Coastal Power Plant Anti-Corrosion Practices

Eric Allen, Daniel Swanberg, *and* **John Yang,** *Stantec, Houston, Texas, USA*

Coastal power plants exposed to a marine environment face significant corrosion challenges, particularly within the seawater circulating water (CW) system. This article explores effective corrosion prevention strategies for managing corrosion issues of seawater handling equipment. Key topics include material selection, cathodic protection (CP), and protective coatings. The discussion will cover CP for condenser water boxes, seawater CW pumps, the interiors of seawater pipes, and seawater intake structures. Additionally, the article will briefly address the coating system selection for above-ground facilities. The analysis and recommendations draw upon extensive corrosion engineering experiences from coastal power plant projects.

Coastal power plants—such as nuclear, coal-fired, and combined cycle power plants— often rely on seawater for their main circulating water (CW) systems. The seawater CW system in these plants typically includes several key components: seawater intake facilities, CW pipelines, condensers, and heat exchangers.

Corrosivity of Seawater

Seawater poses significant threats to materials like carbon steel (CS) and common stainless steels (SS), including SS 304 (S30403) and SS 316 (S31603). These materials often require additional protective measures such as coating and/or cathodic protection (CP). In contrast, super SS alone can withstand normal seawater conditions—a conclusion drawn from empirical experience. Super SS is identified by a pitting resistance equivalent number (PREN) of 40 or greater. The PREN is calculated using the formula:

$$\text{PREN} = \%\text{Cr} + 3.3 \times (\%\text{Mo} + 0.5 \times \text{W}\%) + 16 \times \%\text{N} \quad (1)$$

The family of super SS includes super duplex stainless steel (DSS), super austenitic SS, and super ferritic SS. Figure 1 provides the PREN of some common SS.[1]

Failures of DSS alloy 2205 have frequently been observed, and even more so for SS 316.

Super DSS alloy 2507 (S32750) is commonly used in seawater without additional protection. In coastal power plants near estuaries, seasonal chloride concentration variations may necessitate design factor adjustments, including material selection and potential attenuation calculations.

Titanium is known for its resistance to seawater and is currently utilized for most coastal power plant condenser tubes. Super ferritic SS tubes are also an option.

Material Selection Principles

Material selection involves evaluating both technical suitability and cost effectiveness. Additional factors influencing material selection include availability, ease of fabrication, equipment criticality, expected service life, and ease of maintenance. Each of these considerations plays a crucial role in ensuring the chosen materials perform optimally in their specific applications and conditions at low risk.

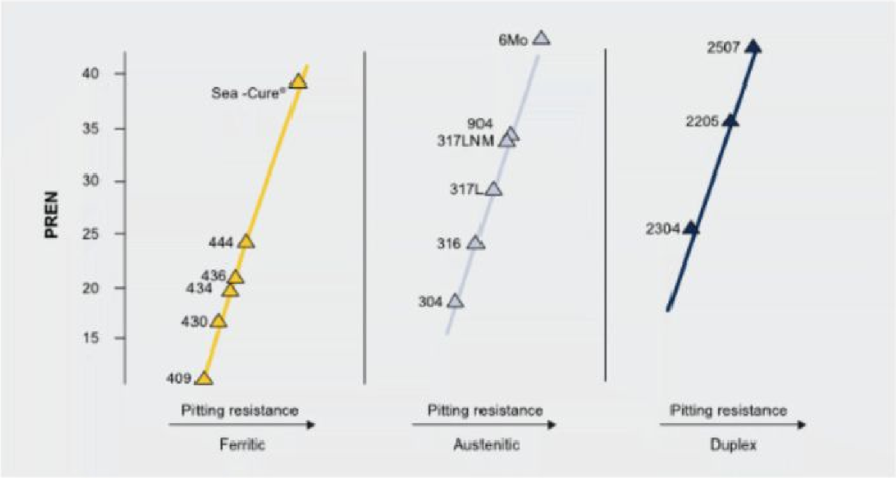
Cathodic Protection of Condenser Water Boxes

Seawater condensers typically employ titanium tubes and tube sheets (i.e., titanium-clad), whereas water boxes are generally constructed from epoxy-lined or rubber-lined CS. Due to the large bare areas of the titanium, most of the rectifier current flows to the titanium. Additionally, bare SS strainers and tube-cleaning ball collectors also draw current.

