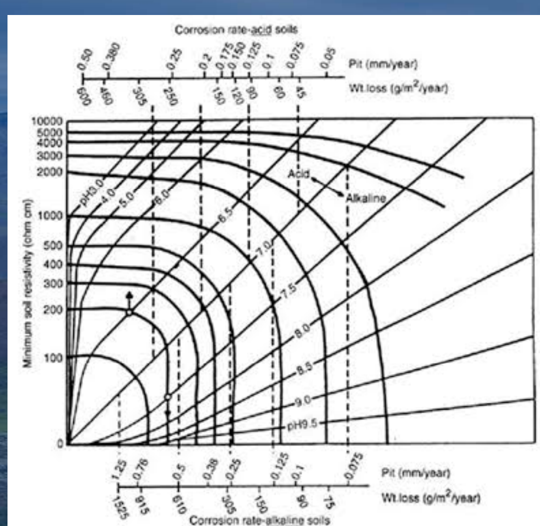
British Corrosion Journal



The Institute of Materials, Minerals and Mining

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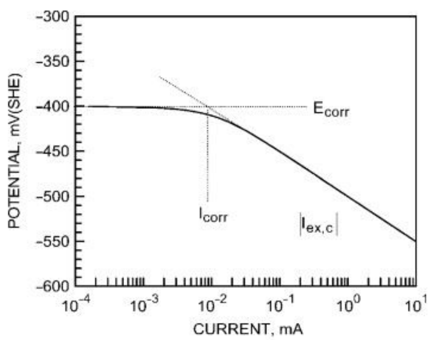
E-Log-I



Tafel extrapolation curve

A procedure for determining the Icorr for a structure is called E-log-I testing or developing a Tafel extrapolation from a V versus log I curve. This technique can be performed in the laboratory or in the field.

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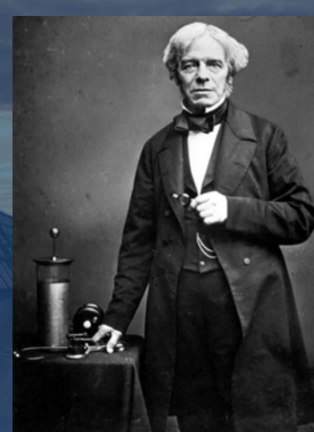
Faraday's Law

$$m = Izt$$

$$\begin{aligned}
where: m &= \text{mass of metal lost to corrosion (grams)} \\
I &= \text{corrosion current (amps)} \\
z &= \text{electrochemical equivalent} = \frac{a}{nF} \text{ (g/A - s)} \\
a &= \text{atomic weight of corroding metal (grams)} \\
n &= \text{electrons transfered in oxidation reaction (mol e}^-\text{)} \\
F &= \text{Faraday's constant (96,500 A - s/mol e}^-\text{)} \\
t &= \text{time of reaction (seconds)}
\end{aligned}$$



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LPR

Linear Polarization Resistance

– used to monitor corrosion rates in real time in aqueous solutions

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ER Probes

Electrical Resistance Probes

– used to monitor corrosion rates in different environments

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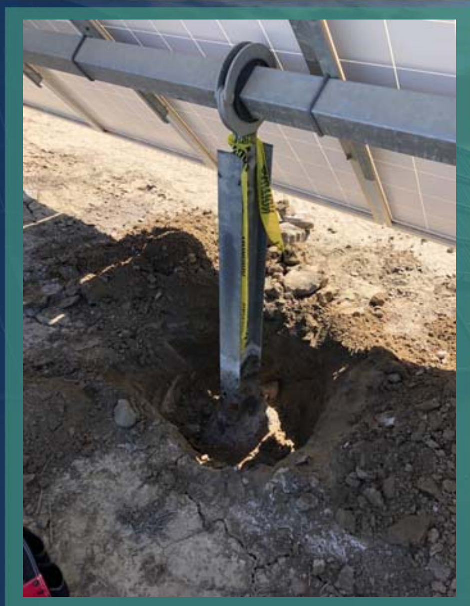
Pile Dig-Ups



