Cathodic Protection Design
for
offshore Wind Turbines

Prof. Stephanos Tsinopoulos

Department of Mechanical Engineering,
University of Peloponnese
Greece

Part 1:

Corrosion Principles of Metals
and
Principles of Cathodic Protection

DEFINITION OF CORROSION

Corrosion is the **spontaneous destruction** of **metals** and **alloys** caused by their:

- ✓ chemical,
- ✓ biochemical, or/and
- ✓ **electrochemical**

interaction with the **surrounding environment**.

Corrosive environments may contain:

- ✓ moisture,
- ✓ oxygen,
- ✓ inorganic and organic acids,
- ✓ high pressure,
- ✓ temperature, or/and
- ✓ chlorides.

During corrosion, **metals** tend to **convert** to **more thermodynamically stable compounds**, such as oxides, hydroxides, salts, or carbonates. The original compounds (minerals and ores) are recovered from metals decreasing in free energy. Hence, **the energy used for forming the metals is emitted during corrosion reactions**. In other words, Metallurgy in reverse!

Consequently, corrosion is a spontaneous, usually slow-progressing, chemical/electrochemical phenomenon.

SIGNIFICANCE AND COST OF CORROSION

Corrosion threats the overall integrity of:

- Ships
- Offshore structures for oil and gas productions
- Offshore wind turbines
- Above and below ground storage tanks
- Underground pipelines
- Reinforced concrete structures (bridges, etc)
- Nuclear facilities, etc.

Corrosion consequences may be:

- Catastrophic failure of structures
- Plant shutdowns
- Waste of resources
- Loss or contamination of product
- Reduction in efficiency
- Costly maintenance, etc.

Estimated cost:

1) About a quarter of the world’s iron and steel production is destroyed by corrosion.
2) The annual global cost of corrosion is over 3% of the world’s GDP, estimated at US$ 2.2 trillion.

CORROSION PRINCIPLES OF METALS

Electrode: In electrochemistry, an **immersed** or **buried metal** in an **electrolyte** forms a two-phase **electrode**. The **metal** is an **electron conductor**, while the **electrolyte** is **conductive** due to its **ions**.

The electrolyte can be freshwater, open seawater, seabed mud, concrete, soil, sand, etc. From the point view of corrosion, **an electrolyte represents** the aqueous **corrosive environment** of the metal.

Corrosion is an electrochemical phenomenon occurring at the interface between the metal and the electrolyte.

The corrosion of steel in aerated seawater are represented by the following two electrochemical reactions:

$$2Fe \rightarrow 2Fe^{++} + 4e^{-}$$

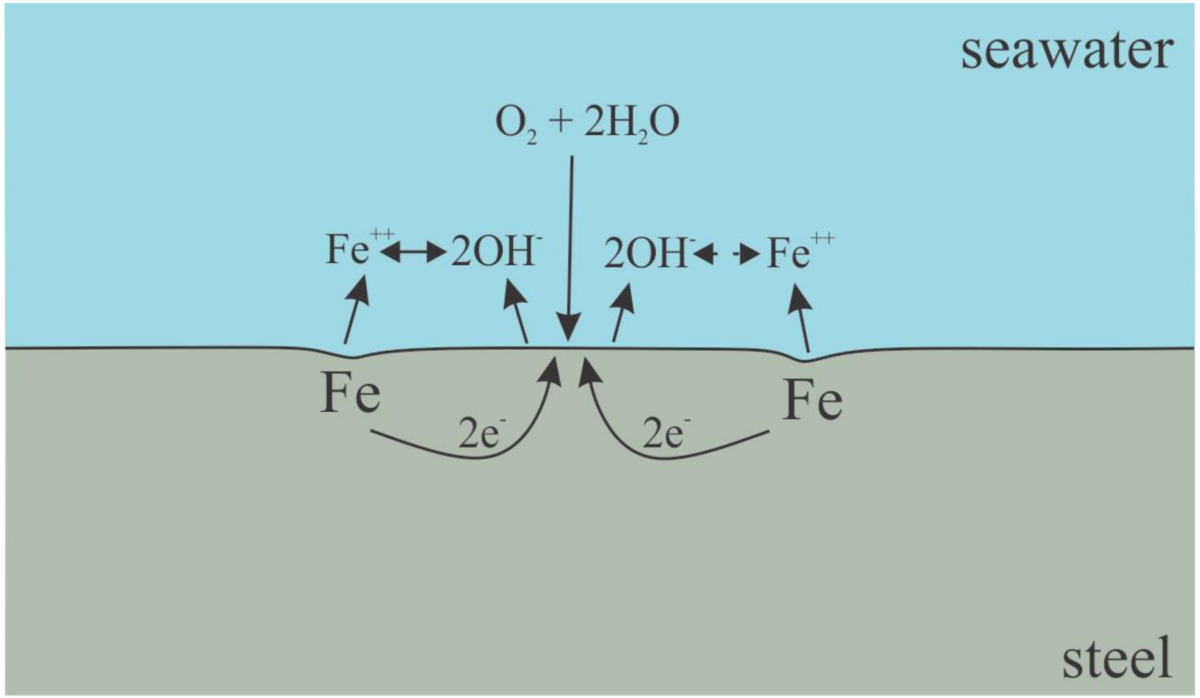
steel → ferrous ions + electrons

Metal Oxidation or anodic reaction

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}$$

disolved oxygen + water + electrons → hdroxyl ions

Oxygen reduction or cathodic reaction



CORROSION PRINCIPLES OF METALS

$$\begin{array}{ccccc} 2\mathrm{Fe} & \rightarrow & 2\mathrm{Fe}^{++} & + & 4e^{-} \\ \text{steel} & \rightarrow & \text{ferrous ions} & + & \text{electrons} \end{array}$$

Metal Oxidation or anodic reaction

$$\begin{array}{ccccccc} O_2 & + & 2H_2O & + & 4e^{-} & \rightarrow & 4OH^{-} \\ \text{disolved oxygen} & + & \text{water} & + & \text{electrons} & \rightarrow & \text{hdroxyl ions} \end{array}$$

Oxygen reduction or cathodic reaction

Remarks:

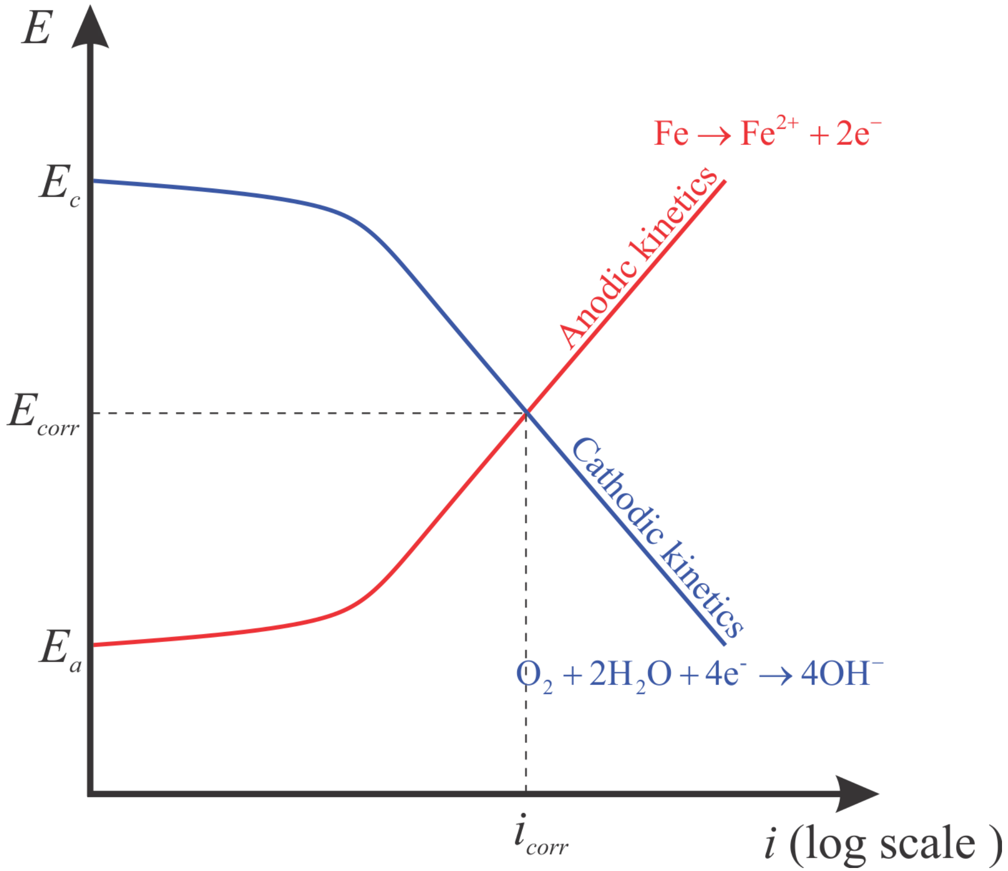
1) The ferrous ions (Fe^{++}) oxidize further to ferric ions (Fe^{+++}). The last products react with hydroxyl ions (OH^{-}) and produce ferric hydroxide ($FeOH_3$), the well-known **rust**.
2) The **anodic reaction** is responsible for **metal consumption**, while the **cathodic** one for the consumption of the electrolyte constituents (e.g., O_2)
3) The summation of the two reactions yields the overall corrosion reaction, where the electrons disappear, i.e:

$$2Fe + O_2 + 2H_2O \rightarrow 2Fe^{++} + 4OH^{-}$$

4) Consequently, at the overall corrosion reaction, the law of **conservation of charge**, which states that **electric charge** can neither be created nor destroyed, is valid. In other words, electrons are always released and consumed at the same rate!
5) Thus, the anodic reaction, and consequently the metal loss, can not occur without the corresponding cathodic one. Therefore, controlling the cathodic reaction rate, the rate of the anodic one can also be controlled, and **consequently the rate of corrosion**!
6) The anodic reaction may occur at an extended surface of the metal (uniform corrosion) or locally at a relatively small area (pit corrosion, crevice corrosion, etc.). The latter case is usually more severe.
7) Due to the formation of hydroxyl ions (OH^{-}), the electrolyte becomes more alkali. As explained later, it favours the formation of calcareous deposit and generates a more benign environment for steel. It is crucial any coating applied to the surface should be able to tolerate the alkali produced (e.g., oil-based and oleo-resinous paints are inappropriate).

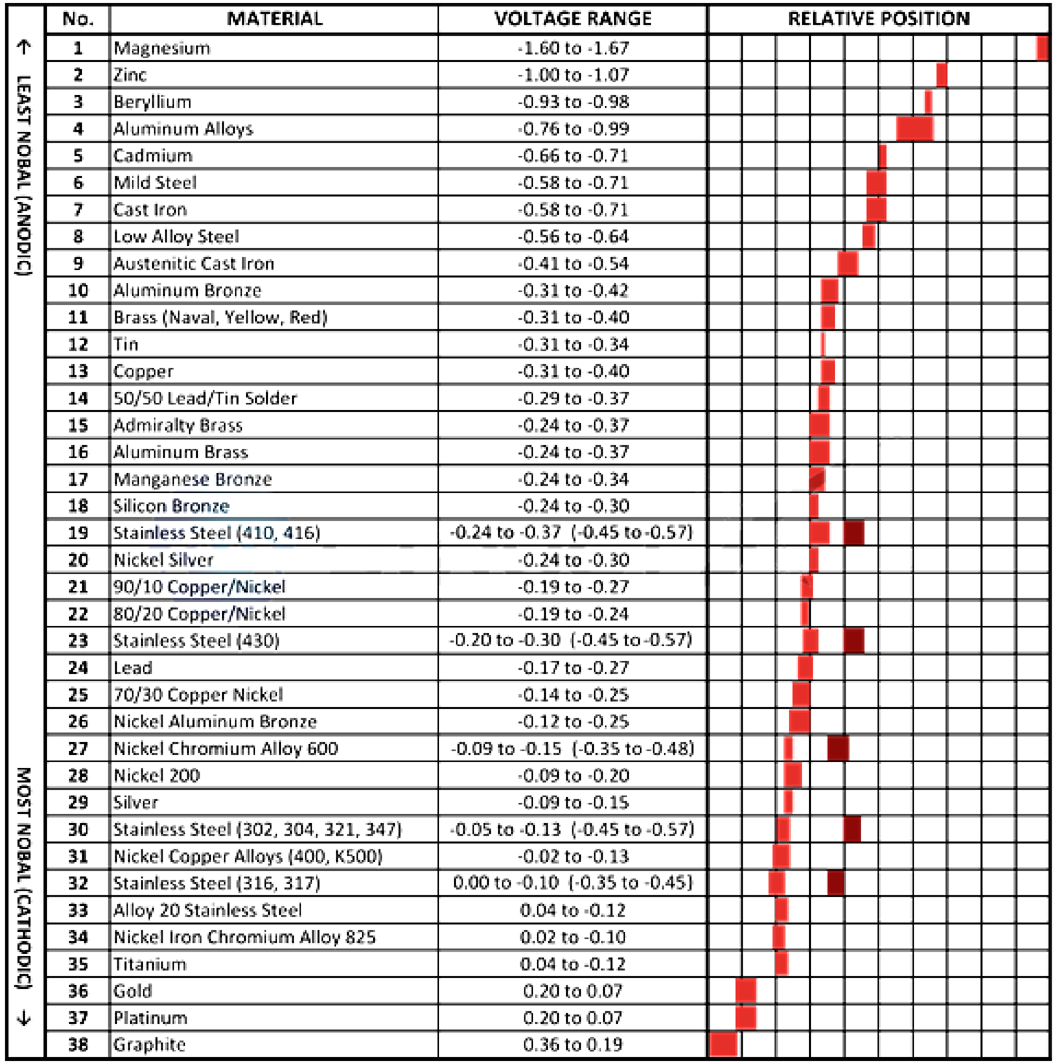
CORROSION PRINCIPLES OF METALS

The polarization diagrams of anodic and cathodic reactions can be schematically represented as follows:



- The anodic and cathodic reaction rates are analogous to the rate that electrons are released and consumed, respectively. For convenience, the **electron rates** are represented by an **electric current density *i***.
- ***E_a* is the potential equilibrium of the anodic reaction**. At E_a no electrons are released, and thus, the anodic reaction rate is zero. Following the “anodic kinetics” curve, the anodic reaction rate increases as the potential become more positive.
- Similarly, ***E_c* is the potential equilibrium of the cathodic reaction**. At E_c, no available electrons exist to be consumed; thus, the cathodic reaction rate is zero. Following the “cathodic kinetics” curve, as the potential becomes more negative, the cathodic reaction rate increases.
- Since the electrons are released and consumed at the same rate, **the electrode is forced to equilibrium at the intersection point** of the “anodic kinetics” and “cathodic kinetics” curves, where the released and the consumed currents are equal. The equilibrium potential and current of the electrode (i.e. of the overall corrosion reaction) are known as E_{corr} and i_{corr}, respectively.
- **E_{corr}** (known as corrosion potential or open circuit potential) is the **potential** exerted by the electrode of a **corroding metal** immersed or buried in a **specific electrolyte**, while **i_{corr}** is an electrical representation of **its corrosion rate.**

CORROSION PRINCIPLES OF METALS



↑ LEAST NOBAL (ANODIC)

