C57.12.24/C57.12.40 Joint Task-Force on Materials and Corrosion

Report on Enclosure Materials, Hardware Compatibility & Cathodic Protection

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Enclosure Materials:

The enclosure (or tank) material for underground transformers and equipment currently varies by product standard and could be copper-bearing carbon-steel, 300-series (austenitic) or 400-series (ferritic) stainless-steels. In addition to mechanical requirements, the best tank material is a function of corrosiveness of the service area, variations of water level in the vault, as well as maintenance practices.

There are numerous factors leading to corrosion in underground vaults, but most notable among them is salt. Coastal areas and regions with heavy snow (that de-ice roads with salt) experience the most severe corrosion. Many US states that experience snow use road salt (excluding some western states) as well as Canadian provinces. The amount of salt applied to roads is a function of snowfall and population density, so dense urban areas that experience heavy snow will often have very corrosive environments in their underground vaults. Figure 1 shows a hypothetical map[1] of corrosive regions for underground vaults in North America; the red regions indicate heavy corrosion, orange regions indicate moderate corrosion, and yellow regions indicate mild corrosion. The shaded regions largely reflect coastal areas and heavy snow regions that use salt to de-ice roads; however, other large urban areas that heavily salt their roads could also experience localized high rates of corrosion. *The proposed map could be validated and improved by using measurement data provided by equipment users (using ASTM G71-81*[12] *). Additionally, the level of corrosion (e.g. heavy, moderate, mild, and low) could be quantified by the galvanic potential for a specified material in a given environment (e.g. copper-bearing steel potential to a common reference electrode).*

Water conditions in the vault will also play a major factor in corrosion. A vault that is almost always dry will mostly only experience atmospheric corrosion. A vault that is constantly submerged will have stagnant water, which may experience oxygen depletion regions, concentrations of corrosive compounds, as well as microbes that can increase corrosion rates by feeding the chemical processes involved in corrosion. A vault that alternates between wet and dry conditions will cyclically experience the issues of a submerged vault, but will also have concentrations of those corrosive compounds deposited on the surface of the equipment in dry conditions. Additionally, vaults in suburban environments may also experience corrosion due to fertilizer run-off from yards.

There is no panacea to solve corrosion everywhere and for everyone. Equipment lifespan, maintenance needs, and initial cost are interrelated, and each utility will weigh their value differently depending on service location. It is also important to note that while no paint system is perfect, it is the first line of defense, and its quality is a major factor. Coating systems can provide a cost-effective solution and often include zinc primer (as a sacrificially anodic material), but appropriate maintenance is necessary. It is possible to protect a carbon-steel enclosure continuously submerged in salt water using cathodic protection. It is also reasonable to use stainless-steel enclosures for vaults that experience prolonged dry periods, but do experience heavy road salt and submerged conditions periodically. There are pitfalls and varying costs for the different conditions an equipment user could experience.

Ultimately equipment users need to know the drivers of corrosion in their area, and find the right balance between the enclosure material and maintenance to provide the expected equipment life at a reasonable cost.