The CP current density for bare metal typically ranges from 70 to 100 mA/m^2. For epoxy-lined water boxes and inlet/outlet pipes, a 2% coating breakdown factor is generally applied, assuming the epoxy lining is similar to coating system 7A, NORSOK M501.[2] It is practical to assume that the CP current will get inside each tube to a depth of approximately 4 to 6 tube diameters.

Impressed current cathodic protection (ICCP) is recommended with a design life of 30 years. Although aluminum anodes can be used, they may need replacement every seven to eight years. Probe-type anodes and reference electrodes are commonly utilized for condenser water boxes. When the buried CW pipe is a concrete pipe, additional anodes should be positioned near the joining flange of the CS pipe, as the concrete pipe will also draw current.

The probe-type mixed metal oxides (MMO) anode connects to the water boxes via thread connection (for epoxy lining) or flange connection (for rubber lining). Typically, two types of reference electrodes are used: zinc and silver-silver chloride (SSC). It is important to note that there are two types of SSC reference electrodes, one of which changes potential when chloride concentration varies. This type of SSC may not be suitable for CW with seasonal changes in chloride concentration. Figure 2 illustrates the probe-type MMO anode and probe-type reference electrodes for epoxy-lined water boxes and pipes.



Comparison of PREN values for different ferritic, austenitic and duplex stainless steels (after ArcelorMittal)

FIGURE 1 **PREN values of common stainless steels.**

Titanium alloys are particularly sensitive to hydrogen embrittlement (HE). For condensers equipped with titanium tubes, it is crucial to ensure that the on-potential is not more negative than $-750\ mV_{SSC}$.

During the initial stage of cathodic polarization, a higher protection current is required. Therefore, the current rating of the rectifier should be higher than the calculated continuing output value.

Cathodic Protection of CW Pipe Interior

The above-ground portions of seawater CW pipelines are typically constructed from epoxy-lined CS. For buried CW pipes, three common materials are used: epoxy-lined CS pipes, prestressed concrete cylinder pipes (PCCP), and non-metallic pipes (such as high-density polyethylene or fiber-reinforced plastic).

An ICCP system is often employed to protect metal pipe interiors. Although aluminum anodes can be utilized, they may require replacement after seven to eight years. Conversely, the lifespan of an ICCP system is typically set for 30 years. The ICCP uses probe-type MMO anodes and probe-type reference electrodes.

A 2% coating breakdown factor is typically applied to epoxy-lined CS. A current

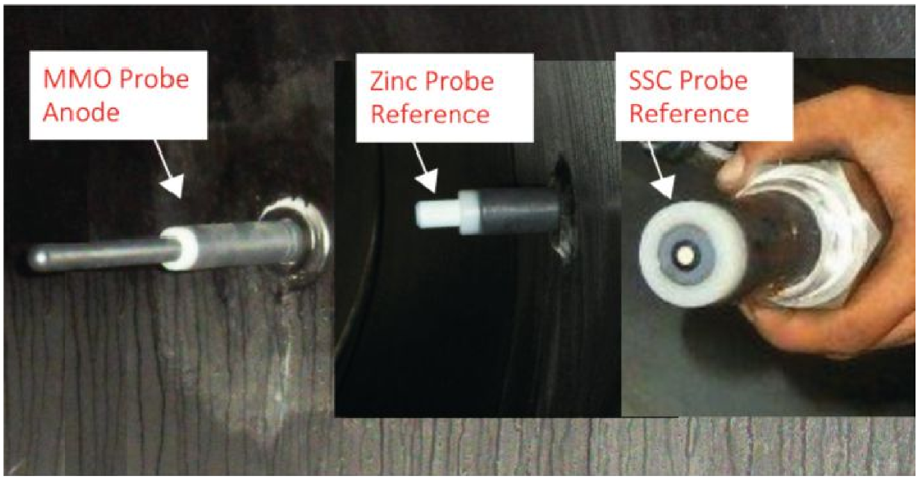


FIGURE 2 **MMO anode and SSC and zinc reference electrodes.**

TABLE 1 ANODE SPACING FOR PIPE INTERIOR CP

Pipe Internal Coating Thickness 600um (7A, Norsok M501)	
Pipe ID (inch)	**Anode Spacing (m)**
8	15
10	17
16	22
24	27
36	33
48	39
54	41
60	43
72	47
84	51
96	55
Coating breakdown factor: 2%	