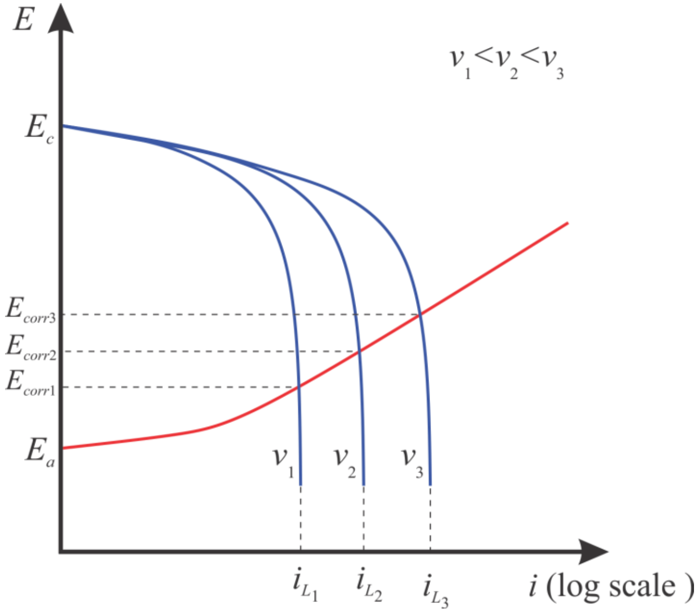
No.	MATERIAL	VOLTAGE RANGE	RELATIVE POSITION
1	Magnesium	-1.60 to -1.67	
2	Zinc	-1.00 to -1.07	
3	Beryllium	-0.93 to -0.98	
4	Aluminum Alloys	-0.76 to -0.99	
5	Cadmium	-0.66 to -0.71	
6	Mild Steel	-0.58 to -0.71	
7	Cast Iron	-0.58 to -0.71	
8	Low Alloy Steel	-0.56 to -0.64	
9	Austenitic Cast Iron	-0.41 to -0.54	
10	Aluminum Bronze	-0.31 to -0.42	
11	Brass (Naval, Yellow, Red)	-0.31 to -0.40	
12	Tin	-0.31 to -0.34	
13	Copper	-0.31 to -0.40	
14	50/50 Lead/Tin Solder	-0.29 to -0.37	
15	Admiralty Brass	-0.24 to -0.37	
16	Aluminum Brass	-0.24 to -0.37	
17	Manganese Bronze	-0.24 to -0.34	
18	Silicon Bronze	-0.24 to -0.30	
19	Stainless Steel (410, 416)	-0.24 to -0.37 (-0.45 to -0.57)	
20	Nickel Silver	-0.24 to -0.30	
21	90/10 Copper/Nickel	-0.19 to -0.27	
22	80/20 Copper/Nickel	-0.19 to -0.24	
23	Stainless Steel (430)	-0.20 to -0.30 (-0.45 to -0.57)	
24	Lead	-0.17 to -0.27	
25	70/30 Copper Nickel	-0.14 to -0.25	
26	Nickel Aluminum Bronze	-0.12 to -0.25	
27	Nickel Chromium Alloy 600	-0.09 to -0.15 (-0.35 to -0.48)	
28	Nickel 200	-0.09 to -0.20	
29	Silver	-0.09 to -0.15	
30	Stainless Steel (302, 304, 321, 347)	-0.05 to -0.13 (-0.45 to -0.57)	
31	Nickel Copper Alloys (400, K500)	-0.02 to -0.13	
32	Stainless Steel (316, 317)	0.00 to -0.10 (-0.35 to -0.45)	
33	Alloy 20 Stainless Steel	0.04 to -0.12	
34	Nickel Iron Chromium Alloy 825	0.02 to -0.10	
35	Titanium	0.04 to -0.12	
36	Gold	0.20 to 0.07	
37	Platinum	0.20 to 0.07	
38	Graphite	0.36 to 0.19	

MOST NOBAL (CATHODIC) ↓

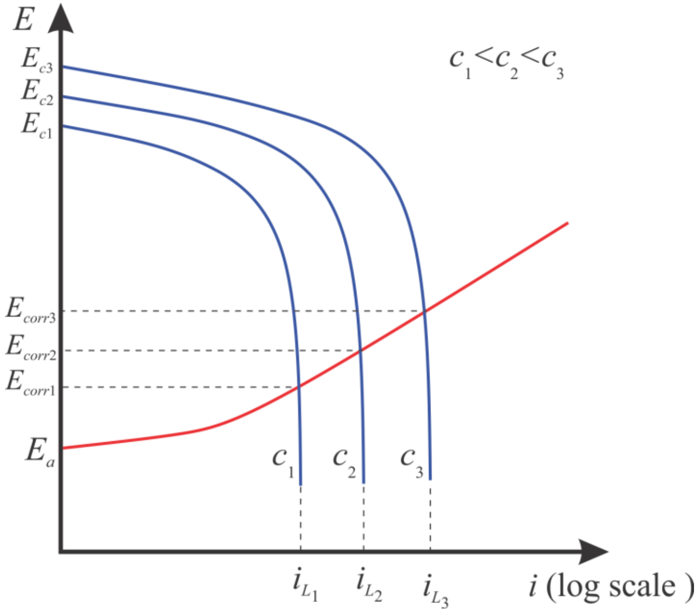
Galvanic series of metals and alloys in seawater
(Potential in V vs Ag/AgCl/seawater)

CORROSION PRINCIPLES OF METALS

Corrosion of steel in seawater: Generally, the anodic reaction at the immersed surface of the steel in seawater is limited by the cathodic reaction rate, which is controlled by the arrival rate of the oxygen at the steel surface. Significant parameters that affect the oxygen arrival are the **dissolved oxygen concentration in the seawater**, the **water flow velocity**. The **solubility of oxygen in seawater** is a function of **temperature** and **salinity** and thus, varies with **depth** and **geographic location**.



Effect on polarization diagram of the water velocity

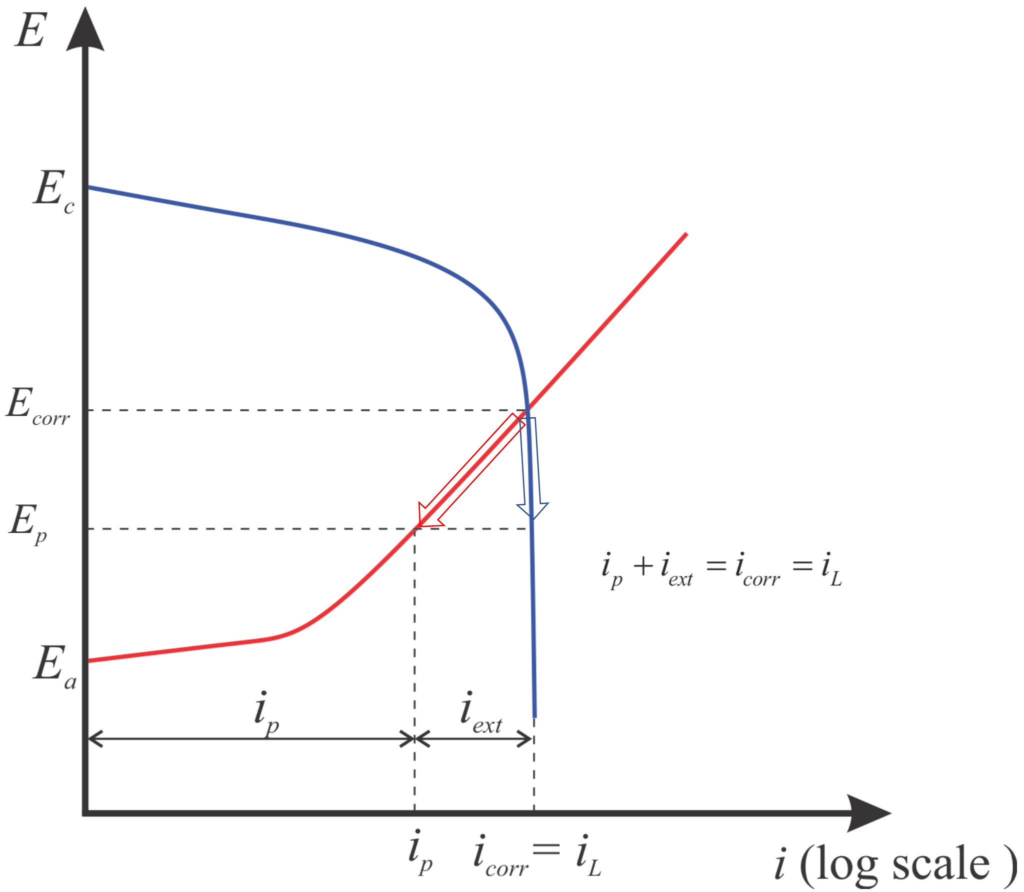


Effect on polarization diagram of the dissolved oxygen concentration in the seawater

Remarks on the "cathodic kinetics" curves

- At first, the cathodic process occurs quickly due to oxygen availability immediately adjacent to the steel surface.
- As soon as the surface concentration of the oxygen falls to zero, a plateau is observed.
- From this point on, **the cathodic reaction rate** (i.e., oxygen reduction) remains **constant**, **equal to i_L (or i_{lim})**.
- In other words, lowering the potential cannot further increase the rate of the process because the kinetics is governed now by the oxygen transfer rate from the bulk of the electrolyte to the surface of the metal, which is a potential independent diffusion process.
- Note: $i_{corr} = i_{lim}$.
- Increasing either the velocity or/and the dissolved oxygen concentration, the limiting current i_{lim} increases.

PRINCIPLES OF CATHODIC PROTECION

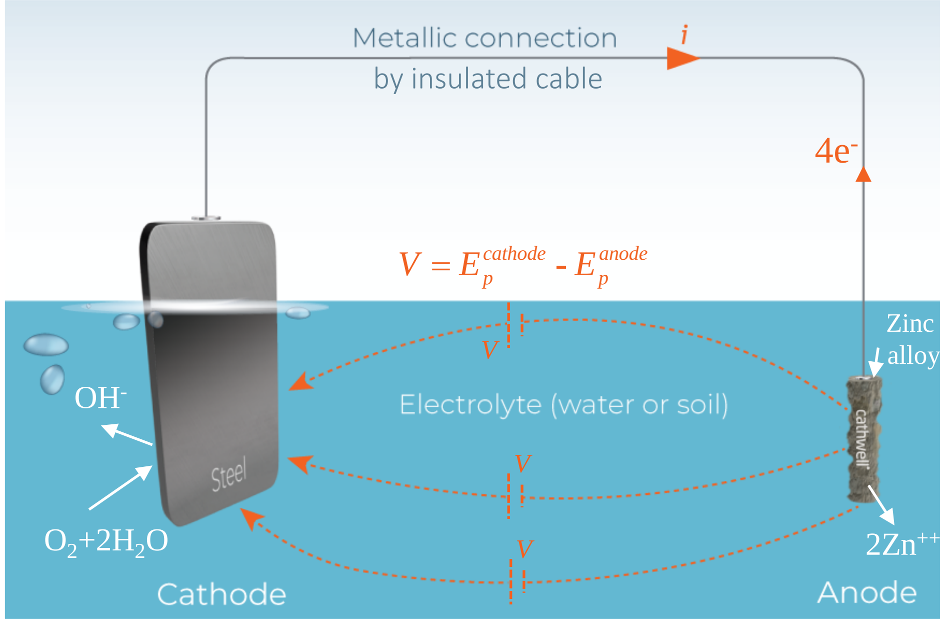


- Let's consider an electrode having at the equilibrium state a corrosion Potential E_{corr} and a corrosion rate i_{corr}.
- Furthermore suppose, an external source supplies electrons i_{ext} to the electrode interface from the bulk metal.
- As a result, the potential becomes more negative, i.e. falls from E_{corr} to a value E_p ($E_p < E_{corr}$).
- At E_p, the anodic reaction rate decreases from i_{corr} to i_p, and therefore, the metal corrodes less.
- **The decreasing of the corrosion potential by supplying an external current is the basis of cathodic protection**.
- Consequently, the cathodic reaction either increases or remains constant if $i_{corr} = i_L$. However, the cathodic process receives now the electrons that it consumes from two sources; a portion i_p from the anodic reaction and a portion i_{ext} from the external source.
- By providing external current $i_{ext} = i_{corr}$ the potential decreases to E_a, and the corrosion is completely stopped.
- Because the anodic kinetics curve is approximately logarithmic, a small polarization (negative shift) gives a large benefit in terms of protection, i.e. the metal is partially protected with some economy in current supplied.

CATHODIC PROTECION METHODS

❖ Sacrificial anode cathodic protection (SACP)

- In this method, **the required electrons** to polarize the steel surface to be protected **are provided using another dissimilar metal** immersed in the **same electrolyte**.
- The corresponding **electrodes**, having corrosion potentials E^c_{corr} and E^a_{corr} respectively, **are electrically connected via the electrolyte** and **a metallic connection** and thus, form a **galvanic cell** (close circuit).
- **The initial electromotive force** (emf) to drive the current is the **positive difference (voltage) of the corrosion potentials** $E^c_{corr} - E^a_{corr} > 0$, with $E^a_{corr} < E^c_{corr}$. I.e., to achieve **positive voltage**, a **more electronegative metal than steel** must be used.
- From an electrochemical point of view, the **more negative electrode** releases electrons to the circuit, dissolves more rapidly than its open circuit equilibrium E^a_{corr}. I.e., **it is sacrificed** and is called that behaves as an **anode**.
- In contrast, **steel** dissolves less, i.e., **it is protected** and acts as a **cathode**.
- To protect steel in seawater **zinc**, **aluminum** or **magnesium** alloys are used as sacrificial anodes.
- They are attached to the steel structure via their steel core, establishing the required metallic connection to transfer the electrons.



CATHODIC PROTECION METHODS

- **Sacrificial anode cathodic protection (SACP)**

Recommended compositional limits for Al-based and Zn-based anode materials (DNV)

Alloying/impurity element	Zn-base	Al-base
Zn	rem.	2.5-5.75
Al	0.10-0.50	rem.
In	na	0.015-0.040
Cd	< 0.07	< 0.002
Si	na	< 0.12
Fe	< 0.005	< 0.09
Cu	< 0.005	< 0.003
Pb	< 0.006	na

Recommended design anode materials properties at seawater (DNV)

Anode material type	Environment	Electrochemical capacity (Ah/kg)	Closed circuit potential (V)
Al-based	seawater	2,000	-1.05
	sediments	1,500	-0.95
Zn-based	seawater	780	-1.00
	sediments	700	-0.95

CATHODIC PROTECION METHODS

❖ Sacrificial anode cathodic protection (SACP)

Sacrificial anodes are available in different weights, dimensions, different inserts and mounting options


Platform anodes


Hull anodes

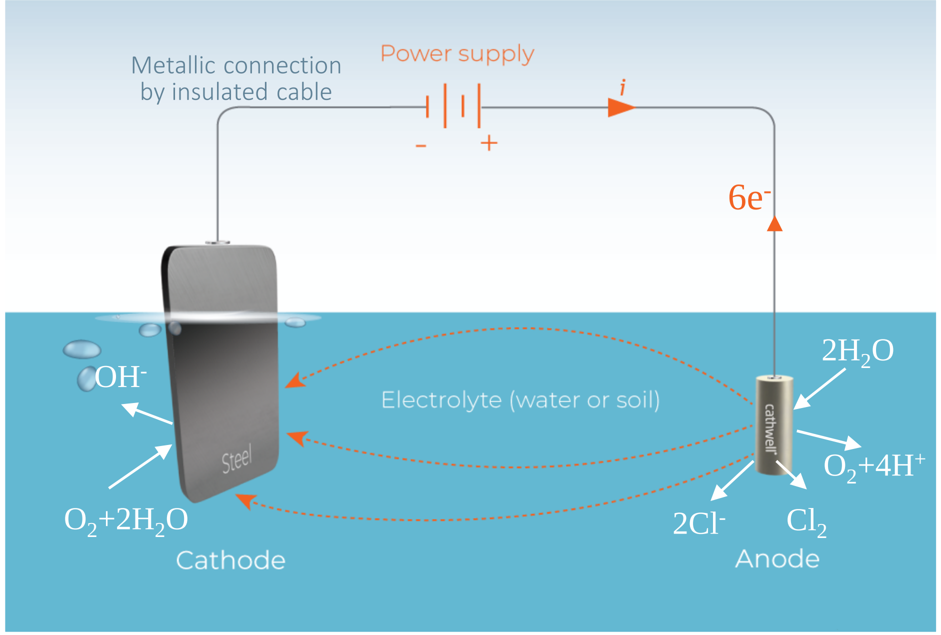

Pipeline bracelet anodes


Pier & piling anodes

Other type of anodes

CATHODIC PROTECION METHODS

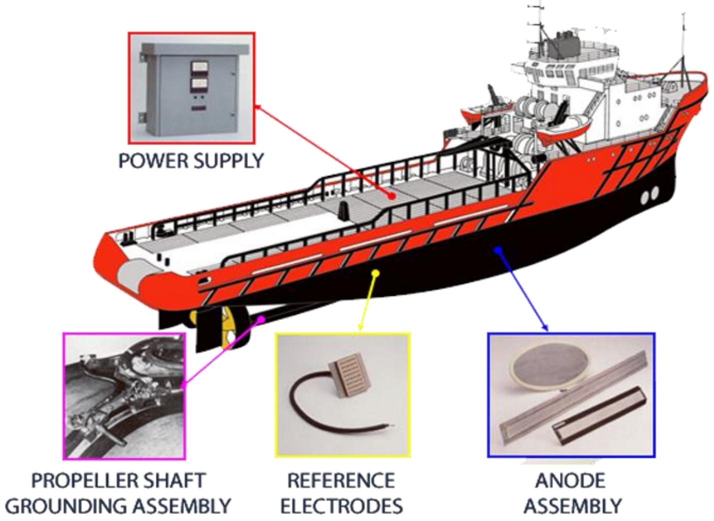
❖ Impressed Current cathodic protection (ICCP)



- In this method, **the driving voltage** to polarize the steel surface to be protected is a **direct current (DC) external power source**. Usually, the DC is produced by an altering current transformer rectifier.
- Consequently, there is no need for anodes made by more electronegative metals than steel to be used. Using noble metals for anodes is a significant advantage because these materials do not dissolve on anodic polarization and practically remain unconsumed (inert anodes). The anodic reactions which provide **the required electrons** involve decomposition of the electrolyte compounds, such as:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^- \quad \text{and} \quad 2Cl^- \rightarrow Cl_2 + 2e^-$$

- Inert anodes are usually made of graphite, thin coatings of platinum, etc.
- The metallic connection must be performed in the right direction, i.e., the **positive pole** of the external power is connected **to the anode**, while its **negative pole** is attached **to the structure**.
- In an **ICCP system**, since the driving voltage can be significantly larger than in an SACP one, **a few anodes are enough** to protect large uncoated surfaces, even if they are embedded in high resistivity electrolytes.
- A **dielectric shield** should usually be applied **in the vicinity of the anodes** to prevent extremely high current densities and **avoid undesired over-polarization** (will be explained later). Dielectric shield materials include epoxy materials, coal-tar epoxy resins, polyurethane coatings, rubber coatings, etc.
- Furthermore, potential sensors (**reference electrodes**) are used, **adjusting the delivered current automatically** to achieve the desired predefined protection potential.