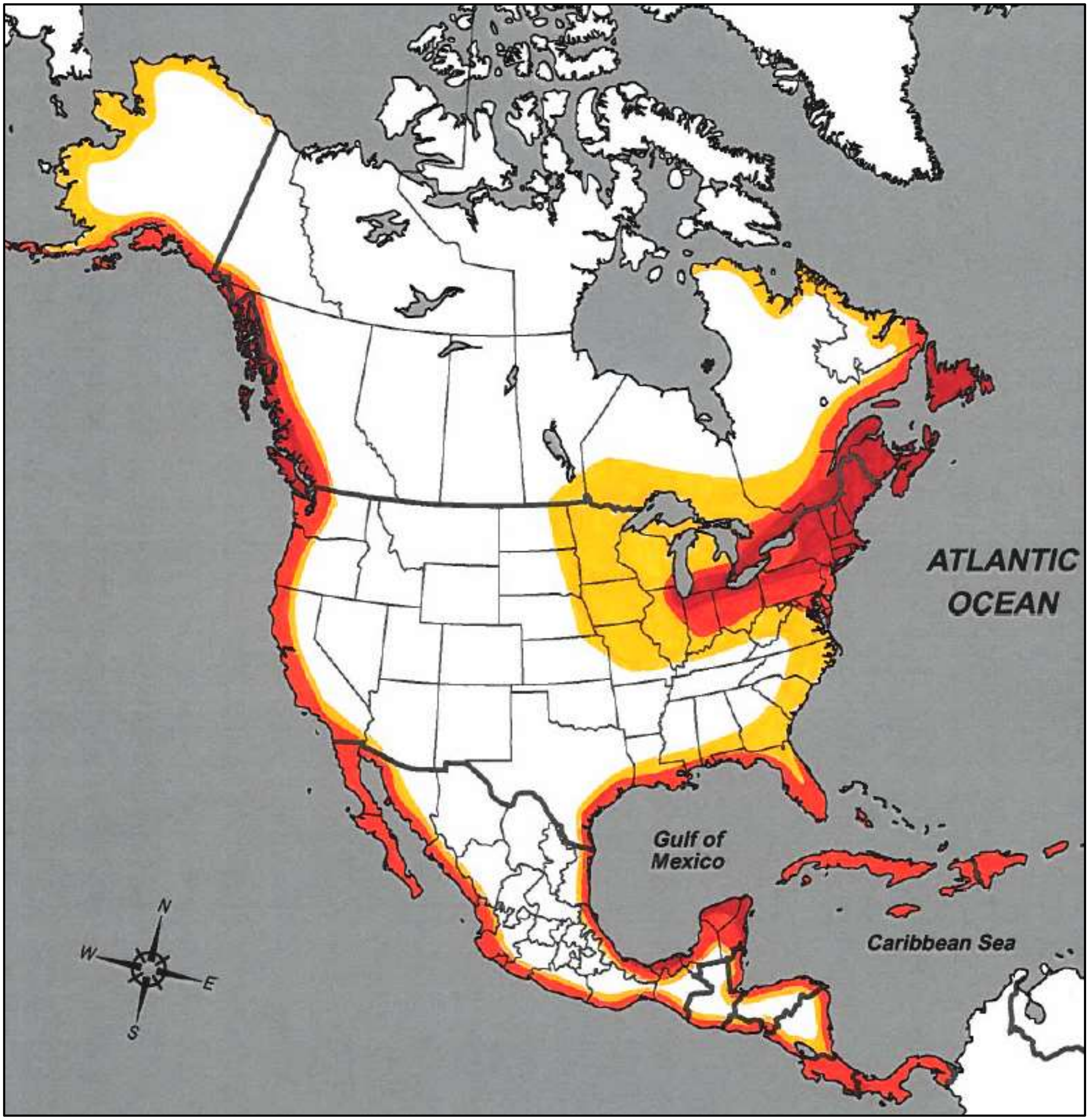


Figure 1: Hypothetical Map of Corrosion in North America
*(**Heavy, Moderate, Mild** & Low Corrosion)*

Copper-bearing Carbon-Steel:

- Copper content ≥ 0.2% (Low Alloy Steel)
  - 0.4% is maximum copper content yielding improved corrosion resistance.[1]
  - 0.2% copper content results in a 2 to 3 times reduction in the corrosion versus without.[1]

400-Series Ferritic Stainless-steel:

- 409 (& 405) grade stainless-steels generally have the lowest carbon content of the ferritic alloys, making them more appropriate for welding. They are less susceptible to pitting corrosion & stress-corrosion cracking than austenitic stainless-steels, and would provide a more cost-effective solution with maintenance.

300-Series Austenitic Stainless-steel:

- Lower carbon "L" grades are the most suitable among 300-series alloys, because submersible enclosures are of welded construction.[1,2,3] (304L, 316L, 317L grades or any alloy with ≤ 0.03% carbon content.)
- Generally considered to have the best corrosion resistance, but are susceptible to pitting and crevice corrosion in stagnant salty water[1,2] (which is difficult to identify during inspection).
- Susceptible to stress corrosion cracking if welded under tension.
- 304 & 316 alloys are difficult to machine, 303Se or other alloys should be permitted for machined parts and pipe fittings (welded or threaded connections).