density of 70 to 100 mA/m^2 is recommended (i.e., bare steel). The CP criteria usually adhere to conventional standards, falling within the range of -800 mV_{SSC} to -1000 mV_{SSC}.

The length of the probe anode should be calculated. It is crucial that the anode length does not exceed the calculated upper limit to prevent fracture due to mechanical forces exerted by the CW. Completing attenuation calculations is necessary to determine appropriate anode spacing. Table 1 illustrates the recommended anode spacing.[3]

Cathodic Protection of CW Pump Interior

CW pumps are typically vertical turbine pumps that are available in various types, including pull-out. Pump shafts can be enclosed or open, with enclosed shafts using lubricating water that may be filtered seawater or fresh water. Conventional pump shaft materials such as SS 410 (S41000) or SS 416 (S41600) would be adequate if fresh water is used.

When the entire pump is made of alloy 2507, CP is unnecessary. Howver, CP is required for pumps primarily constructed of SS 316 or alloy 2205. Using alloy 2205 (PREN = 33 to 35) offers a more conservative option than SS 316 (PREN = 23 to 28). It is recommended to use alloy 2507 for the pump shaft and associated couplings.

Other materials, like Ni-Resist cast iron, can also be used for CW pump bodies, although Ni-Resist CW pumps still require CP. ICCP is typically used for pump interior with a CP current density in the range of 50 to 60 mA/m^2. While literature often suggests very high current densities for pump interior CP, empirical experience indicated that the required current density was significantly lower.

The internal CP of the CW pump discharge pipe is typically included in the same CP system, with an on-potential ranging from -800 to -900 mV_{SSC}. For additional CP criteria, refer to ISO 15589-2.[4] Since DSS is not immune to hydrogen embrittlement, it is not recommended to set the on-potential more negative than -900 mV_{SSC}.

Plate anodes or probe-type anodes are typically used. SSC and zinc-flanged probe-type reference electrodes are generally installed side by side. Additionally, the CW pump shaft should be grounded with grounding brushes. Figure 3 illustrates the MMO plate anode and flanged probe reference electrodes. The design life for the CW pump internal CP is 30 years, with an auto-potential control rectifier.