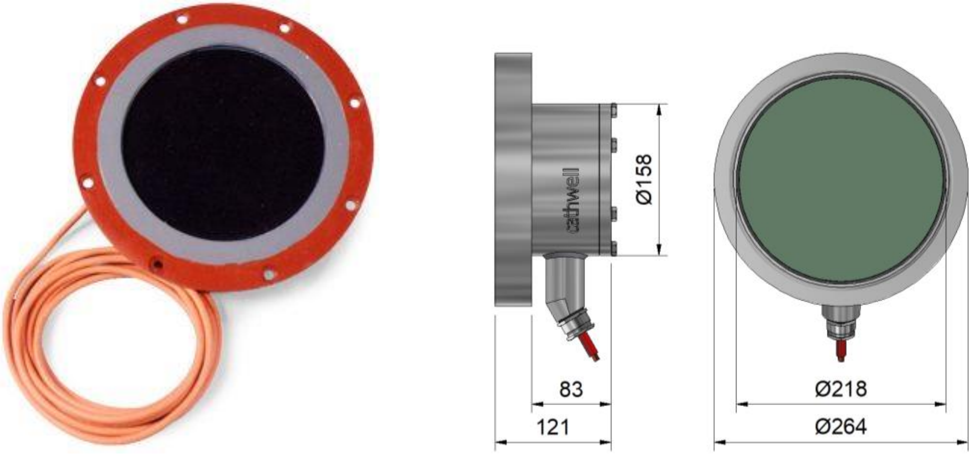


CATHODIC PROTECION METHODS

❖ Impressed Current cathodic protection (ICCP)

Anode for ICCP systems are available in different shape and mounting options, delivering current up to 350A.

Elliptical anodes



Disc anodes

Linear anodes

Linear loop anodes

CATHODIC PROTECION METHODS

SACP vs. ICCP systems

	Advantages	Disadvantages
Sacrificial Anode Cathodic Protection (SACP)	No need for external power source	Current output is limited. It has limited driving potential
	Less complex installation	
	Uniform distribution of current	Poorly coated structures need more anodes
	Minimum maintenance	
	Minimum cathodic interference	The system is ineffective in high resistivity environments

	Advantages	Disadvantages
Impressed Current Cathodic Protection (ICCP)	The system is adjustable	Overprotection leads to coating damage and hydrogen embrittlement
	High current can be impressed with a single ground bed	
	Single installation can protect larger metallic surface	The system is affected by interference problems
	Uncoated and poorly coated structures can be effectively protected	
	Voltage and current can be varied to meet changing conditions over time	External power is necessary, thus the system is vulnerable to power failure

REFERENCE ELECTRODES

To measure the potential of an electrode (structure/electrolyte potential), a second electrode, with defined and reproducible potential with respect to its electrolyte (a so-called reference electrode) must be used.

The reference electrodes most used for marine CP systems are Silver/Silver chloride/seawater (Ag/AgCl/seawater) and Zinc/seawater. The latter is cheaper, but the former is more accurate.

The potentials of various reference electrodes with respect to standard hydrogen electrode (SHE or NHE) at 25^{o}C are given in the following table.

Electrode	Potential shift (Volt)
Silver/silver chloride/saturated KCl	+0.20
Silver/silver chloride/seawater	+0.25
Calomel (normal KCl)	+0.28
Calomel (saturated KCl)	+0.24
Zinc/seawater	-0.78

Silver/silver chloride reference electrode

Zinc reference electrode

PROTECTION CRITERIA

Steel

- ***Minimum negative potential level***

As already mentioned, the corrosion is completely stopped at a steel surface, decreasing the potential from E_{corr} to E_a by providing external current. However, to achieve this, an excessive amount of current is required, which is not practical from an economic point of view. Experiments and experience have shown that when **carbon steel in aerated sea water** is polarized up to **-0.80V (Ag/AgCl/sw RE)**, the corrosion rate decreases to an acceptable level. Consequently, this is the general the minimum negative potential level used for the cathodic protection of carbon steel in aerated sea water.

In case of steel in **anaerobic conditions** (e.g. some seabed muds), due to the possibility of microbially-assisted corrosion, the accepted minimum negative potential level is **-0.90V (Ag/AgCl/sw RE).**

- ***Maximum negative potential level – Over-protection***

Excessive polarization of steel (to values below E_a) energies a second cathodic reaction. This is the **electrolysis of water** that produces hydrogen gas:

$$2H_2O + 2e^- \rightarrow 2OH^- + H_2$$

Beyond the current waste, this situation (so-called **over-protection**) can be highly damaging because the hydrogen gas generation may disrupt the protective calcareous deposits (see slide 20). Furthermore, it can cause delamination of the coating/paint and embrittlement of the steel, especially in the case of high strength steel (yield strengths >700MPa).

For **mild steel**, a maximum negative potential limit of **-1.1V (Ag/AgCl/sw RE)** is generally accepted, while for **high strength steels**, due to the risk of hydrogen embrittlement, this limit is lower, equal to **-0.95V (Ag/AgCl/sw RE)**.

PROTECTION CRITERIA

❖ Recommended potentials for the cathodic protection of various metals in seawater (BS EN)

Material	Minimum negative potential (Volt vs Ag/AgCl/seawater)	Maximum negative potential (Volt vs Ag/AgCl/seawater)
Iron and steel		
Aerobic environment	-0,80	-1,10
Anaerobic environment	-0,90	-1,10
High strength steels	-0,80	-0,95^1
Aluminum alloys (Al Mg & Al Mg Si)	-0,80 (negative potential swing 0,10 V)	-1,10
Stainless steel Austenitic steel		
(PREN^2 ≥ 40)	-0,30	no limit
(PREN < 40)	-0,60	no limit
Duplex	-0,60	High negative potential should be avoided
Copper alloys		
Without aluminum	-0,45 to -0,60	no limit
With aluminum	-0,45 to -0,60	-1,10
Nickel base alloys	-0,20	High negative potential should be avoided

Notes: 1) For high strength steel susceptible to hydrogen assisted cracking the limit is -0.83V vs Ag/AgCl/seawater.
2) PREN = Cr%+3.3Mo%+16%N

ENVIROMENTAL FACTORS ON CURRENT DEMAND

The current required to achieve the recommended potentials for cathodic protection depends on several environmental factors.

- **Dissolved oxygen**

As already mentioned, (Slide 9), the dissolved oxygen in the electrolyte is correlated with the corrosion rate. Consequently, the required current density for protection is proportional to the rate of dissolved oxygen that diffuses to the steel surface. The dissolved **oxygen concentration** in seawater **decreases** as **water depth**, **temperature** and **salinity increase**.

Furthermore, **sea currents and waves increase** the transfer rate of the dissolved oxygen to the steel surface and, thus, the **current density requirement** for cathodic protection.

- **Calcareous deposits**

When the cathodic protection is applied, the anodic reaction rate is lower, but the cathodic one remains energized. Thus, an excess amount of hydroxyl ions is produced at the steel surface. This high concentration of hydroxyl ions triggers a few other reactions, the products of which are calcium carbonate ($CaCO_3$) and magnesium hydroxide ($Mg(OH)_2$).

Both products are insoluble and **form a protective film** at the steel surface, known as **calcareous deposit**, which acts as a paint coating.

Thus, after a high initial temporary current density requirement for a rapid cathodic polarization to form a high protective the calcareous film, a significant decrease in demand is observed.

Note that **mechanical damage** (e.g., during a storm) or **excessive hydrogen** generation may **damage the film**. Thus, the cathodic protection system at any time, even at the end of its design life, must be capable of delivering increased current to depolarize the steel surface and reform the calcareous deposit. The above-mentioned current demands, the first for the initial polarization, the second since the calcareous deposit is formed, and the third for the repolarization after a damage of the film, are referred to standards and recommendations as **initial**, **maintenance or mean** and **final**, respectively.

CURRENT DEMANDS FOR DESIGN CP SYSTEMS

Recommended by **DNV** initial, mean and final design current densities (A/m^2) for seawater exposed bare steel metal surfaces as a function of depth and climatic region based on surface water temperature

Depth (m)	Tropical (> 20 °C)			Sub-tropical (12- 20 °C)			Temperate (7-11 °C)			Arctic (< 7 °C)		
	initial	mean	final	initial	mean	Final	initial	mean	final	initial	mean	Final
0-30	0.150	0.070	0.100	0.170	0.080	0.110	0.200	0.100	0.130	0.250	0.120	0.170
>30-100	0.120	0.060	0.080	0.140	0.070	0.090	0.170	0.080	0.110	0.200	0.100	0.130
>100-300	0.140	0.070	0.090	0.160	0.080	0.110	0.190	0.090	0.140	0.220	0.110	0.170
>300	0.180	0.090	0.130	0.200	0.100	0.150	0.220	0.110	0.170	0.220	0.110	0.170

Recommended by **NACE** initial, mean and final design current densities (mA/m^2) for seawater exposed bare steel metal surfaces for various productive areas

Production Area	Water Resistivity (ohm-cm)	Water Temp. (°C)	Wave Action	Lateral Water Flow	Current density demand (mA/m^2)			Slope ohm-m^2
					Initial	Mean	Final	
Gulf of Mexico	20	22	Moderate	Moderate	110	55	75	4.1
U.S. West Coast	24	15	Moderate	Moderate	150	90	100	3.0
Cook Inlet	50	2	Low	High	430	380	380	1.0
Northern North Sea	26 to 33	0 to 12	High	Moderate	180	90	120	2.5
Southern North Sea	26 to 33	0 to 12	High	Moderate	150	90	100	3.0
Arabian Gulf	15	30	Moderate	Low	130	65	90	3.5
Australia	23 to 30	12 to 18	High	Moderate	130	90	90	3.5
Brazil	20	15 to 20	Moderate	High	180	65	90	2.5
West Africa	20 to 30	5 to 21	Low	Low	130	65	90	3.5
Indonesia	19	24	Moderate	Moderate	110	55	75	4.1
South China Sea	18	30	Low	Low	100	35	35	

PROTECTIVE COATINGS

- **Organic coatings**

  Organic coatings are semi-permeable membranes. If applied well on the surface to be protected, **act as a barrier** to oxygen and water and delay corrosion.

  However, bulk **corrosion occurs** at the base of existing **holidays, bare patches and pinholes**. The paint does the primary protection, but the cathodic protection reinforces it at the weak spots.

  The coating, reducing the exposed area to the corrosive environment, decreases the total current requirement for protection, improves the potential distribution and reduces the interference effects.

  In fact, coatings and cathodic protection complement each other. The coatings save current, and the cathodic protection acts complementary at mechanically damaged areas, at weak spots and as the coating degrades with time.

  Coating systems may integrate several layers of different types of coatings, however, the compatibility between the coats (layers) must be ensured.

- **Metallic coatings**

  Metallic coatings are generally composed by non-ferrous metals, usually zinc, aluminum and its alloys. Non-ferrous metals are more electronegative than carbon steel. These metallic coatings provide protection to steel structures against corrosion by both galvanic action and barrier. Moreover, the metallic coatings protect steel sacrificially at damaged areas or at small pores in the coatings.

The ideal coating system should assure the proper performance of the structure during its service life without requiring structural repairs. The major factors to be considered in the selection of a coating system are: 1) the type of structure and its importance, 2) environmental conditions, 3) service life, 4) required durability, 4) coating performance, and 5) costs including its application and surface preparation.

PROTECTIVE COATINGS

- **Classification of paint coating systems according to EN ISO 12944-5:2007**

Paint Coating Types Classification		Typical Examples	Typical Binders
Irreversible coatings	Air-drying paints (oxidative curing)	–	Epoxy ester Alkyd Urethane alkyd
	Water-borne paints (single pack)	– – –	Polyurethane resins (PU) Acrylic polymers Vinyl polymers
	Chemically curing paints	Epoxy paints (two-pack)	Epoxy Epoxy vinyl/epoxy acrylic Epoxy combinations
		Polyurethane paints (two-pack)	Polyester Acrylic Fluoro resin Polyether Polyurethane combinations
	Moisture-curing paints	– – –	Ethyl silicate (one-pack) Ethyl silicate (two-pack) Polyurethane (one-pack)
Reversible coatings	– – –	– – –	Chlorinated rubber Vinyl chloride copolymers Acrylic polymers

PROTECTIVE COATINGS

- **Classification of paint coating systems according to DNV**

Category	Coating System	Applied Layers	Total nominal dry film thickness (μm)
I	Epoxy paint coating	One	20
II	Marine paint coating (epoxy, polyurethane or vinyl based)	One or more	250
III	Marine paint coating (epoxy, polyurethane or vinyl based)	Two or more	350

PROTECTIVE COATINGS

- **Coating breakdown factors**

Coatings deteriorate with time due to mechanical damage, erosional effects of waves and current and cleaning operations to remove marine growth.

The coating deterioration is considered in the design of a CP system, introducing the **so-called breakdown factor**, f_c. The factor f_c describes the anticipated reduction in cathodic current density due to the application of an electrically insulating coating. When $f_c = 0$, the coating is considered fully (100%) electrically insulating, i.e., the cathodic current density demand becomes zero. When $f_c = 1$ the coating has no protective properties, and the current density would be the same as for a bare steel surface.

DNV recommends the use of a simple linear model to describe coating deterioration, i.e.,

$$f_c(t) = a + b \cdot t$$

where t (years) is the coating age and a and b are constants depended on coating properties and environment. The constant a stands for an initial coating breakdown factor related mainly to mechanical damage occurring during the installation of the structure, while b represents a coating deterioration rate to take into account the coating ageing and possible small mechanical damage occurring to the coating during the structure life.

Recommended by DNV values of *a* and *b* for coating categories I, II and III

Depth	**I**	**II**	**III**
(m)	$a = 0.10$	$a = 0.05$	$a = 0.02$
0-30	$b = 0.10$	$b = 0.025$	$b = 0.012$
>30	$b = 0.05$	$b = 0.015$	$b = 0.008$

CORROSION ALLOWANCE

In cases where corrosion cannot be mitigated at an acceptable level (via cathodic protection or/and a protective coating), an additional metal thickness to the wall is added, the so-called corrosion allowance (CA).

Indicatively for offshore wind turbines, DNV recommends the CA of surfaces of primary structural parts exposed in the splash zone (the term will be explained later) with and without coating shall be calculated as

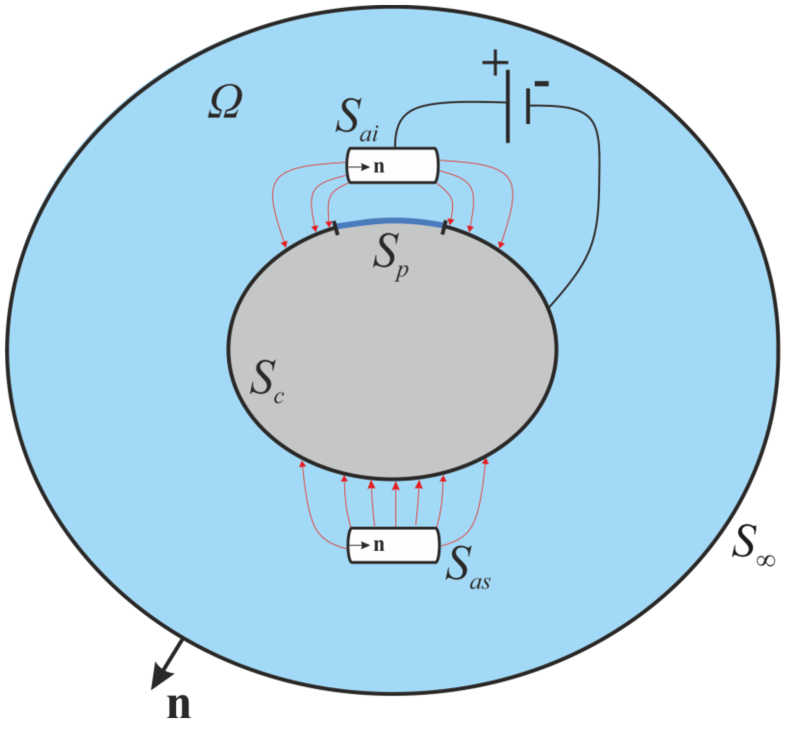
$$CA = V_{corr}\left(T_d - T_c\right)$$

where V_{corr} is the expected maximum rate, T_c is the design life of the coating as provided by the manufacturer and T_d the design life of the structure. Minimum values for design corrosion rate are given in the following table.