Copper-Bearing Steel	409 Stainless-Steel	304L Stainless-Steel	316L Stainless-Steel
Advantages: • Lowest cost • Readily available • Weldability • Better corrosion resistance than mild steel	Advantages: • Improved corrosion resistance • Moderate cost • Weldability • Machinable	Advantages: • Better corrosion resistance • Readily available	Advantages: • Best corrosion resistance • Somewhat readily available
Disadvantages: • Requires excellent coating system • Requires cathodic protection in highly corrosive environments, or plans for shorter equipment life	Disadvantages: • Increased cost • Not readily available, may require bulk purchase for thicker plates • Cathodic protection preferred for applications in continuously submerged highly corrosive locations	Disadvantages: • High cost • More difficult to machine parts • Susceptibility to pitting and stress-corrosion cracking • Cathodic protection best for applications in continuously submerged highly corrosive locations	Disadvantages: • Very high cost • Very difficult to machine parts • Susceptibility to pitting and stress-corrosion cracking • Cathodic protection best for applications in continuously submerged highly corrosive locations

Figure 2: Advantages & Disadvantages of Enclosure Materials

Suggested Enclosure Material Options:

Minimum Corrosion Resistance — Copper-bearing Carbon-Steel:

- At minimum, the enclosure should be constructed of copper-bearing steel material (with ≥0.20% copper content)
- Copper-bearing steel is appropriate in vaults that are typically dry or not highly corrosive, or in vaults that are typically submerged when the equipment has cathodic protection

Improved Corrosion Resistance — 400-Series Ferritic Stainless-steel:

- 400-series stainless-steels are appropriate for vaults that experience prolonged dry periods, but are also submerged periodically in mild to moderate corrosive environments. In highly corrosive environments that are typically submerged cathodic protection is recommended.
- At minimum, the enclosure should be constructed of 409-grade in mild corrosive environments. Other ferritic stainless-steel alloys with higher corrosion resistance (with ≥11.5 chromium and ≤ 0.08% carbon content) could be used.
- Equipment that is continually submerged in highly corrosive environments may also require cathodic protection.

Highest Corrosion Resistance — 300-Series Austenitic Stainless-steel:

- 300-series stainless-steels are appropriate for vaults that experience prolonged dry periods, but are also submerged periodically in moderate to highly corrosive environments.
- At minimum, the enclosure should be constructed of 304L grade in moderately corrosive environments. In highly corrosive environments enclosures should be constructed of 316L grade. In extreme cases, 317L grade or other stainless-steel alloy with higher corrosion resistance (and ≤ 0.03% carbon content) may be needed.
- Equipment that is continually submerged in highly corrosive environments may also require cathodic protection.