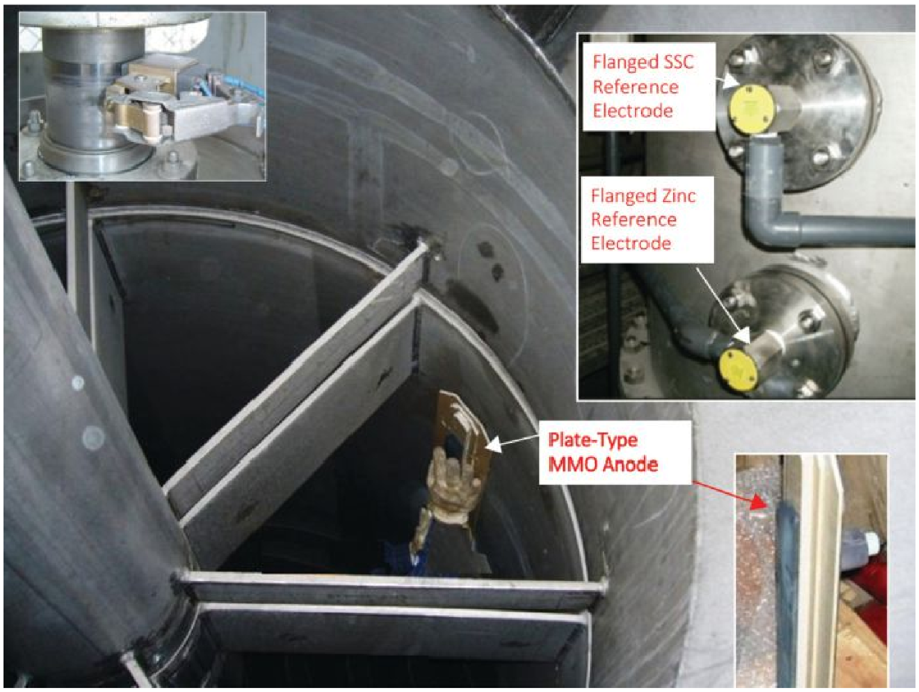


FIGURE 3 Plate-type MMO anode and flanged reference electrodes.

Cathodic Protection of Seawater Intake Structures

The CP system of seawater intake facilities is an open system, leading to a significant portion of the CP current dispersing to other facilities. Components within the seawater intake area include stop logs, bar screens, trash rake devices, traveling screens, guides, CW pump exteriors, and washing pumps. Auxiliary CW pumps may also be located in the intake bays.

A current density of 70 to 100 mA/m^2 is typically used for bare metal. However, it's important to note that approximately 70% to 80% of the current may flow to facilities not directly intended for CP. Except for the stop logs and traveling screen frames, intake structures are predominantly made of SS 316L. Seawater intake structures require a substantial amount of current, making ICCP the preferred choice. Wall-mount MMO anodes and reference electrodes (e.g., SSC and zinc) are commonly used with an ICCP system design life of 30 years.

Stop logs are generally protected with aluminum anodes. Given that stop logs are usually stored on grade, these aluminum anodes do not require frequent replacement. The initial polarization required higher current. It is advisable to increase the direct current (DC) rating of the rectifier by approximately 1.5 times the calculated value.

To avoid interference with the CW pump interior CP system, which typically uses an auto-potential control rectifier, a manual control rectifier is recommended for seawater intake CP. Figure 4 illustrates the anodes and reference electrodes used in the seawater intake area.

Overall, for CP current density in seawater, Figure 2 of ISO 15589-2 offers very practical and applicable values.

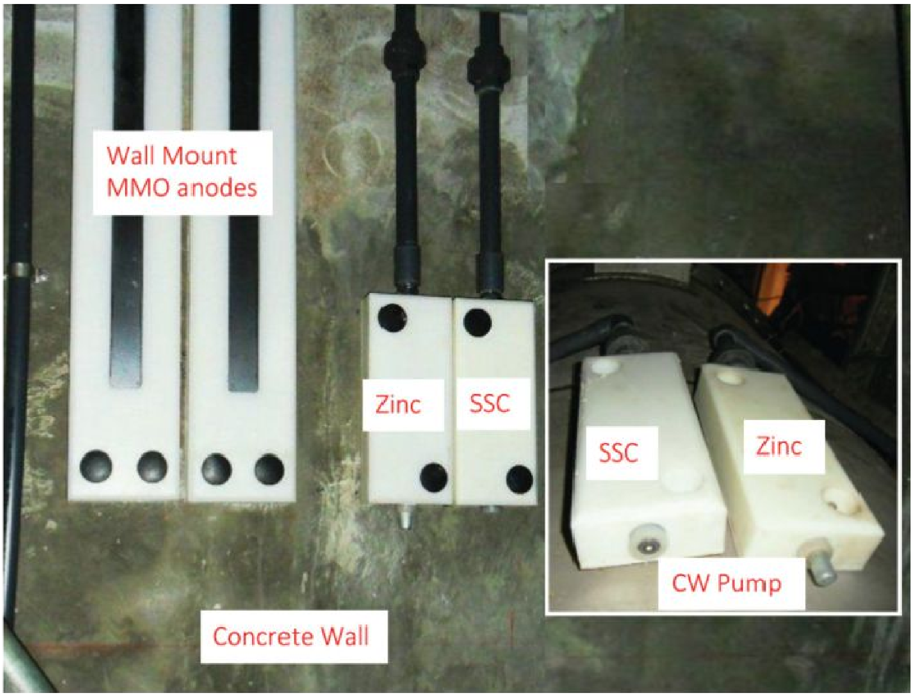


FIGURE 4 Wall mount MMO anodes and reference electrodes.