Region	**V_{corr} External Surface**	**V_{corr} Internal Surface**
Temperate climate (annual mean surface temperature of seawater ≤ 12ºC)	0.30 mm/yr	0.10 mm/yr
Subtropical and tropical climate	0.40 mm/yr	0.20 mm/yr

MODELLING FOR THE DESIGN CP SYSTEMS

- **Formulation of the mathematical problem**



Consider a metallic structure with cathodic and anodic surfaces S (=$S_c \cup S_p$) and S_a (=$S_{as} \cup S_{ai}$), respectively, immersed into an infinitely extended homogeneous isotropic electrolyte Ω of constant conductivity σ. The surface S consists of a cathodic surface S_c and a dielectric shielded S_p, while S_a consists of an impressed current anode S_{ai} and a sacrificial anode S_{as}. The galvanic cell is surrounded by a large artificial boundary S_∞.

The problem is to determine the potential distribution and the current at any point of Ω, including its boundaries *S*.

In the galvanic cell, a current flow appears in the electrolyte, due to the potential difference between anodic and cathodic surfaces. The principle of **charge conservation**, assuming absence of sources and sinks, is described by the equation:

$$\nabla \cdot \mathbf{J} = 0 \ \text{ or } \operatorname{div}\mathbf{J} = 0 \ \text{ or } \frac{\partial J_x}{\partial x} + \frac{\partial J_y}{\partial y} + \frac{\partial J_z}{\partial y} = 0 \tag{1}$$

where $\mathbf{J}(J_x, J_y, J_z)$ the being the current density vector and ∇ the gradient operator.

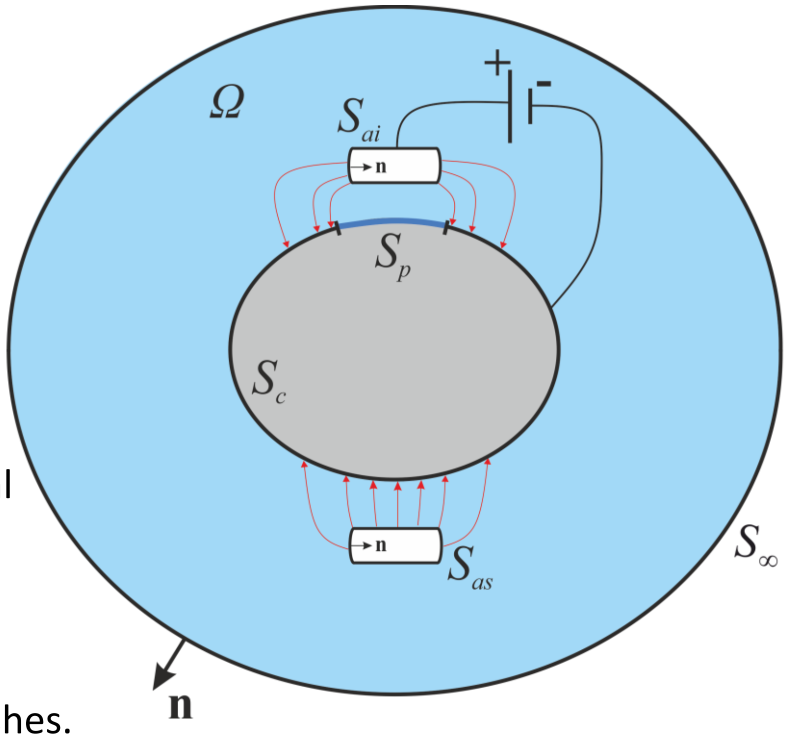
At steady-state conditions, the current density is proportional to the electric potential gradient (**Ohm's law**):

$$\mathbf{J} = \sigma \mathbf{E} = -\sigma \nabla \varphi = -\sigma \left(\frac{\partial \varphi}{\partial x}, \frac{\partial \varphi}{\partial y}, \frac{\partial \varphi}{\partial y} \right) \tag{2}$$

where, the vector $\mathbf{E}$ and the scalar φ stand for the electric field intensity and the electric potential, respectively.

MODELLING FOR THE DESIGN CP SYSTEMS

- **Formulation of the mathematical problem**



Under the assumption of homogenous electrolyte, Eq. (1), in conjunction with Eq. (2), reduces to the **Laplace equation**

$$\nabla^2\varphi = 0 \text{ or } \frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}+\frac{\partial^2\varphi}{\partial z^2}=0 \qquad (3)$$

The current density i at surface with a normal unit vector $\mathbf{n}$, in terms of φ is expressed as follows

$$i=\mathbf{n}\cdot\mathbf{J}=-\sigma\,\mathbf{n}\cdot\nabla\varphi=-\sigma\,\partial_n\varphi \qquad (4)$$

where $\partial_n\varphi=\mathbf{n}\cdot\nabla\varphi$ or $\partial_n\varphi=n_x\frac{\partial\varphi}{\partial x}+n_y\frac{\partial\varphi}{\partial y}+n_z\frac{\partial\varphi}{\partial z}$ is the directional derivative concerning the normal unit vector $\mathbf{n}$.

Boundary conditions

At perfectly electric insulated boundary S_p and at the artificial boundary S_∞ the current density vanishes.

$$i(\mathbf{x})=-\sigma\,\partial_n\varphi(\mathbf{x})=0\ ,\ \ \mathbf{x}\in S_p \qquad (5)$$

$$i(\mathbf{x})=-\sigma\,\partial_n\varphi(\mathbf{x})=0\ ,\ \ \mathbf{x}\in S_\infty \qquad (6)$$

Boundary condition (6), imposed at S_∞, implies that Gauss law, which states that the total electric flux through any closed surface is equal to the total charge enclosed by the surface, is fulfilled.

MODELLING FOR THE DESIGN CP SYSTEMS

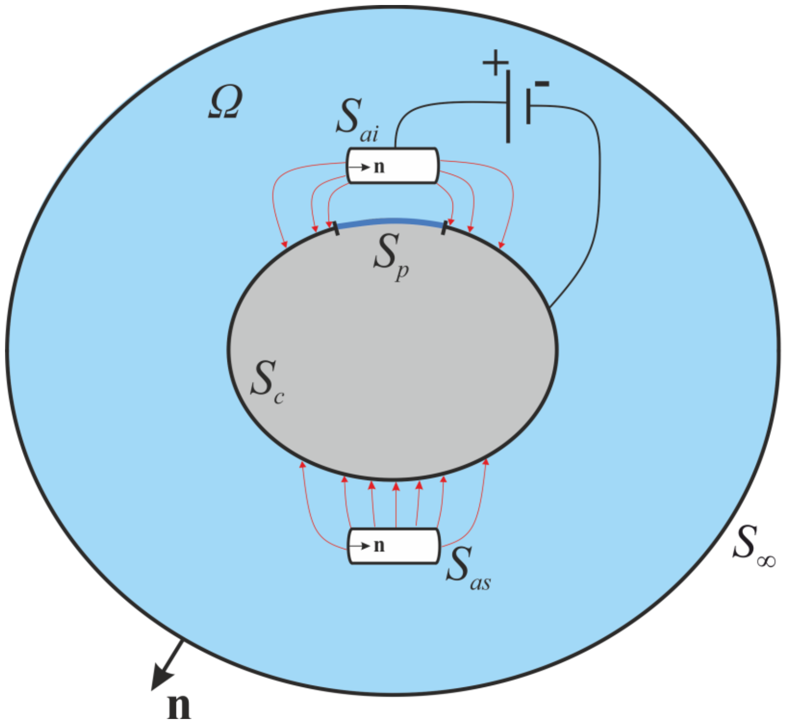
○ Formulation of the mathematical problem

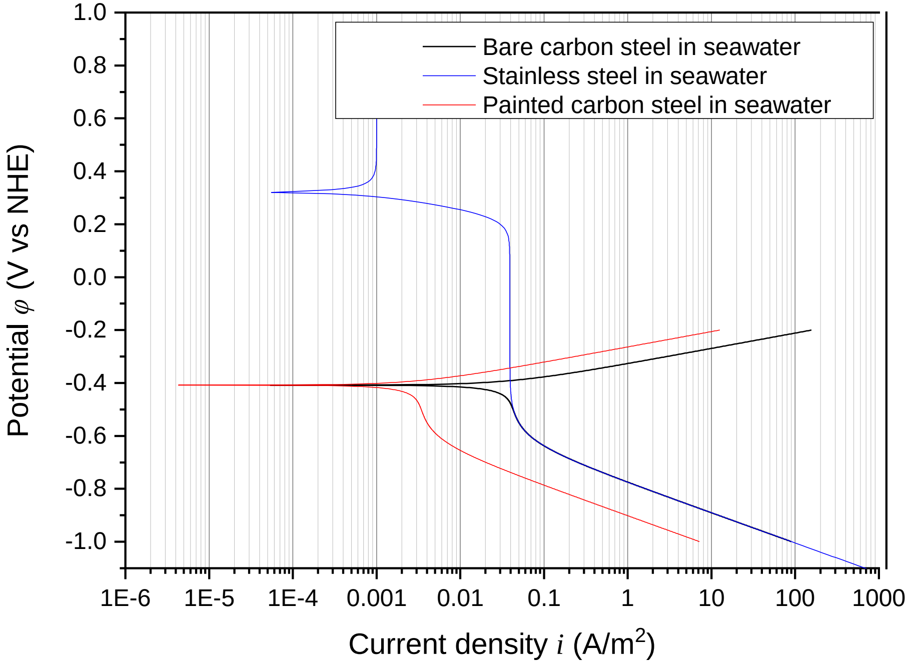
Boundary conditions

At the cathode S_c, a nonlinear Robin boundary condition between potential and current density is imposed, known as polarization curve, which is usually derived experimentally, considering the real conditions of the galvanic cell, i.e.:

$$i_c(\mathbf{x}) = f\left(\varphi_c(\mathbf{x})\right), \mathbf{x} \in S_c \tag{7}$$

with f being the polarization curve at the cathode S_c.



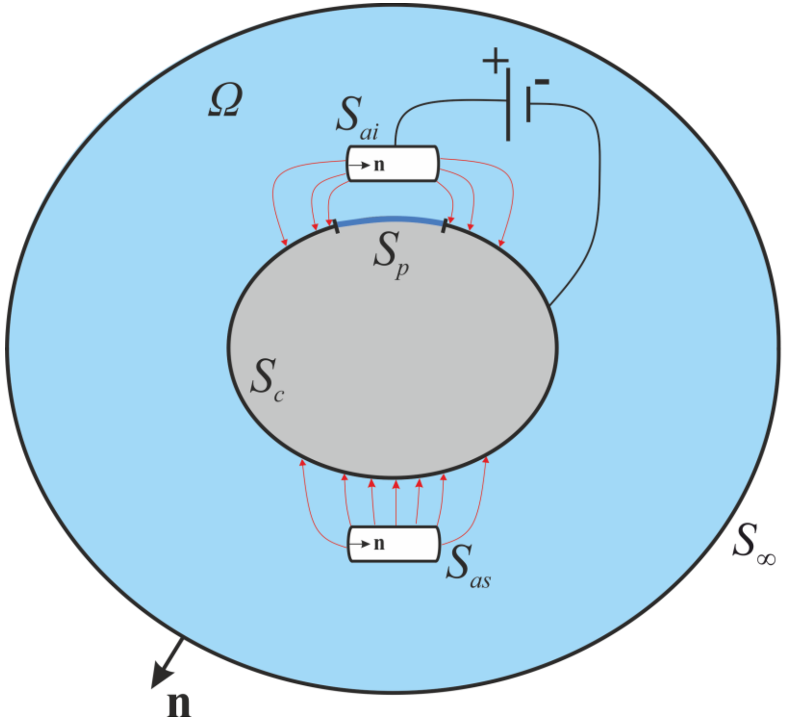


Typical polarization curves; (a) Bare carbon steel, (b) Stainless steel, (c) Painted carbon steel.

MODELLING FOR THE DESIGN CP SYSTEMS

○ Formulation of the mathematical problem

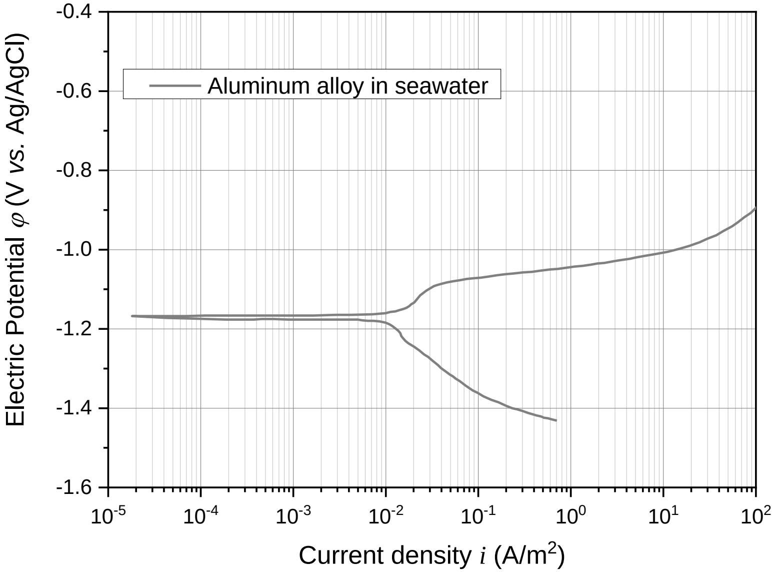
Boundary conditions



At the **sacrificial anode** S_{as}, either constant potential or nonlinear Robin boundary condition between potential and current density is imposed:

$$\left.\begin{array}{c} \varphi_a(x) = \varphi_0 \\ \text{or} \\ J_a(x) = g\left(\varphi_a(x)\right) \end{array}\right\} x \in S_{as} \qquad (8)$$

with g being the polarization curve at the sacrificial anode S_{as}.



Typical polarization curve of an aluminum alloy sacrificial anode

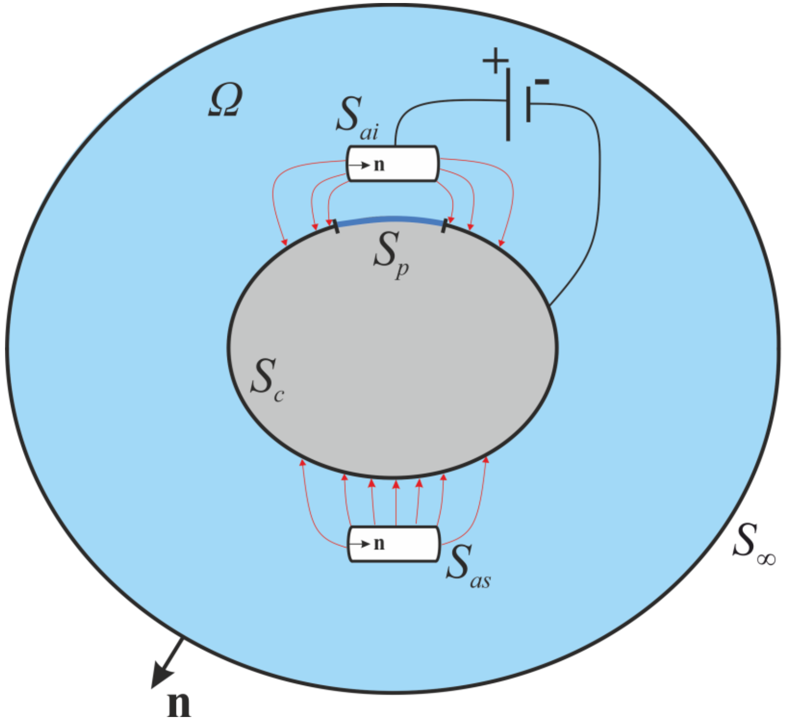
MODELLING FOR THE DESIGN CP SYSTEMS

○ Mathematical formulation of a CP problem

Boundary conditions

At the **impressed anode** S_{ai}, constant current density is imposed:

$$i_a(\mathbf{x}) = -\sigma\,\partial_n\varphi(\mathbf{x}) = i_0 \quad , \quad \mathbf{x}\in S_{ai} \tag{9}$$



○ Solution of a CP problem

The Laplace's equation (3) and the boundary conditions (4)-(9), form a well-imposed boundary value problem, the solution of which can be performed for complex real-life structures numerically, employing one of the following methods:

- ✓ Finite elements (FEM),
- ✓ Finite differences (FDM),
- ✓ **Boundary Elements (BEM)**.