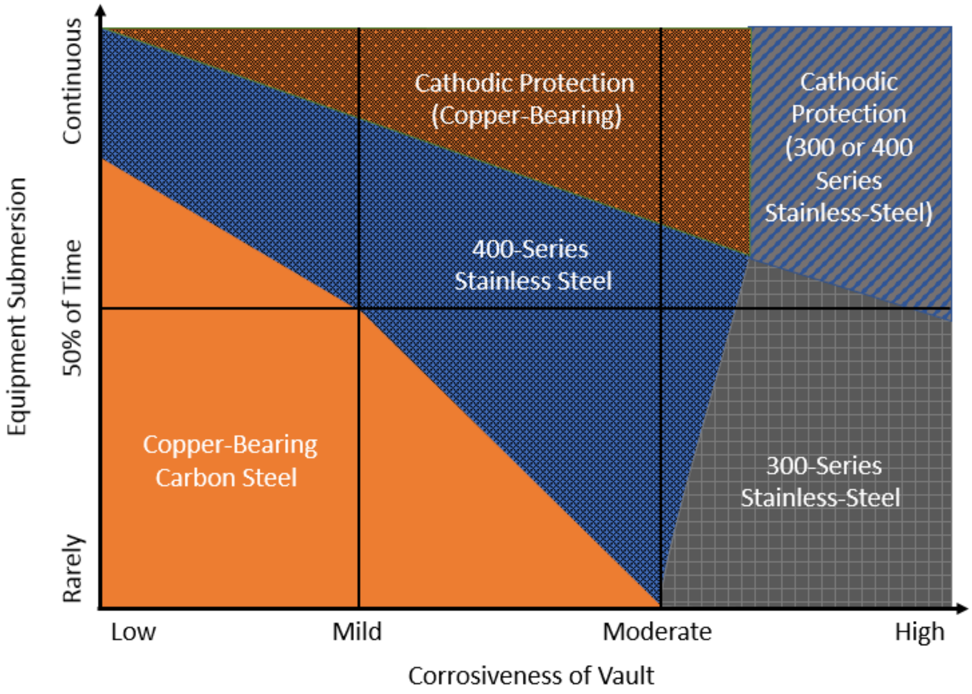


Figure 3: Conceptual Enclosure Suitability Chart

Hardware & Accessory Material Compatibility

Hardware selection is driven by mechanical requirements as well as a need to minimize corrosion. Due to the corrosive environment typically found in underground vaults carbon-steel hardware is not a permitted material, even if plated due to wear from use. Traditionally 300-series stainless-steel or silicon-bronze have been used for external hardware. Given that the equipment may be subjected to continuous or periodic submersion (in an electrolytic solution) galvanic corrosion is a concern over the life of the equipment.

Galvanic corrosion is driven by:

1. Intrinsic galvanic (voltage) potential between dissimilar metals
2. Relative exposed surface areas of the two metals
3. Conductivity of the electrolyte

The conductivity of the electrolyte (in the underground vault) is outside the control of the equipment designer, however the equipment user could have limited control over that parameter. However, the design can minimize galvanic potential between the hardware fasteners and the tank, as well as limiting the relative surface area between the dissimilar materials.

Providing electrical insulation between different metal materials is the simplest method. Therefore, metal flanges should be painted prior to hardware being attached, and then after painting. This will provide a nonconductive coating between the flange and hardware external to the threads. Additionally, both male & female threads should be coated with a nonconductive lubricant, which will limit the relative surface area between the threads of the dissimilar metals as well as limit water (electrolyte) ingress. However, handling and maintenance may damage the insulating coating and create defects (holidays) regardless the coating applied by the manufacturer.

When limiting galvanic potential, it should be noted that stainless-steels typically have two states. The *passive* state exists when stainless-steel has its *passive* oxide coating, which is its typical state when dry and exposed to oxygen. The *active* state exists when stainless-steel has been stripped of its protective oxide coating, which is common after being exposed to acids or when the material is located in a crevice (oxygen depletion zone). For instance, the galvanic potential between *passive* stainless-steel and carbon-steel is much higher than potential between *active* stainless-steel and carbon-steel. This fact reduces the rate of corrosion between stainless-steel and carbon-steel threads (in the presence of an electrolyte), because they are located in a crevice. Silicon-bronze does not generally have different galvanic potential states.

The galvanic potential between silicon-bronze and carbon-steel is nearly as high as *passive* stainless-steel, so more corrosion should be expected between the threads when silicon-bronze is used versus stainless-steel for a carbon-steel tank. However, the galvanic potential is low between silicon-bronze and stainless-steel, so it would be a good hardware material for stainless-steel tanks.

It should be noted that silicon-bronze hardware or brass pipe-fittings could be successfully used on copper-bearing steel enclosures with an intermediate stainless-steel material (such as a pipe, or pipe-fitting.)

Additionally, pairing aluminum alloys with stainless-steel or silicon-bronze results in an unacceptably high galvanic potential and should be avoided except for special cases or if special precautions are taken.