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Pull, Clean and Weight Test Piles

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Once the rate of corrosion is known

- Corrosion Allowance can then be determined

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2 Galvanization of Steel Piles

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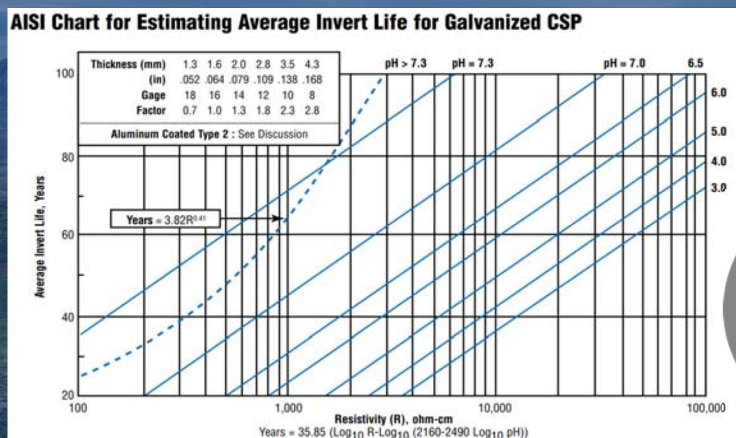
Corrosion of Galvanized Corrugated Steel Pipe in Soil



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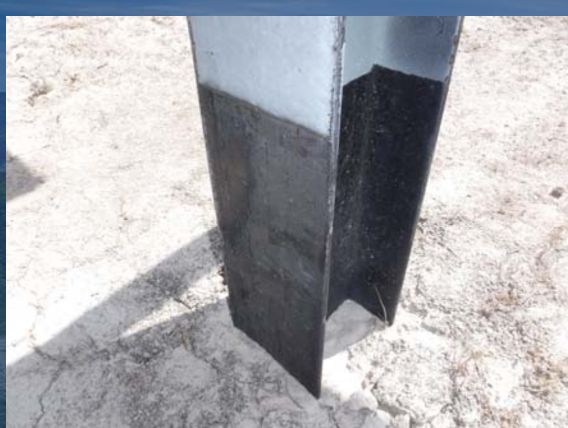
3 Dielectric Coating



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Concrete Encasement Supports

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Cathodic Protection

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Sacrificial Anodes

Magnesium anodes in vertical anode beds

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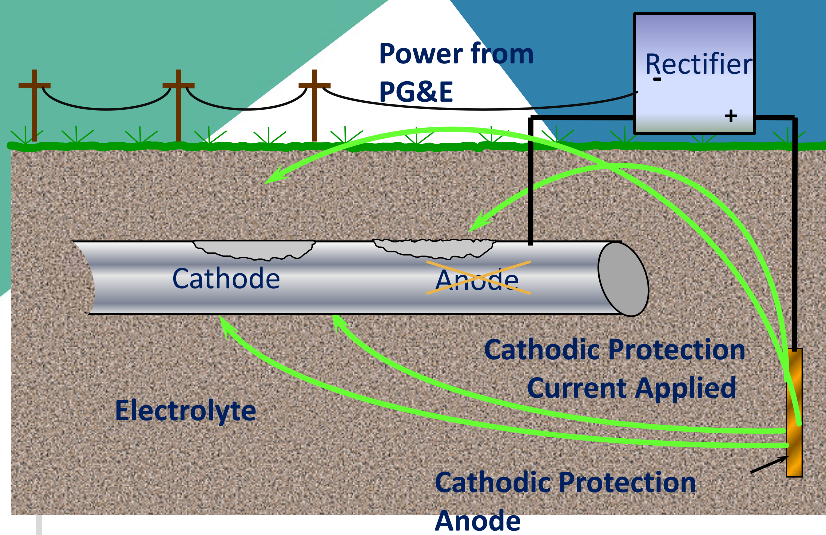
What is Impressed Current Cathodic Protection?