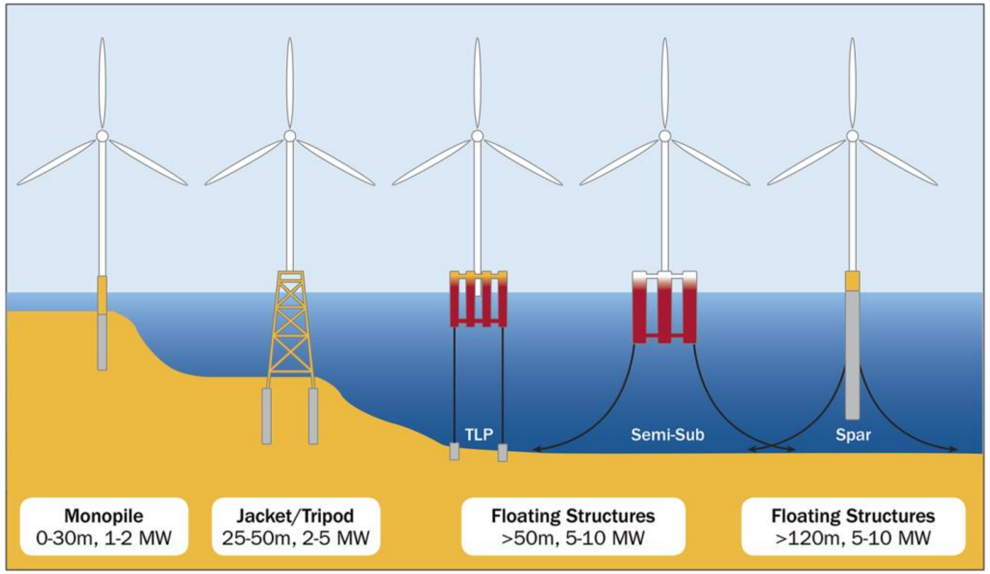
BEM, as compared to FEM and FDM offers two remarkable advantages:

- ✓ The high solution accuracy, especially in terms of current density.
- ✓ The reduction of the dimensionality of the problem by one. Thus, although the electrochemical process occurs, both on surfaces of the structure, as well as, in the volume of electrolyte, only the surfaces (boundaries) are needed to be discretized. **This feature makes the BEM an ideal tool for modelling problems involving infinite and semi-infinite domains**.

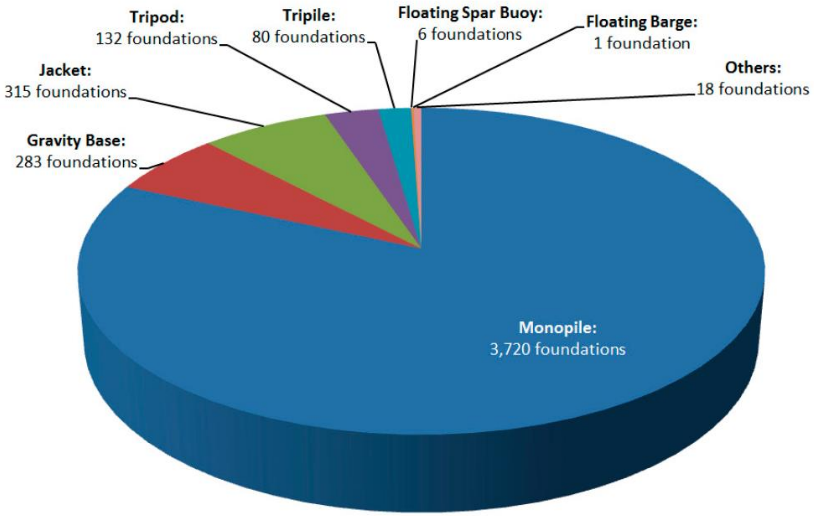
Part 2:

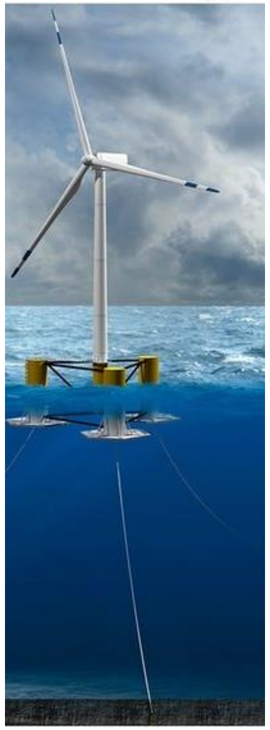
Cathodic Protection for wind Turbines

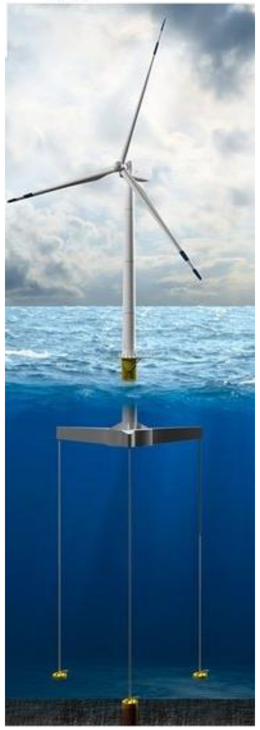
TYPES OF OFFSHORE WIND TURBINE FOUNDATIONS

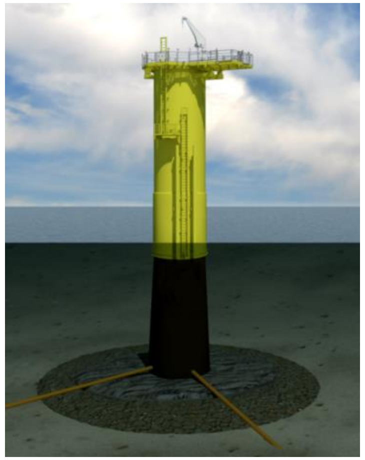


TLP: Tension Leg Platform, Semi-sub: semi-submersible, Spar: Spar Buoy

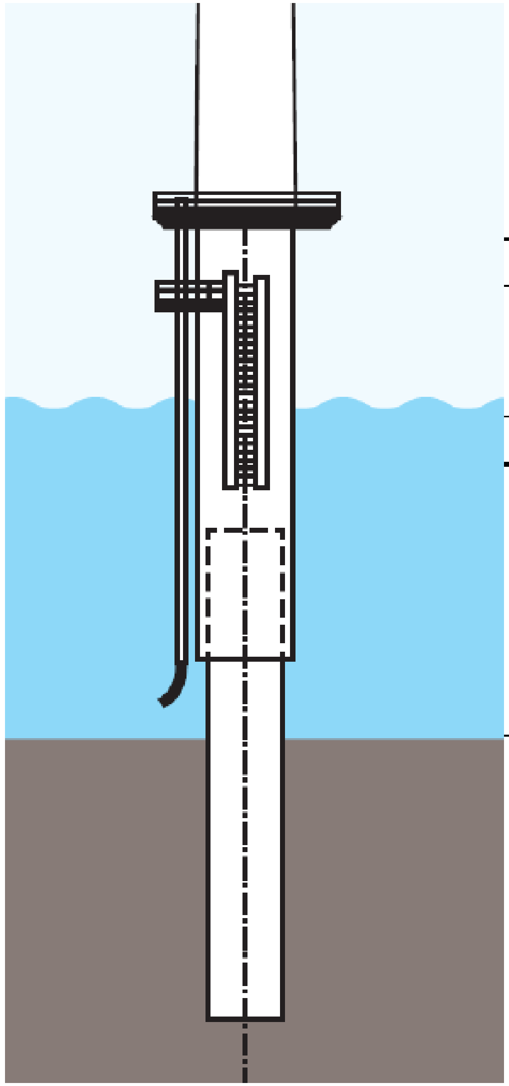


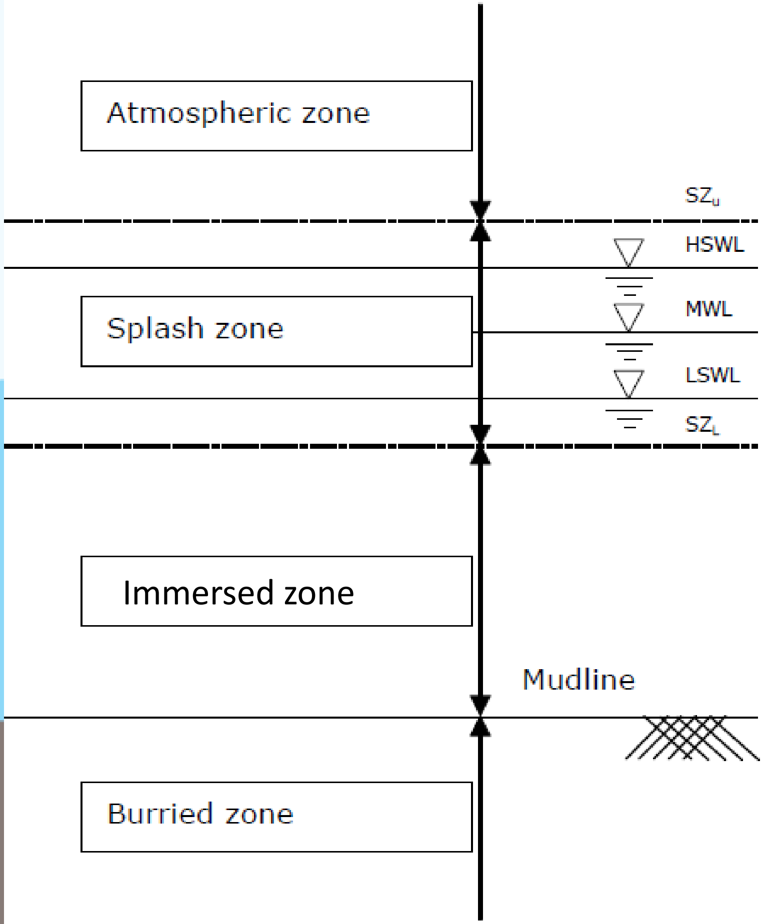






LEVELS AND ZONES IN SEAWATER ENVIRONMENT





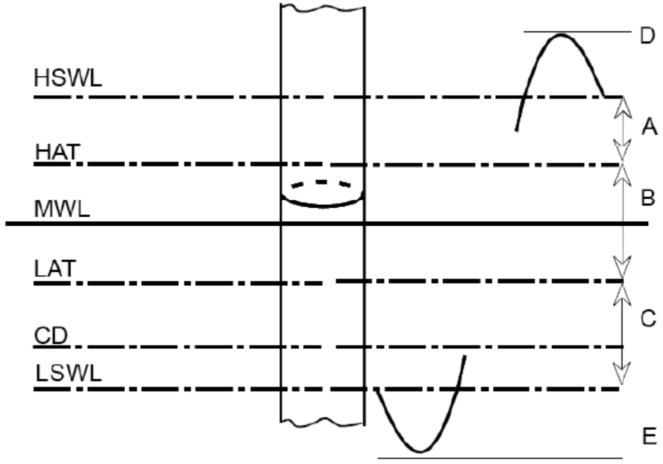
Atmospheric zone

Splash zone

Immersed zone

Burried zone

Note: Both Immersed and buried zones consist the Submerged zone



HSWL highest still water level

HAT highest astronomical tide

MWL mean water level

LAT lowest astronomical tide

CD chart datum (often equal to LAT)

LSWL lowest still water level

A positive storm surge

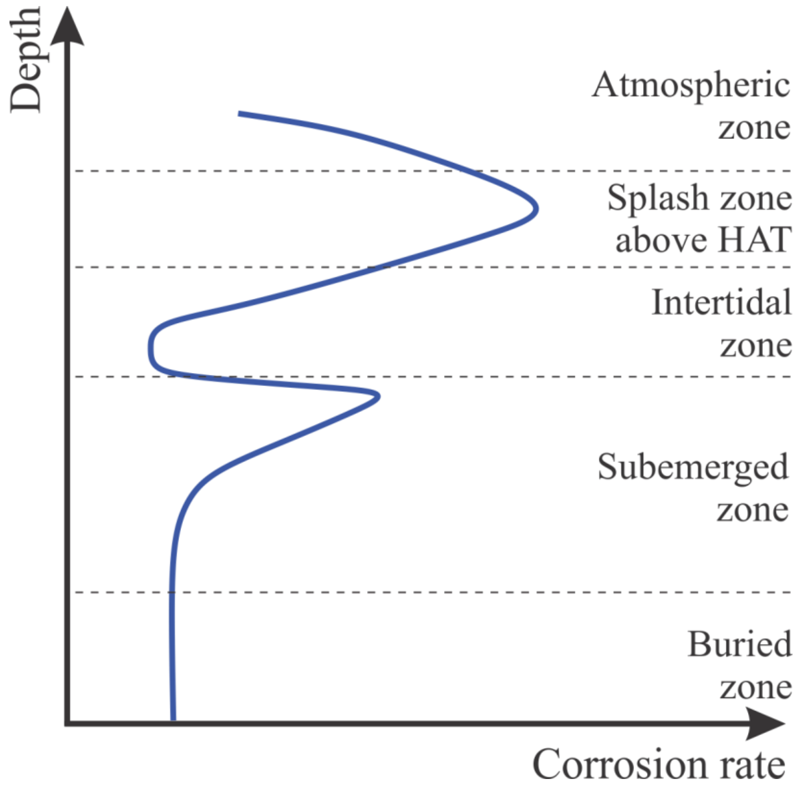
B tidal range

C negative storm surge

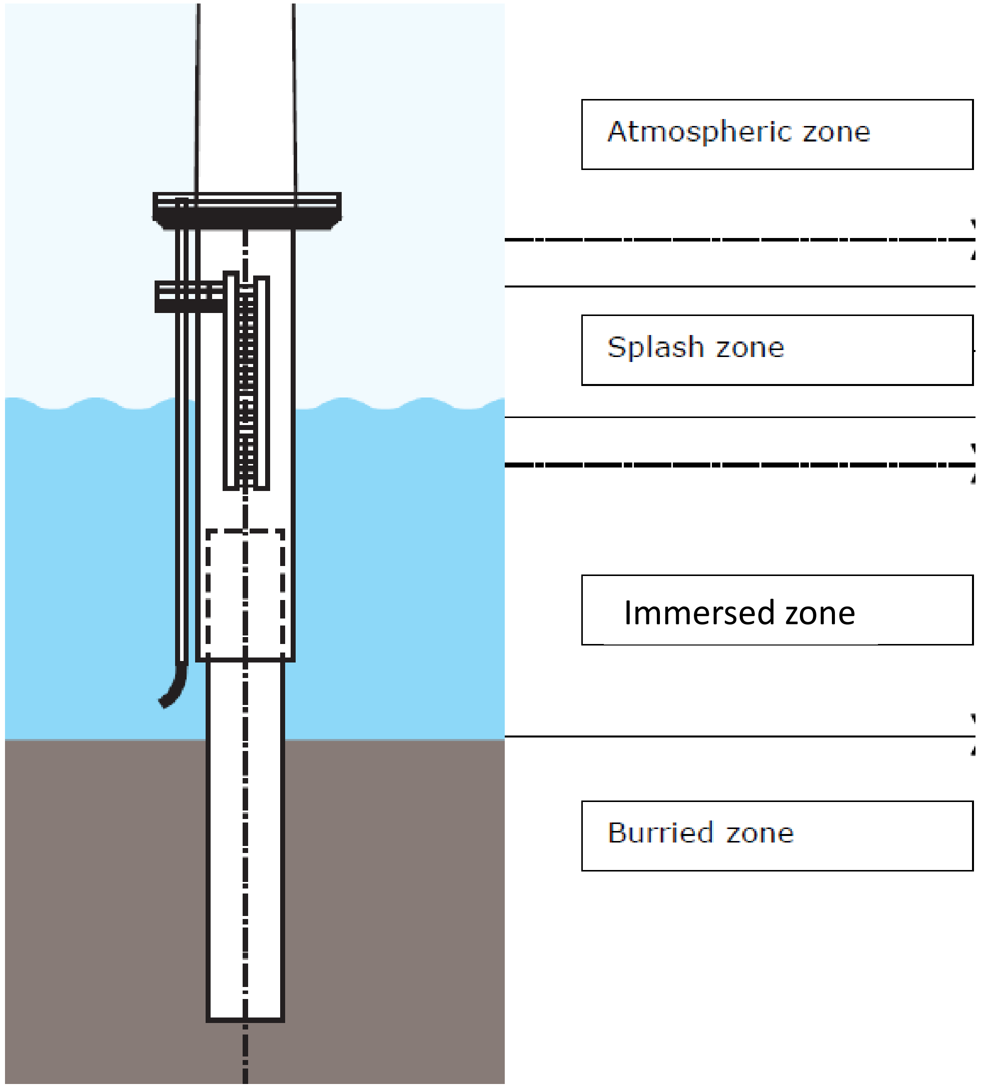
D maximum crest elevation

E minimum trough elevation

CORROSION RATE ALONG DEPTH

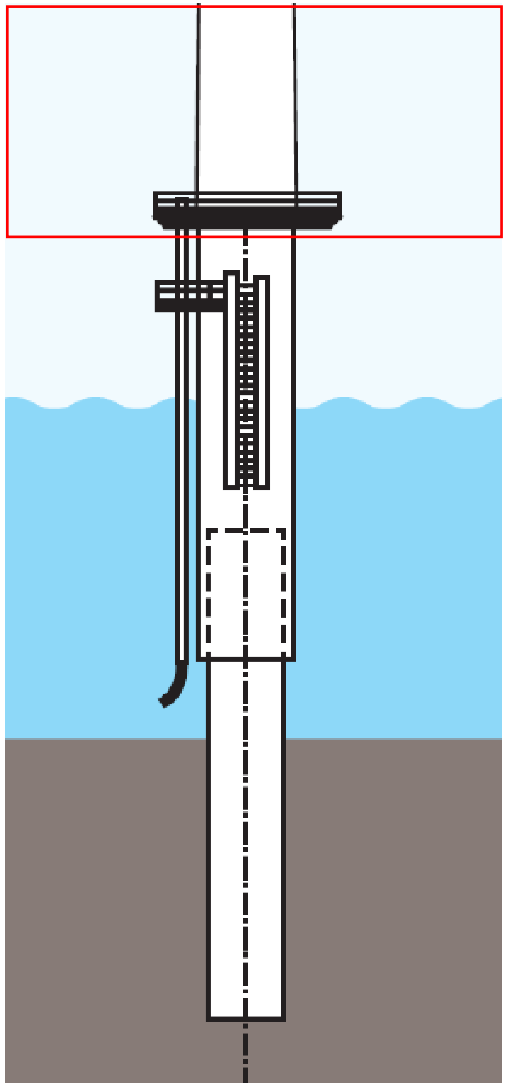


Environmental zone	Corrosion rate (mm/y)
Atmospheric zone	0.050-0.075
Splash zone above high tide	0.20-0.40
Splash zone below high tide (Intertidal zone)	0.05-0.25
Submerged zone	0.10-0.20
Buried in soil	0.06-0.10