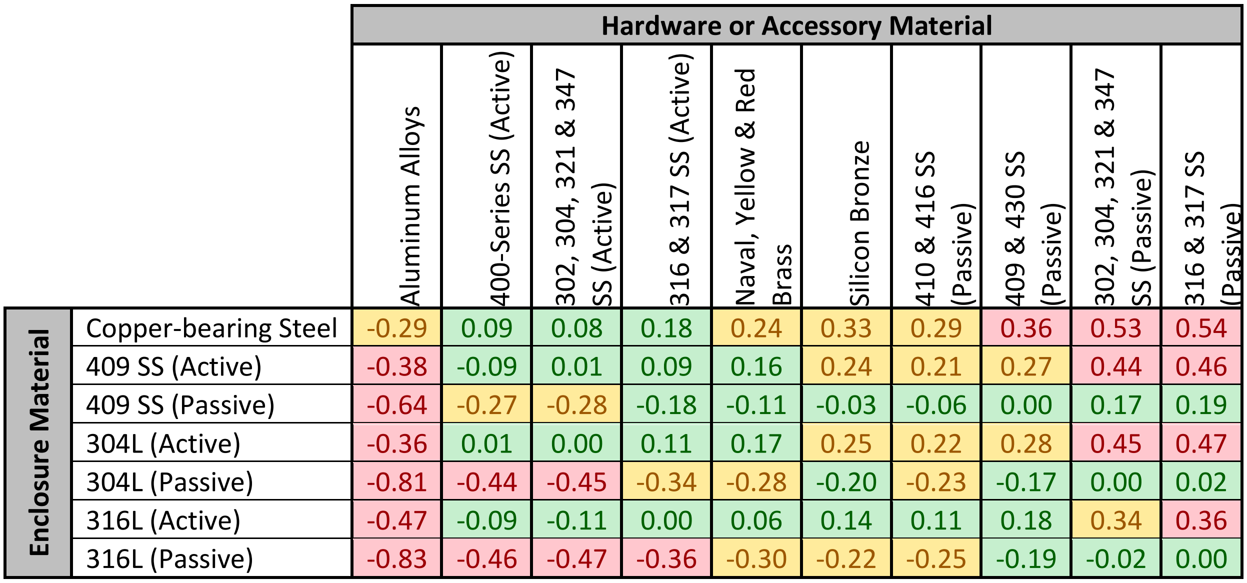
The tables below summarize the suggested hardware materials for copper-bearing steel and stainless-steel tanks:

	Fastening Hardware or Accessory Material		
Tank Material	300-Series Stainless-Steel	400-Series Stainless-Steel	Silicon-Bronze
Copper-Bearing Carbon-Steel	✓	✓	
409 Stainless-steel	✓		✓
304L Stainless-Steel	*	✓	✓
316L Stainless-Steel	*	✓	✓

Figure 4: Quick Reference Hardware Compatibility Chart

✓ Compatible materials

* Compatible if non-galling stainless-steel grades or proven methods are used[4]



		Hardware or Accessory Material									
		Aluminum Alloys	400-Series SS (Active)	302, 304, 321 & 347 SS (Active)	316 & 317 SS (Active)	Naval, Yellow & Red Brass	Silicon Bronze	410 & 416 SS (Passive)	409 & 430 SS (Passive)	302, 304, 321 & 347 SS (Passive)	316 & 317 SS (Passive)
Enclosure Material	Copper-bearing Steel	-0.29	0.09	0.08	0.18	0.24	0.33	0.29	0.36	0.53	0.54
	409 SS (Active)	-0.38	-0.09	0.01	0.09	0.16	0.24	0.21	0.27	0.44	0.46
	409 SS (Passive)	-0.64	-0.27	-0.28	-0.18	-0.11	-0.03	-0.06	0.00	0.17	0.19
	304L (Active)	-0.36	0.01	0.00	0.11	0.17	0.25	0.22	0.28	0.45	0.47
	304L (Passive)	-0.81	-0.44	-0.45	-0.34	-0.28	-0.20	-0.23	-0.17	0.00	0.02
	316L (Active)	-0.47	-0.09	-0.11	0.00	0.06	0.14	0.11	0.18	0.34	0.36
	316L (Passive)	-0.83	-0.46	-0.47	-0.36	-0.30	-0.22	-0.25	-0.19	-0.02	0.00