Buried Metallic Pipelines

Buried metallic pipelines, including those made of CS and SS, require both external coating and CP. Both sacrificial anode CP (SACP) and ICCP are acceptable methods. Due to the complexity of buried pipelines in power plants, SACP may offer advantages over ICCP. All protected pipelines should be electrically isolated using insulating flanges.

The general CP criterion is -850 mV or more negative with respect to a copper sulfate reference electrode. Additional CP criteria can be sourced from NACE SP 0169[5] or ISO 15589-1.[6] For a typical power plant, a small rectifier can meet the current requirements, which typically range from 0.5A to 3A, for a CP system with a 30-year design life. Experience has shown that the life of sacrificial anodes can reach up to 30.years.

A 2% coating breakdown factor is generally appropriate unless data indicate that the pipelines have inferior coating systems. The CP current density should be determined based on soil corrosivity, typically ranging from 5 to 30 mA/m^2 (bare metal). For buried ductile iron (DI) pipes, corrosion protection measures typically follow AWWA C105.[7]

Above-Grade Tanks

CP for on-grade tank bottom plate exterior is applicable only to tanks resting on foundations made of a concrete ring wall with sand pad infill, and not applicable for tanks with a full concrete foundation. ICCP with MMO anodes (e.g., ribbon, wire, or Flex) is typically employed. For comprehensive guidelines, refer to API 651.[8]

Coating Systems

Coating system selection for coastal power plants typically adheres to ISO 12944-5.[9] For buried metallic pipelines, common coating options include three-layer polyethylene (3LPE), fusion-bonded epoxy (FBE), liquid epoxy, and polyurethane.

Based on ISO 9223[10] and ISO 12944-2,[11] the atmospheric exposure classification for coastal power plants is C5. Table 2 shows the coating systems for C5.

For austenitic SS, such as SS 304L and SS 316L, when under thermal insulation, coatings must be applied to avoid stress corrosion cracking (SCC). For guidance on the coating systems under insulation, refer to NACE SP0198[13] and API RP 583.[14]

Importance of Corrosion Prevention Measures in Coastal Power Plants

The marine environment presents significant corrosion challenges to coastal power plants, particularly for facilities handling seawater. It is crucial to incorporate stringent corrosion prevention measures during the design stage and throughout construction. For condenser water boxes and CW pipe internal surfaces, CP should be applied as soon as practical, or the seawater should be drained and internal surfaces rinsed with fresh water. Following

TABLE 2 ISO 12944-5 TABLE C.5 COATING SYSTEMS

System No.	Priming coat				Subsequent coat(s)	Paint system		Durability			
	Binder type	Type of primer	No. of coats	HDFT in µm	Binder type	Total no. of coats	NDFT in µm	l	m	h	vh
C5.01	EP, PUR, ESI	Misc.	1	80 to 160	EP, PUR, AY	2	180	X			
C5.02	EP, PUR, ESI	Misc.	1	80 to 160	EP, PUR, AY	2–3	240	X	X		
C5.03	EP, PUR, ESI	Misc.	1	80 to 240	EP, PUR, AY	2–4	300	X	X	X	
C5.04	EP, PUR, ESI	Misc.	1	80 to 200	EP, PUR, AY	3–4	360	X	X	X	X
C5.05	EP, PUR, ESI	Zn (R)	1	60 to 80	EP, PUR, AY	2	160	X			
C5.06	EP, PUR, ESI	Zn (R)	1	60 to 80	EP, PUR, AY	2–3	200	X	X		
C5.07	EP, PUR, ESI	Zn (R)	1	60 to 80	EP, PUR, AY	3–4	260	X	X	X	
C5.08	EP, PUR, ESI	Zn (R)	1	60 to 80	EP, PUR, AY	3–4	320	X	X	X	X

NOTE 1 For abbreviations see Table A.1.
NOTE 2 In addition to polyurethane technology, other coating technologies may be suitable, e.g. polysiloxanes, polyaspartic and fluoropolymer [fluoroethylene/vinyl ether co-polymer (FEVE)].

appropriate plant layup procedures may be another way to prevent issues.