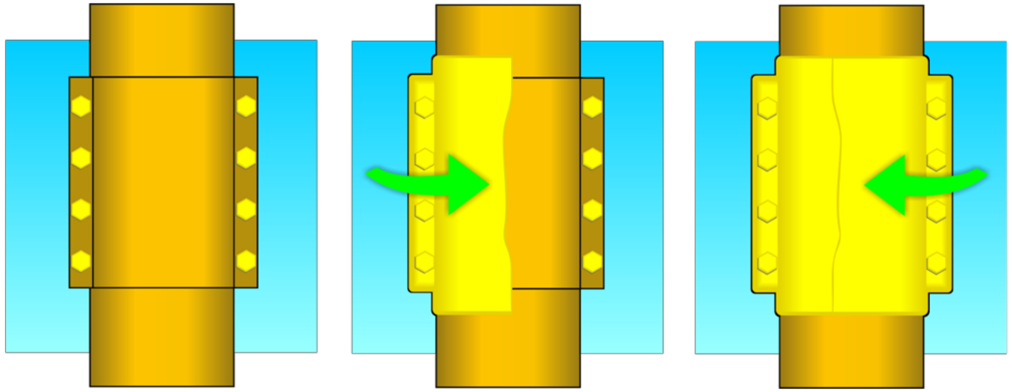
CORROSION PROTECTION OF ATMOSPHERIC ZONE

At the **atmospheric zone,** the steel tower and topside structure suffer actions from a marine aerosol. Unlike the splash zone, the structure is not directly attacked by water splashes. The winds carry the salts in the form of solid particles or as droplets of saline solution. The quantity of salt present decreases as a function of height distance from the mean water line (MWL).



According to DNV:

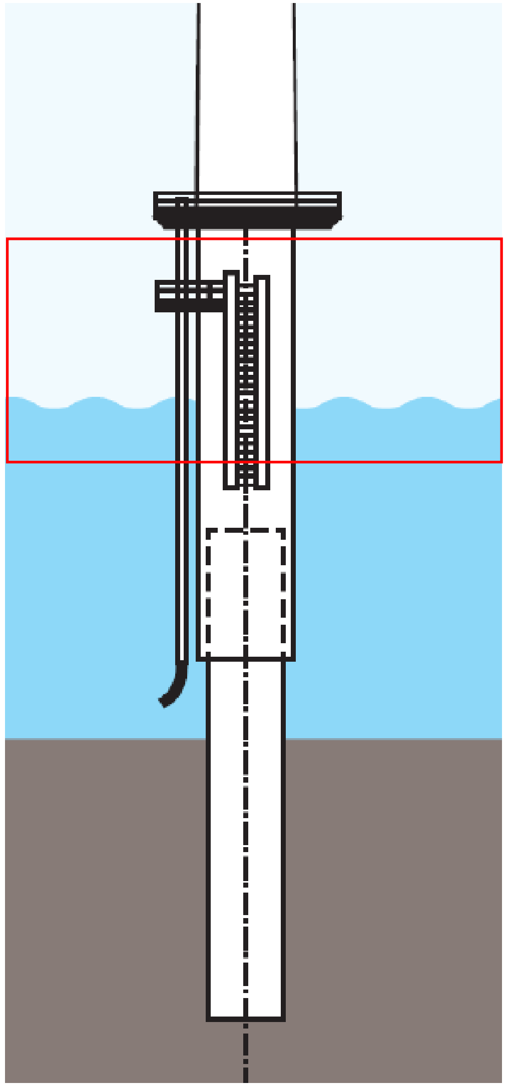
- ✓ **External and internal surfaces** of steel structures exposed in the **atmospheric zone shall be protected by the coating**.
- ✓ **Corrosion-resistant materials** are applicable for specific critical components, for example, **stainless steel** for **bolting** and other **fastening devices** and glass-reinforced plastic (GRP) for grating.



Protection of bolted steel connections

CORROSION PROTECTION OF SPLASH ZONE

At this part of the splash zone, the structure is directly exposed to seawater due to the action of tide and waves (water splash). The **corrosive environment is severe**, the **maintenance of a coating system is not practical** and **cathodic protection is not effective** for parts located **above mean water line** (MWL). Corrosion becomes more significant as water evaporates, and salts remain on the surface of the substrate.



According to DNV:

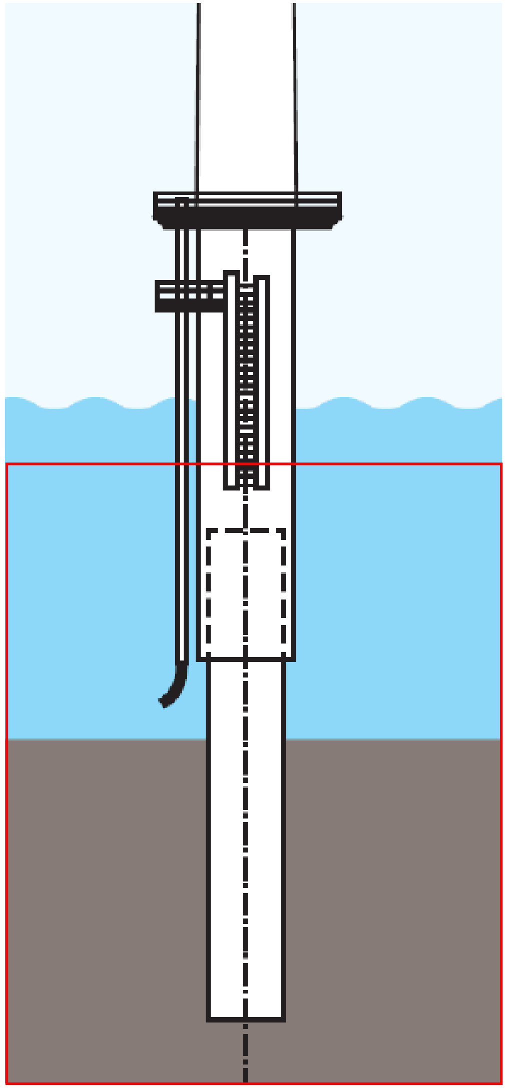
- ✓ **External and internal surfaces** of steel structures in the splash zone **shall** be protected by a **corrosion control system**. **Coating is mandatory for external surfaces of primary structures**. Maintenance of coating systems in the splash zone is not practical and coating of primary structures shall therefore be combined with a **corrosion allowance**.
- ✓ For **internal surfaces** of primary structures, use of coating is optional. The necessary **corrosion allowance** for internal surfaces shall be calculated assuming $T_C = 0$ when no coating is used.
- ✓ **Coatings** for corrosion control in the splash zone shall as a **minimum extend** to **MWL – 1.0 m**. This zone is often coated using a multi-layer scheme involving glass flakes- reinforced polymer to help protect against mechanical damage.
- ✓ For parts of the splash zone located **below MWL**, **cathodic protection may be assumed** for design purposes to be fully protective, and **no corrosion allowance** is required.

CORROSION PROTECTION OF SUBMERGED ZONE

The **submerged zone** consists of the region below the lower limit of the splash zone (**immersed zone**), including the scour zone and the zone of permanently **buried** structural parts.

According to DNV:

- The **external surfaces of the submerged zone**:
  - ✓ **It is mandatory shall have cathodic protection**.
  - ✓ Use of **coating** is **optional** and is then primarily intended to reduce the required CP capacity.
  - ✓ Use of coating may also be advised to reduce the danger of microbiologically influenced corrosion (MIC) in absence of CP.
  - ✓ The design of CP shall take into account possible scouring causing free exposure to seawater of surfaces initially buried in sediments.
  - ✓ The design of CP shall also take into account current drain to all external surfaces to be buried in sediments. Steel surfaces buried in deep sediments need no corrosion protection, but will still drain current from a CP system due to the electrochemical reduction of water to hydrogen molecules on such surfaces.
- The **Internal surfaces** of the submerged zone **shall be protected** by **either CP or corrosion allowance**, with or without coating in combination.



CATHODIC PROTECTION

Either sacrificial anode cathodic protection (SACP) or impressed current cathodic protection (ICCP) can be used.

According to DNV, **SACP** is well established and is **generally preferred for such structures**.

Use of ICCP for offshore structures may offer certain advantages, but there is no generally acknowledged design standard available giving detailed requirements and advice as for galvanic anode systems. Even with adequate design, ICCP systems are more vulnerable to environmental damage and third-party damage than SACP systems, in particular cables to anodes and reference electrodes are vulnerable.

○ **Highlights on SACP according to DNV**

- ✓ The **initial design current density** demands referred in DNV-RP-B401 is recommended to **be increased by 50%** for all initially bare steel surfaces in order to account for the effect of **high seawater currents**, such as in shallow waters with large differences between HAT and LAT.
- ✓ The **CP system** shall have a **design life** which as a minimum shall **be equal** to the **design life of the structure**.
- ✓ In areas with **large tidal zones**, the **surface area up to HAT** shall be considered for CP design.
- ✓ **Anodes** to be used on a structure shall preferably be of **identical or similar size**.
- ✓ **Anodes** shall be **located** minimum **1.0 m below LAT** and minimum **1.0 m above the seabed**.
- ✓ **Anodes** shall be **uniformly distributed**, where reasonable practicable, to avoid interference reducing their current output. In case there are reasons to assume a **significant interaction between anodes**, an analysis by a **computer model should be carried out** to determine a reduction factor for the anode current output.
- ✓ **Anodes** shall be **located close to complex and critical points** such as node areas, but **not closer than 600 mm to nodes**.

CATHODIC PROTECTION

- **Highlights on ICCP according to DNV**
  - ✓ Adequate **potential distribution shall be confirmed by computer-based modelling** of cathodic protection and utilizing some empirical time dependent relation between the cathodic current density and the protection potential (polarization curve). The **CP modelling shall further demonstrate** that **the number and location of fixed reference electrodes** is adequate to confirm that the structure is protected as required by the design.
  - ✓ The steel surfaces must be protected **without exposing** to more negative potentials than **–1.10 V** rel. Ag/AgCl/seawater, which may otherwise lead to damage of any paint coating and possibly also to hydrogen induced damage to the steel structure.
  - ✓ To this end, impressed current **anodes should be located as far as practical from any structure member** (usually a minimum distance of 1.5 m, but proportional to current magnitude).
  - ✓ **Dielectric shields are used to avoid overprotection close to ICCP anodes** and to facilitate adequate current distribution. In the immediate vicinity of anodes, a prefabricated polymeric sheet is normally applied, whilst a relatively thick layer of a special paint coating is applied as an outer shield.
  - ✓ The electric power capacity shall correspond to a minimum of 150% anode current.
  - ✓ ICCP systems shall be designed for remote control of anode current output based on recordings from fixed reference electrodes. Minimum two reference electrodes per rectifier shall be provided.

CASE STUDY:
PRELIMINARY DESIGN OF A SACP SYSTEM FOR A MONOPILE

Design based on semi-analytical/empirical relations

- Data and design criteria according to DNV

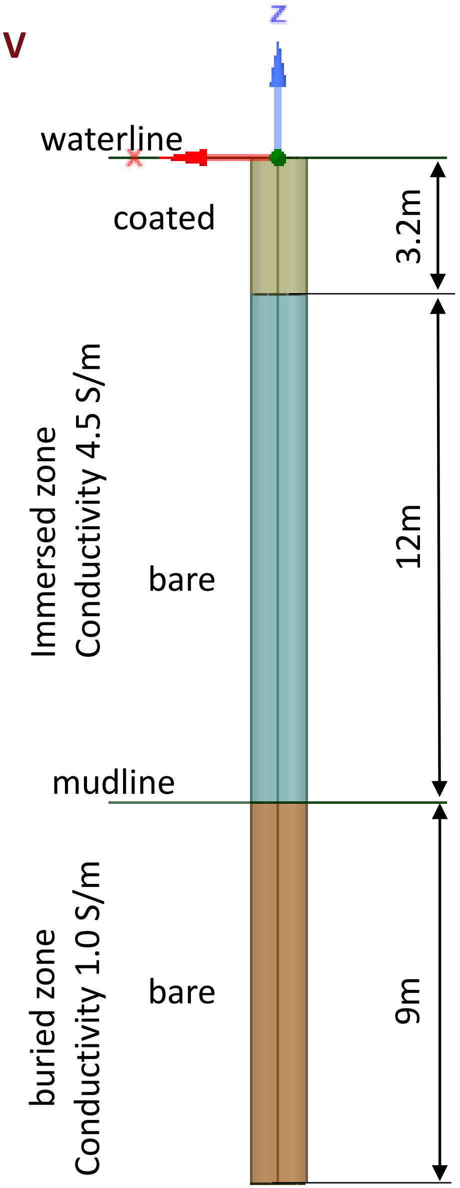
Geometry	
Wall:	Pipe Pile
Diameter (m) D =	1.3

Coating	
Total thickness (μm):	350
DNV Category:	III
Coating Break down factor constants	
a =	0.02
b =	0.012

Design Life	
Design Life (yrs) t_f =	35

Protection Potential (V vs Ag/AgCl/sw)	
Seawater E^c_{sw} =	-0.8
Mud E^c_{mu}=	-0.9

Conductivity σ (S/m)	
Seawater σ_{sw} =	4.5
Mud σ_{cm}=	1.0



Protection Current Density (mA/m^2) for bare metal			
Region:	Tropical		
Depth (m):	0-30		
Increment (%) for seawater currents:	50%		
	Tidal Zone (Coated)	Immersed Zone (Uncoated)	Buried Zone (Uncoated)
Initial i_{ci} =	225	150	25
Mean i_{cm} =	70	70	20
Final i_{cf} =	100	100	20

Anodes	
Material:	Aluminum Alloy
Alloy Density (kg/m^3) ρ =	2750
Electrochemical Capacity (Ah/kg) ε =	2500
Closed circuit potential (V vs Ag/AgCl/sw) E_a =	-1.05
Length (m) L =	1.21
Section:	Square
Side (m) a =	0.25
Utilization factor ($L \geq 4r$) u =	0.9
Distance (mm) from wall :	300

CASE STUDY:
PRELIMINARY DESIGN OF A SACP SYSTEM FOR A MONOPILE

○ **Calculation of coating break down factors**

$$f_c(t) = a + b \cdot t$$

$f_c(t)$: coating break down factor

For CAT III:

$a = 0.02$

$b = 0.012$

Initial f_{ci} : $t = 0$

Mean f_{cm} : $t = t_f / 2 = 35/2 = 17$ yrs

Final f_{cf} : $t = t_f = 35$yrs

Coating Break down factors

	Tidal Zone (Coated)	Immersed Zone (Uncoated)	Buried Zone (Uncoated)
Initial f_{ci} =	0.02	1	1
Mean f_{cm} =	0.21	1	1
Final f_{cf} =	0.42	1	1

○ **Calculation of cathodic surface cathodic areas**

$$A_c^k = \pi \cdot D \cdot L_k$$

$D = 1.3$m the pile's diameter

L_k the length of the k^{th} zone

Cathodic surface areas

	Length L(m)	Area A_c (m^2)
Tidal Zone	3.2	13.07
Immersed Zone	12	48.19
Buried Zone	9	36.757
SUM		**98.02**

Design based on semi-analytical/empirical relations

○ Calculation of Cathodic Current demand

Initial: $I_{ci}^{k} = f_{ci}^{k} \cdot i_{ci}^{k} \cdot A_{c}^{k}$

Mean: $I_{cm}^{k} = f_{cm}^{k} \cdot i_{cm}^{k} \cdot A_{c}^{k}$

Final: $I_{cf}^{k} = f_{cf}^{k} \cdot i_{cf}^{k} \cdot A_{c}^{k}$

f_{ci} : coating break down factor

i_c : current density demand

A_c: cathodic area

Cathodic Current demand (A)				
	Tidal Zone (Coated)	Immersed Zone (Uncoated)	Buried Zone (Uncoated)	**TOTAL**
Initial I_{ci} =	0.03921	7.229	0.9189	**8.19**
Mean I_{cm} =	0.1921	3.373	0.7351	**4.30**
Final I_{cf} =	0.549	4.819	0.735	**6.10**

- Calculation of initial anode resistance

$$\left.\begin{aligned} L &= 1.21\text{m} \\ a &= 0.25\text{m} \\ r_{eq} &= \frac{4a}{2\pi} = 0.159\text{m} \end{aligned}\right\} L / r_{eq} = 7.6 \rightarrow \text{Long slender stand-off anode type:}$$

$$R_{ai} = \frac{\rho_{sw}}{2 \cdot \pi \cdot L} \cdot \ln\left(\frac{4 \cdot L}{r_{eq}} - 1\right) = \frac{0.222}{2 \cdot \pi \cdot 1.21} \cdot \ln\left(\frac{4 \cdot 1.21}{0.159} - 1\right) = 0.070576\,\text{Ohm}$$

$$\rho_{sw} = 1/\sigma_{sw} = 1/4.5 = 0.222\,\text{Ohm} \cdot \text{m}$$

r_{sw} : seawater resistivity

σ_{sw} =4.5 S/m the conductivity of the seawater

L=1.21m the length of the anode

a =0.25m the side of the square section of the anode.