Figure 5: Galvanic Potential Compatibility Chart

Potentials calculated from ASTM G82-98 for flowing seawater[13] (worst-case scenario). Values listed are averages of the minimum and maximum potential differences for each material combination. (*Note that the difference in average values could also be used for each material.*)

Limits per ASTM C876-15[11]:

Green (90% probability no corrosion):	0.2 > V > -0.2
Yellow (corrosion is uncertain):	-0.2 ≥ V ≥ -0.35 or 0.2 ≤ V ≤ 0.35
Red (90% probability of corrosion):	V < -0.35 or V > 0.35

Photos of Hardware & Accessories on Equipment Installed in Underground Vaults:

Examples showing galvanic corrosion:

Figure 6: Brass Pipe Cap (not shown) on Steel Pipe

Figure 7: Bronze Sampler Valve on Steel Pipe Flange

Figure 8: Bronze Drain Valve on Steel Pipe

Figure 9: Silicon-Bronze Padlock on Steel

Photos of Hardware & Accessories on Equipment Installed in Underground Vaults:

Examples showing galvanic corrosion:

Figure 10: Thermometers with Aluminum Case on Silicon-Bronze Threads

Figure 11: Brass Pipe Plug on Steel Threads

Photos of Hardware & Accessories on Equipment Installed in Underground Vaults:

Examples not showing galvanic corrosion:

Figure 12: Silicon-Bronze Pressure Relief Valve on Stainless Flange (Welded to Steel Tank)

Figure 13: 300-Series Stainless Hardware on Steel Enclosure

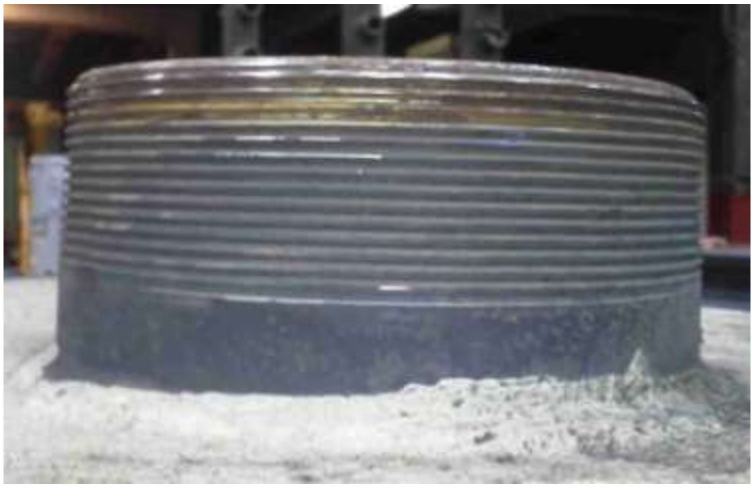


Figure 14: Brass Pipe Cap (not shown) on Stainless-Steel Pipe

Cathodic Protection:

Cathodic protection is a corrosion control strategy that exploits galvanic corrosion. In underground vaults the typical reaction involves copper alloys (the cathode) corroding iron alloys (the anode) in an electro-chemical galvanic reaction, unless other materials are present. Passive (sacrificial anode) and active (impressed current) are the two types of cathodic protection.

These protection methods were primarily developed to protect oil & gas equipment, which are usually constructed of carbon steel. Active cathodic protection is largely used on land-based equipment (such as gas pipelines, storage tanks, etc.) Passive cathodic protection is largely used off-shore (including pipelines, drilling rigs, etc.) In principle, both methods could be used for underground electrical equipment, but passive cathodic protection is more commonly used in underground vaults for electrical equipment due to its relative simplicity (vs active cathodic protection).

Passive (sacrificial anode) cathodic protection schemes introduce a more anodic metal (such as zinc, magnesium, or aluminum) which will corrode sacrificially to protect the iron alloy (the steel tank) which is cathodic versus the sacrificial anode. The virtue of this method is that it requires no external power or control systems. The anode will take effect anytime it is immersed in water (electrolyte) and there is a defect in the coating of the enclosure, so it is an excellent complement to a robust coating on the enclosure (which is why it is commonly used for offshore applications[1]). Passive cathodic protection would require regular inspection and replacement of anodes, but such maintenance work has been successfully implemented by electric utilities.