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Solar Panel with Tracker System

No electrical continuity exists between the piles and the tracker bar

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Case Studies

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Case Study #1

- Assume HDG W6x9 piles with 8 feet of embedment, 25-year design life
- Sandy soils with lean and stiff clay, groundwater at 25 feet

Chemical Analysis	Range of Results	Corrosion Classification
Resistivity (Lab)	213 - 728 ohms-cm	Corrosive to Severely Corrosive
Resistivity (in-situ)	357 – 5,230 ohms-cm	Moderately to Severely Corrosive
pH	7.8 – 8.7	Non-Corrosive
Chloride	70 - 448 mg/kg	Non-Corrosive to Corrosive
Sulfate	600 – 9,600 mg/kg	Mildly to Very Corrosive

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Case Study #1

- HDG Zn 4 yrs – 18.25 yrs
- Steel 6.4 mils – 75 mils

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Case Study #2

- Assume HDG W6x9 piles with 8 feet of embedment, 25-year design life
- Sandy soils with medium stiff clay soils with groundwater @ 4 feet

Chemical Analysis	Range of Results	Corrosion Classification
Resistivity (In-Situ)	>32,000 ohm-cm	Non-Corrosive
Resistivity (Laboratory)	>32,000 ohm-cm	Non-Corrosive
pH	5.11 - 6.11	Corrosive
Sulfate	2.4 mg/l	Non-Corrosive
Chloride	15 mg/l	Non-Corrosive

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Case Study #2

- HDG Zn 4 yrs – 25 yr design life
- Steel 0 mils – 55 mils

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Case Study #3

- Assume HDG W6x9 piles with 8 feet of embedment, 25 year design life
- Sandy soils with no groundwater encountered *(one of driest places in world)*

Chemical Analysis	Range of Results	Corrosion Classification
Resistivity (In-Situ)	73 – 6,700 ohms-cm	Severely to Moderately Corrosive
pH	7 - 9	Non-Corrosive
Chloride	30 - 210 mg/kg	Non-Corrosive to Moderately Corrosive
Sulfate	361 – 82,125 mg/kg	Moderately to Severely Corrosive

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Case Study #3

- HDG Zn 4 yrs – 25 yr design life
- Steel 0 mils – 165 mils

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So, what does all this mean?

Remember to use

"Good Engineering Judgement"



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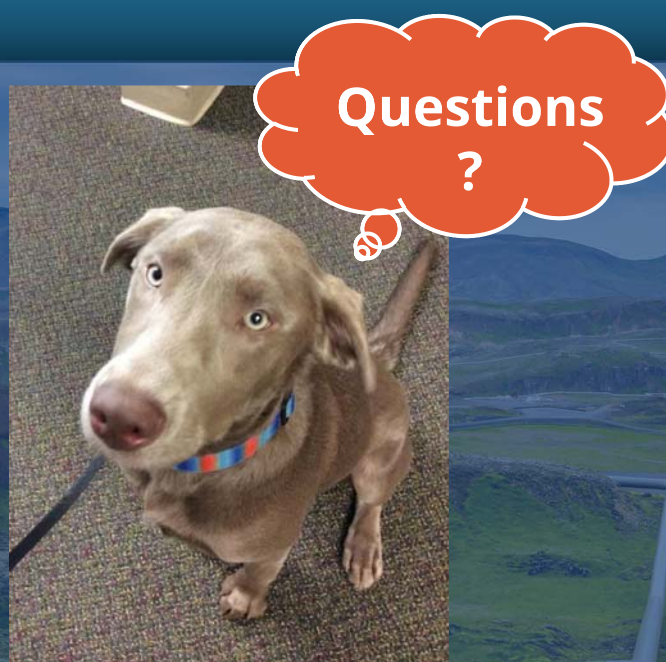

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