CASE STUDY:
PRELIMINARY DESIGN OF A SACP SYSTEM FOR A MONOPILE

Design based on semi-analytical/empirical relations

- **Calculation of final anode resistance**

✓ Utilization factor at the end of design life u=0.9

✓ Final length: $L_f = (1 - 0.1 \cdot u) \cdot L = 0.91 \cdot 1.21 = 1.1011\,\text{m}$

✓ Final Volume: $V_f = (1-u)V_i$ or $L_f \cdot 2 \cdot \pi \cdot r_{eq}^f = (1-u)L \cdot 2 \cdot \pi \cdot r_{eq}$ or $r_{eq}^f = 0.052759\,\text{m}$

✓ Final Anode resistance:

$$R_{af} = \frac{\rho_{sw}}{2 \cdot \pi \cdot L_f} \cdot \ln\left(\frac{4 \cdot L_f}{r_{eq}^f} - 1\right) = \frac{0.222}{2 \cdot \pi \cdot 1.1011} \cdot \ln\left(\frac{4 \cdot 1.1011}{0.052759} - 1\right) = 0.11\ \text{Ohm}$$

- **Anode Current output**

✓ Protection Potential: E_c = - 0.8 (V vs Ag/AgCl/sw)

✓ Anode closed circuit potential: E_a = - 1.05 (V vs Ag/AgCl/sw)

✓ Initial anode current output:

$$I_{ai} = \frac{E_c - E_a}{R_{ai}} = \frac{-0.8 - (-1.05)}{0.070576} = 3.5423\text{A}$$

✓ Final anode current output:

$$I_{af} = \frac{E_c - E_a}{R_{af}} = \frac{-0.8 - (-1.05)}{0.11} = 2.273\text{A}$$

CASE STUDY:
PRELIMINARY DESIGN OF A SACP SYSTEM FOR A MONOPILE

○ **Required number of anodes**

✓ Required anodes to fulfil the design criterion of the initial current:

- Total Initial cathodic current demand: $I_{ci} = 8.19\ \mathrm{A}$
- Initial anode current output: $I_{ai} = 3.5423\ \mathrm{A}$
- Required number of anodes: $N_1 = \mathrm{INT}\left(\dfrac{I_{ci}}{I_{ai}}\right) + 1 = \mathrm{INT}\left(\dfrac{8.19}{3.5423}\right) + 1 = \mathrm{INT}(2.31) + 1 = 3$

✓ Required anodes to fulfil the design criterion of the final current:

- Total final cathodic current demand: $I_{cf} = 6.1\ \mathrm{A}$
- Final anode current output: $I_{af} = 2.273\ \mathrm{A}$
- Required number of anodes: $N_2 = \mathrm{INT}\left(\dfrac{I_{cf}}{I_{af}}\right) + 1 = \mathrm{INT}\left(\dfrac{6.1}{2.273}\right) + 1 = \mathrm{INT}(2.68) + 1 = 3$

✓ Required anodes to fulfill both criteria: $N = \mathrm{MAX}(N_1, N_2) = 3$

○ **Check whether the effective lifetime of the used anodes is greater than design lifetime**

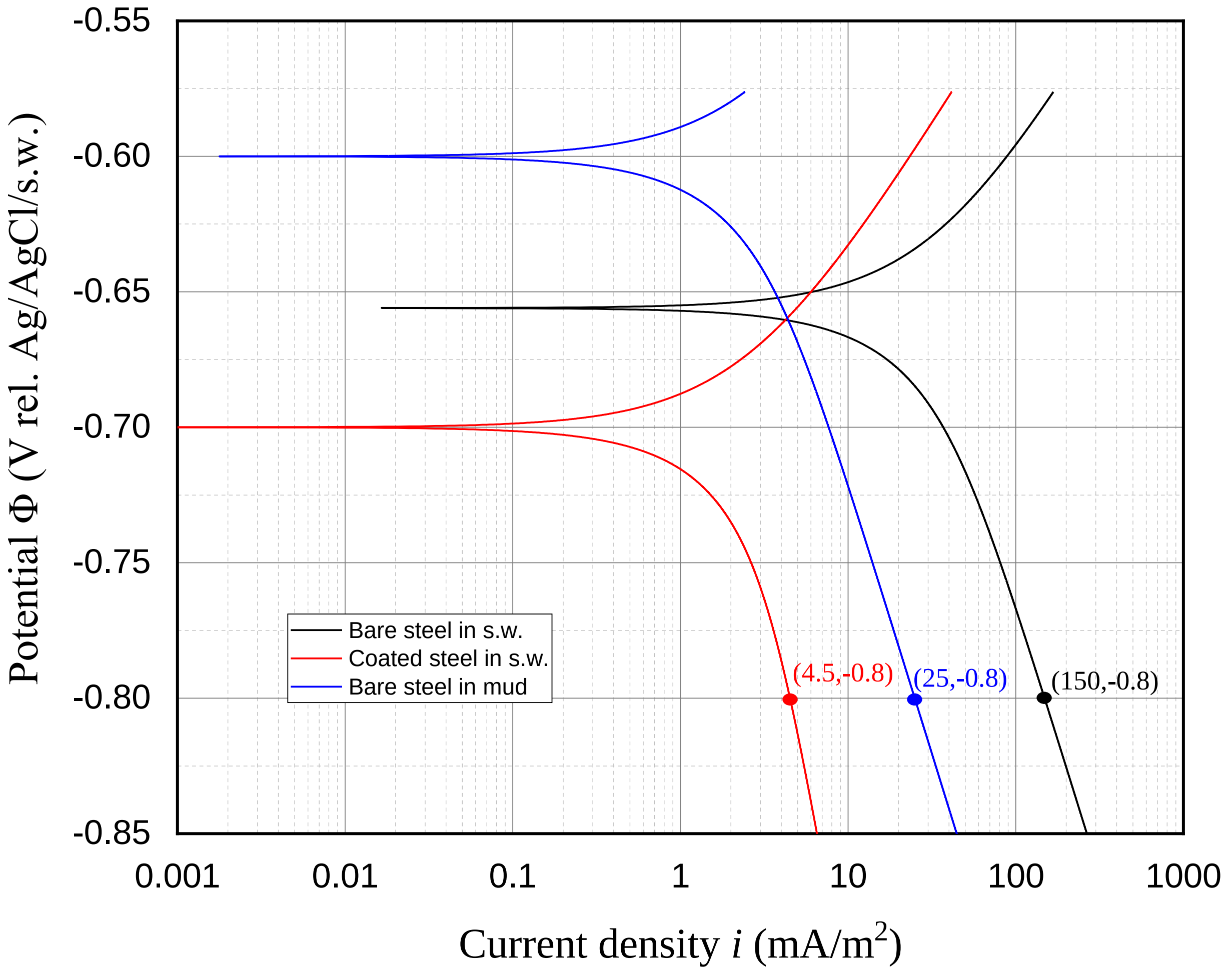
- ✓ Design lifetime: t_f = 35 yrs
- ✓ Number of used anodes: $N = 3$
- ✓ Alloy Density: ρ = 2750 kg/m^3
- ✓ Length of the anode: L = 1.21m
- ✓ Anode section length: a = 0.25m
- ✓ Anode Volume: $V = L \cdot a \cdot a = 1.21 \cdot 0.25^2 = 0.75625\,\text{m}^3$
- ✓ Anode mass: $m_a = \rho \cdot V = 2750 \cdot 0.75625 = 208\,\text{kg}$
- ✓ Anode Capacity: ε = 2500 Ah/kg
- ✓ Utilization factor: u=0.9
- ✓ Mean cathodic Current: I_{cm} = 4.3A
- ✓ Mean anode current: $I_{am} = \frac{I_{cm}}{N} = \frac{4.3}{3} = 1.433\,\text{A}$

✓ **Anodes effective lifetime L:**

$$L = \frac{m_a \cdot u \cdot \varepsilon}{I_{am} \cdot 8760} = \frac{208 \cdot 0.9 \cdot 2500}{1.433 \cdot 8760} = 37.28 \geq 35 = t_f$$

The used artificial polarization curves to fulfil the design criteria of DNV are shown in the following figure.

Initial state

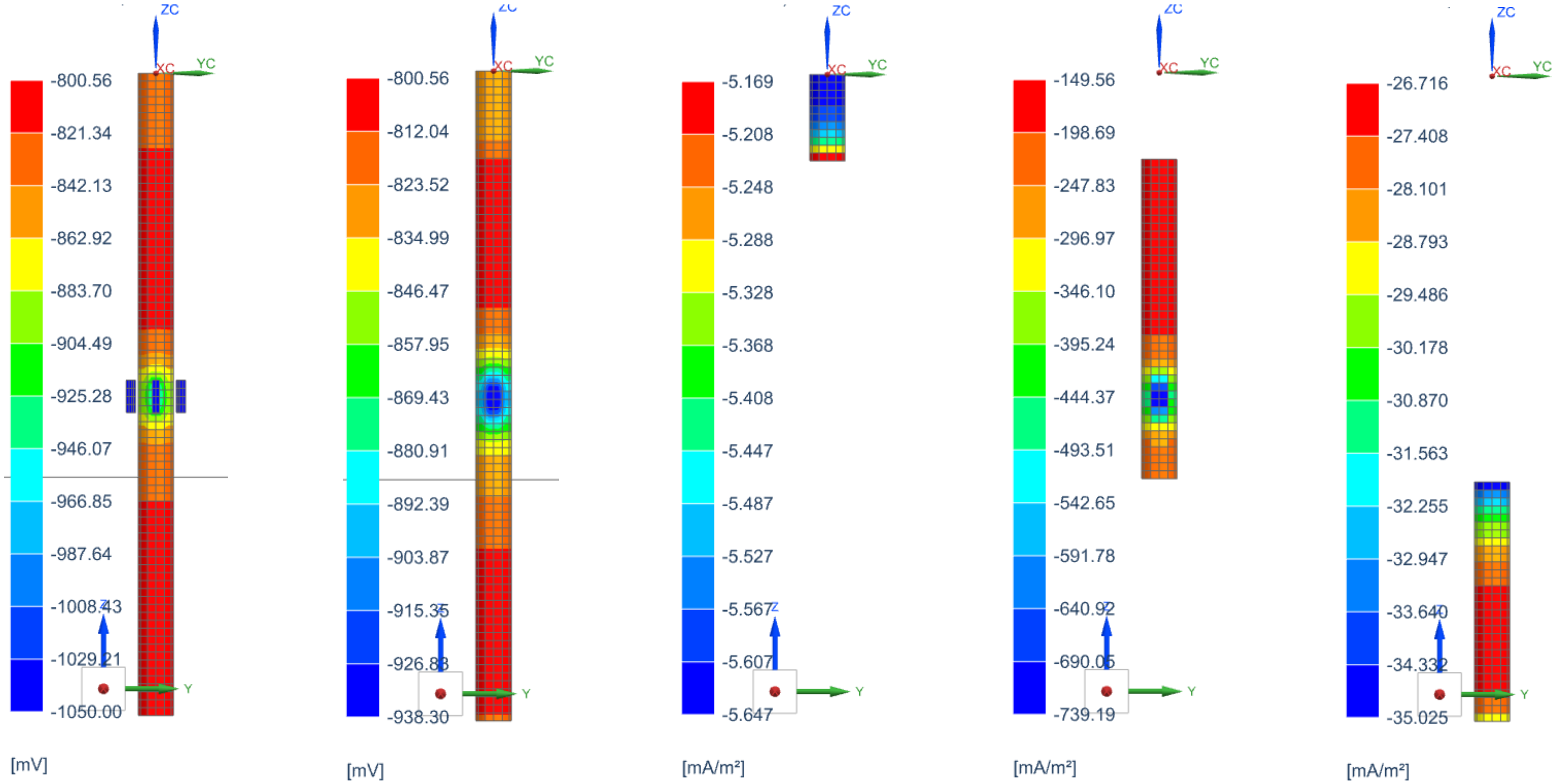


CASE STUDY:
PRELIMINARY DESIGN OF A SACP SYSTEM FOR A MONOPILE

Computer-based design based on modeling with BEM

Three (3) anodes placed at z=-12m

Initial state

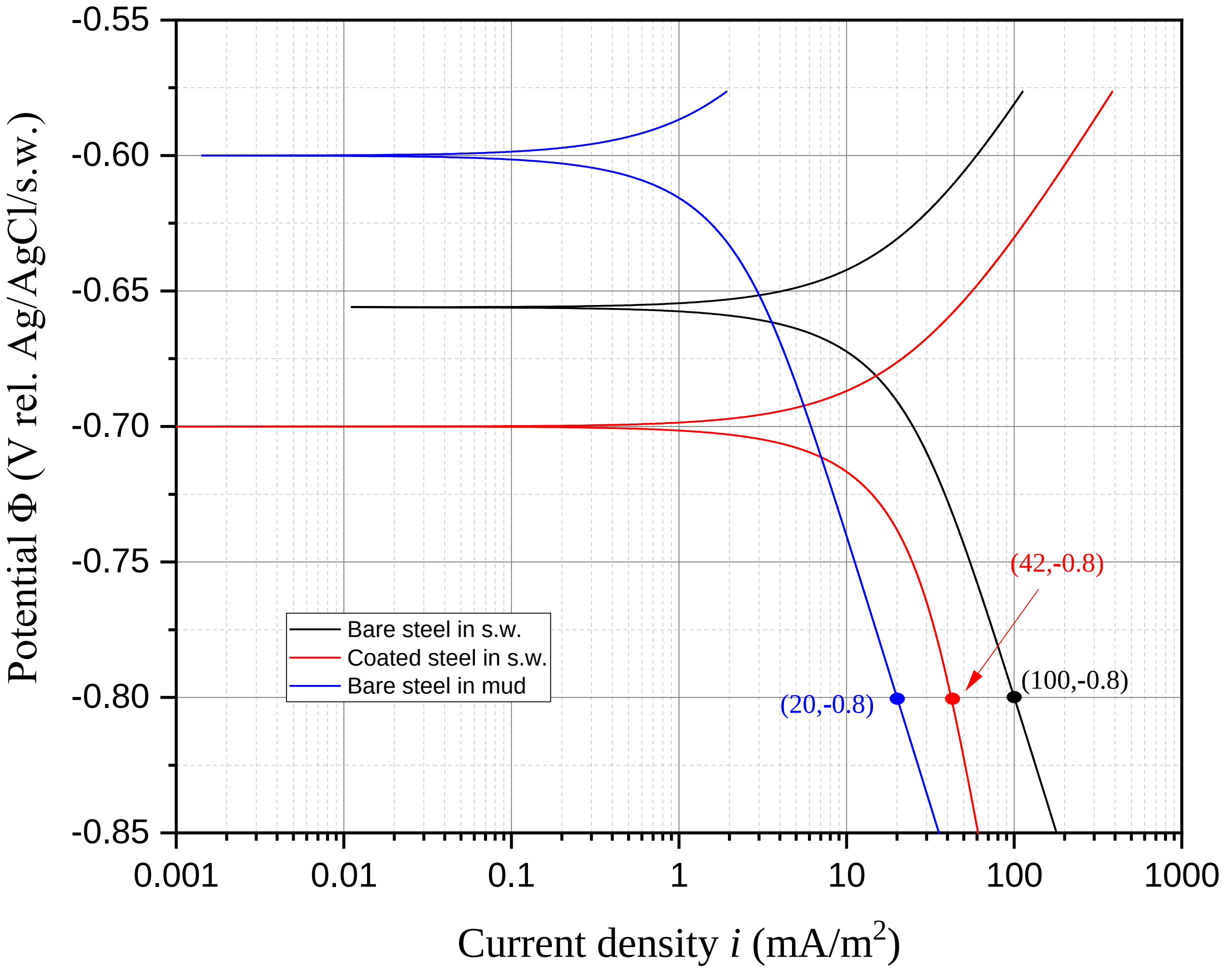


CASE STUDY:
PRELIMINARY DESIGN OF A SACP SYSTEM FOR A MONOPILE

Computer-based design based on modeling with BEM

The used artificial polarization curves to fulfil the design criteria of DNV are shown in the following figure.