Several key codes and standards from organizations like AMPP, ISO, API, NORSOK, and EN can be referenced as guidance. There have been numerous instances of failure — due to inadequate material selection, lack of internal communication among design departments, and site personnel not anticipating severe corrosion threats during startup — that have led to costly restorations.

For the coating selection of above-grade facilities, a conservative approach is advised to minimize the need for repairs during the warranty period. It's important to highlight the value of an experienced corrosion engineer, particularly one with high-level AMPP certifications, as they are valuable assets in managing and mitigating corrosion risks.

References

1 International Molybdenum Association, "Stainless Grade and Properties" (London, UK: 2008) https://www.imoa.info/molybdenum-uses/molybdenum-grade-stainless-steels/steel-grades.php

2 NORSOK M501, "Surface Preparation and Protective Coating" (Lysaker, Norway: Standards Norway, 2012).

3 J. Yang, J. Liang, "A Right Way to Calculate CP Potential Attenuation," CORROSION 2022, paper no. 17599 (Houston, TX: NACE, 2022).

4 ISO 15589-2, "Cathodic Protection of Pipeline Transportation Systems – Offshore Pipelines" (Geneva, Switzerland: ISO, 2017).

5 NACE SP0169-2013, "Control of External Corrosion on Underground or Submerged Metallic Piping Systems" (Houston, TX: NACE, 2013).

6 ISO 15589-1, "Cathodic Protection of Pipeline Transportation Systems – On-Land Pipeline" (Geneva, Switzerland: ISO, 2017).

7 AWWA C105/A21.5-18, "Polyethylene Encasement for Ductile Iron Pipe Systems" (Denver, CO: AWWA, 2018).

8 API RP 651, "Cathodic Protection of Above Ground Petroleum Storage Tanks," Fourth Ed. (Washington, DC: API, 2014).

9 ISO 12944-5, "Corrosion Protection of Steel Structures by Protective Paint Systems, Part 5: Protective Paint Systems" (Geneva, Switzerland: ISO, 2018).

10 ISO 9223, "Corrosion of Metals and Alloys–Corrosivity of atmospheres–Classification, Determination and Estimation" (Geneva, Switzerland: ISO, 2012).

11 ISO 12944-2, "Corrosion Protection of Steel Structures by Protective Paint Systems, Part 2: Classification of Environments" (Geneva, Switzerland: ISO, 2017).

12 ISO 12944-9, "Corrosion Protection of Steel Structures by Protective Paint Systems, Part 9: Protective Paint Systems and Laboratory Performance Test Methods for Offshore and Related Structures" (Geneva, Switzerland: ISO, 2018).

13 NACE SP0198-2017, "Control of Corrosion Under Thermal Insulation and Fireproofing Materials – A Systems Approach" (Houston, TX: NACE, 2017).

14 API RP 583, "Corrosion Under Insulation and Fireproofing" (Washington, DC: API, 2014).

ERIC ALLEN is the manager of asset integrity programs for Stantec's BC-2057 Energy Coastal Group in Houston, Texas, USA. He is an expert in corrosion and integrity management with more than 15 years of experience in corrosion engineering and pipeline integrity management. Additionally, he is an expert in offshore asset management.

DANIEL SWANBERG is the team lead of the Integrity and Corrosion team within Stantec's BC-2057 Energy Coastal Group. He has 17 years of industry experience in the energy sector, with expertise in various areas including corrosion engineering, asset integrity management, etc.

JOHN YANG is a corrosion and integrity engineer within Stantec's BC-2057 Energy Coastal Group, email: Fuchenyang@yahoo.ca. He holds an AMPP/NACE CP4 certification and has more than 20 years of experience in corrosion engineering and pipeline integrity management.