Active (impressed current) cathodic protection is more complicated to implement because the equipment enclosures are usually solidly grounded. Active cathodic protection would also require coordination with other underground structures, otherwise unintended corrosion of other equipment may occur[5]. While active cathodic protection is a possible solution, it is recommended that users consult with corrosion engineers prior to implementing any such system.

Several ASTM, NACE, and European standards and IEEE documents have been listed for reference:

- ASTM G82-98[13] provides a procedure to develop a galvanic series for a specific location
- ASTM G71-81[12] provides procedures for testing and evaluating corrosion for material combinations
- ASTM C876-15[11] provides galvanic potential limits (in the appendix) which could be used to determine when cathodic protection may be needed
- IEEE National Electric Safety Code[5], cathodic protection article[6], and related working group presentations[7,8,9,10]
- The NACE[14,15,16] and European Standards[17,18] listed largely concern active (impressed current) cathodic protection, but are still valuable references.

Ultimately, passive (sacrificial anode) cathodic protection provides a proven method to protect equipment in highly corrosive environments[1,2,10,15], and could provide a more cost-effective solution than stainless-steel enclosures for certain environments. Such systems have been successfully implemented by utilities using underground equipment[10].

References:

1. Roberge, Pierre R., *Handbook of Corrosion Engineering*, 2000
    - Corrosion mapping: pages 58-61
    - Austenitic pitting susceptibility: pages 364-365
    - Austenitic stainless-steel weldability: page 712
    - Copper-bearing carbon steel: pages 737, 746-747
    - Cathodic protection: chapter 11
        - Sacrificial anode (passive) cathodic protection: pages 871-878
2. Fontana, Mars G., *Corrosion Engineering*, 1987
    - Galvanic Corrosion: pages 41-51
    - Austenitic stainless-steel weldability: pages 74-83
    - Grade 304 & 316 pitting susceptibility in seawater: page 73
    - Cathodic Protection: pages 294-300
3. General Electric, *GEC-1128 Understanding Stainless-steel*
4. Fastenal, *Thread Galling* (https://www.fastenal.com/en/72/galling)
5. IEEE C2-2017, *National Electrical Safety Code*, 2017
    - See §093.E.5 regarding metals used underground with grounding conductors
    - See §215.C.4 regarding galvanic insulators on overhead lines
    - See §391.B.3 regarding coordination of corrosion-control systems
6. Durham, Marus O & Robert A., *Cathodic Protection*, IEEE Industry Applications Magazine (Volume: 11 , Issue: 1 , Jan-Feb 2005)
    - Also includes additional references for active cathodic protection systems
7. Ho, Patrick, Corrosion Presentation to IEEE C57.12.24 Working Group, Fall 2017
8. Ho, Patrick, Stainless Steel Presentation to IEEE C7.12.40 Working Group, Spring 2018
9. Kenner, Bob, Corrosion and Cathodic Protection Presentation to IEEE C57.12.24 Working Group, Spring 2018
10. Shin, Jane, [Sacrificial] Anodes for Submersible Network Transformers Presentation to IEEE C57.12.40 Working Group, Spring 2018
11. ASTM C876-15, *Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete*, 2015
12. ASTM G71-81 (2014), *Standard Guide for Conducting and Evaluating Galvanic Corrosion Tests in Electrolytes*, 2014
13. ASTM G82-98 (2014), *Standard Guide for Development and Use of a Galvanic Series for Predicting Galvanic Corrosion Performance*, 2014
14. ASTM NACE / ASTM G193-12d, *Standard Terminology and Acronyms Relating to Corrosion*, 2012
15. NACE SP0169-2013 (formerly RP0169), *Standard Practice Control of External Corrosion on Underground or Submerged Metallic Piping Systems*, 2013
16. NACE TM0497-2018, *Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems*, 2018
17. European Standard BS EN 13636:2004, *Cathodic protection of buried metallic tanks and related piping*, 2004
18. European Standard BS EN 15112:2006, *External cathodic protection of well casing*, 2006