Final state

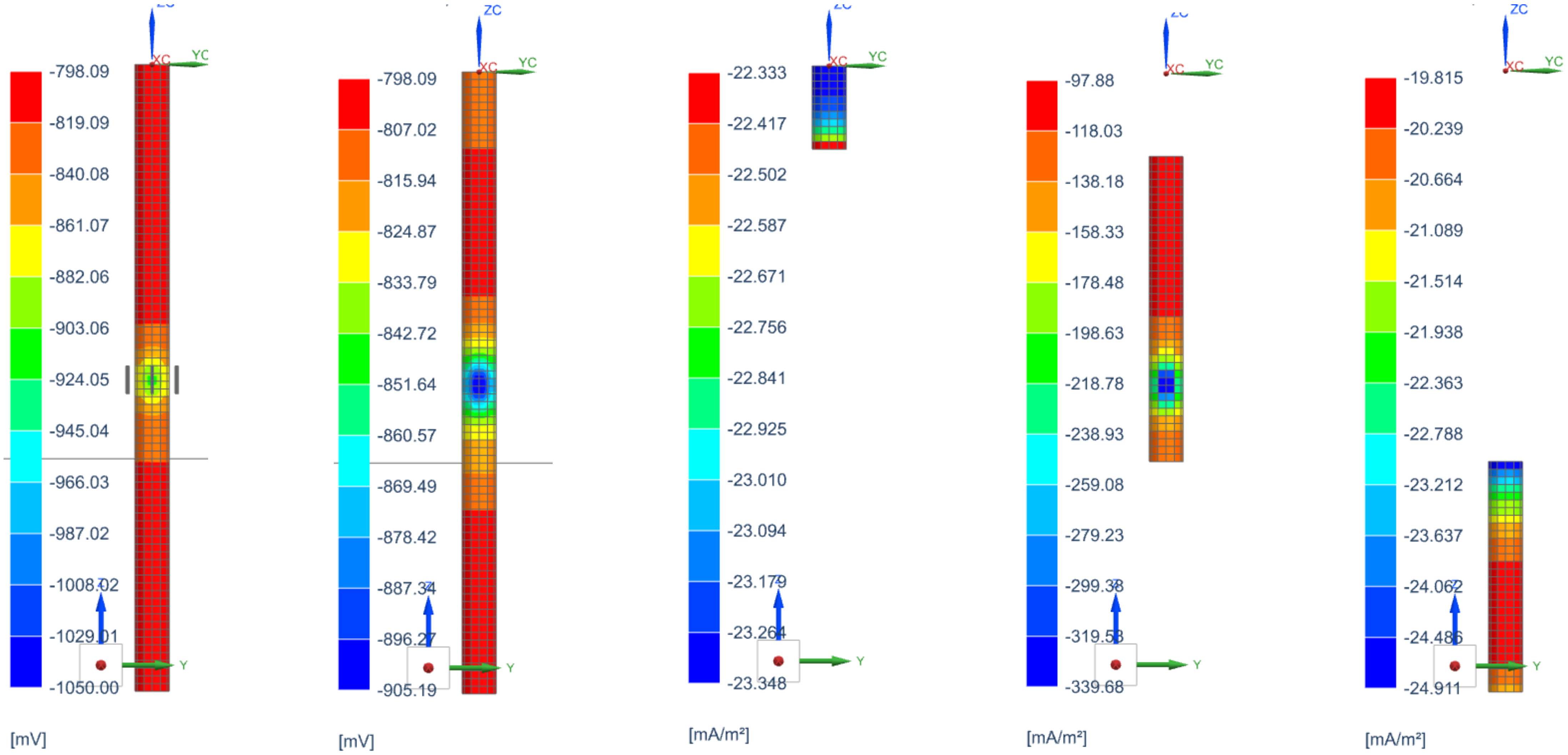


CASE STUDY:
PRELIMINARY DESIGN OF A SACP SYSTEM FOR A MONOPILE

Computer-based design based on modeling with BEM

Three (3) anodes placed at z=-12m

final state

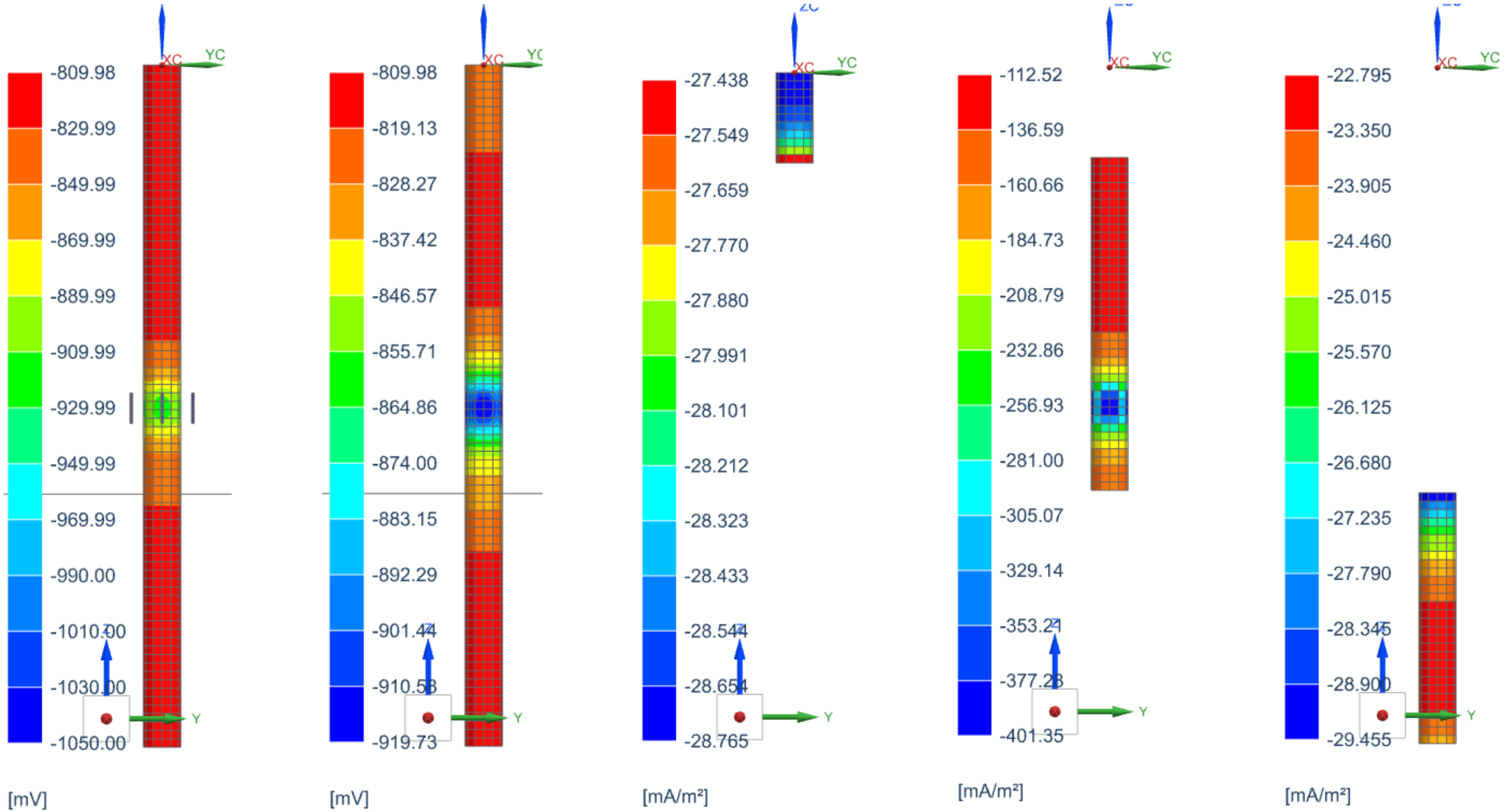


CASE STUDY:
PRELIMINARY DESIGN OF A SACP SYSTEM FOR A MONOPILE

Computer-based design based on modeling with BEM

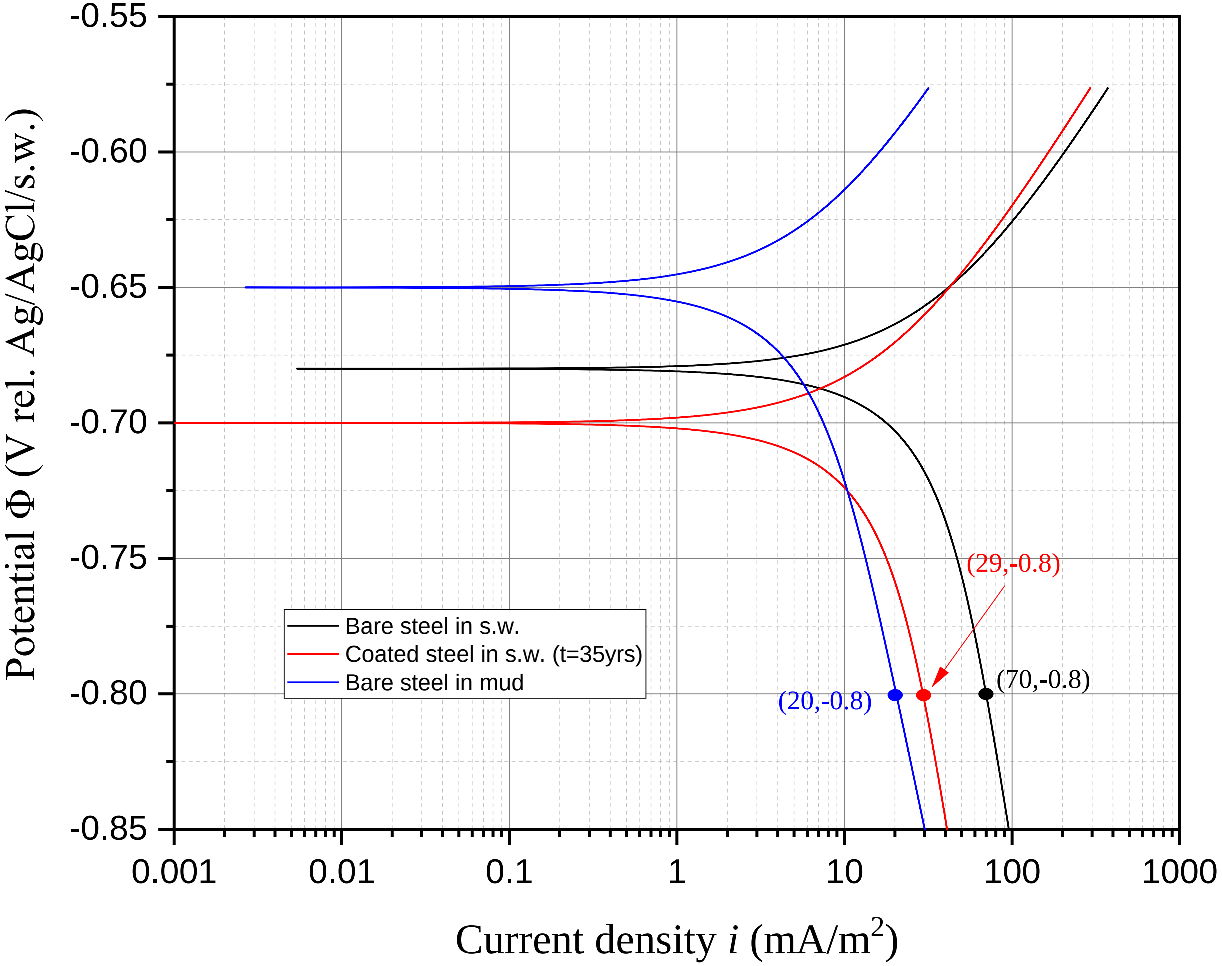
Four (4) anodes placed at z=-12m

final state



The used artificial polarization curves to fulfil the design criteria of DNV are shown in the following figure.

mean state

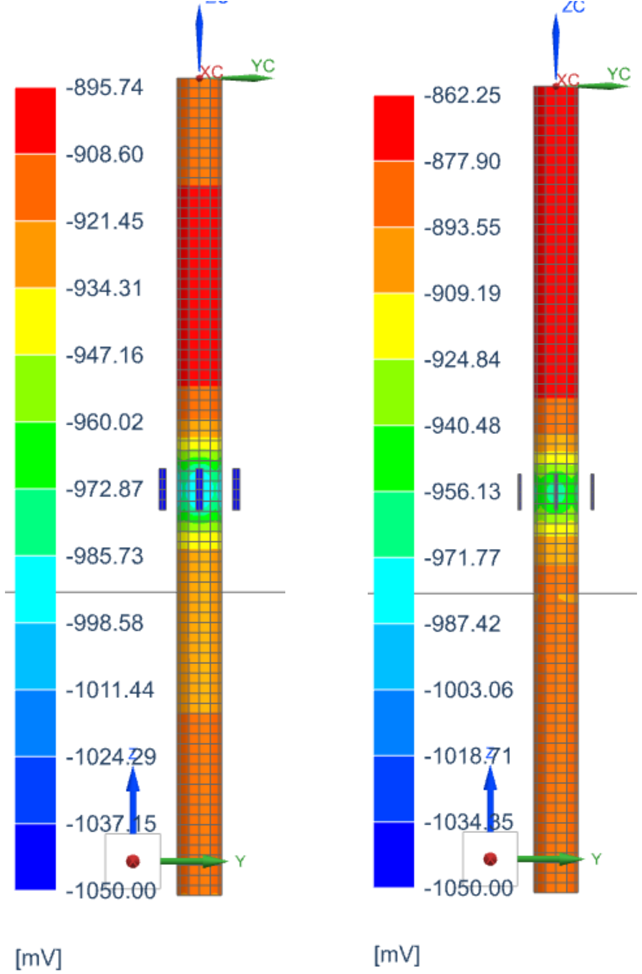


CASE STUDY:
PRELIMINARY DESIGN OF A SACP SYSTEM FOR A MONOPILE

Computer-based design based on modeling with BEM

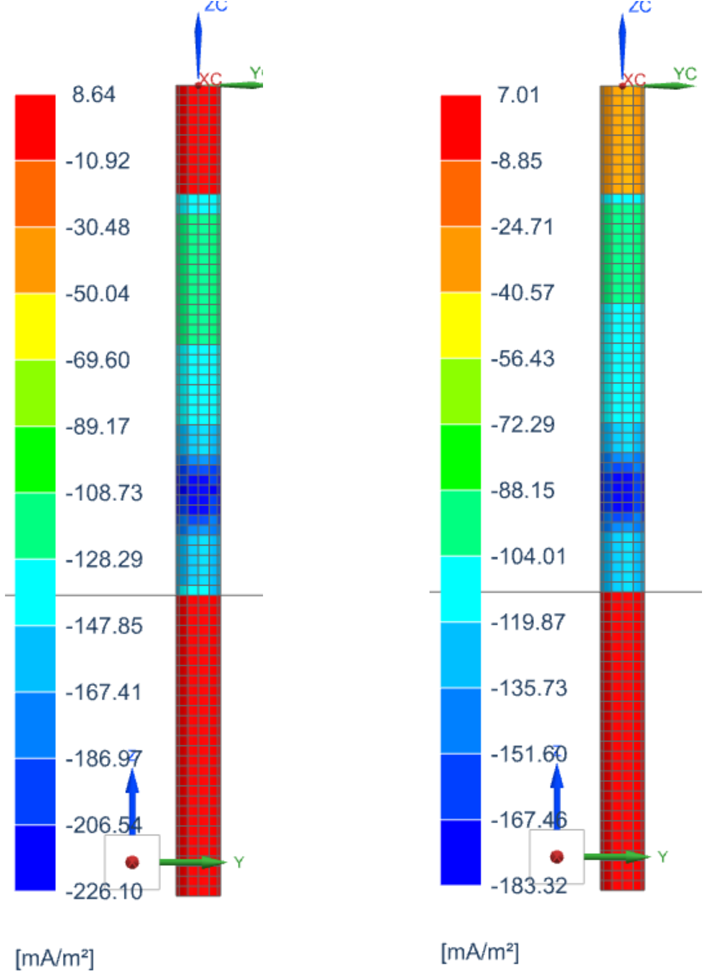
Four (4) anodes (1.21x0.25x0.25) placed at z=-12m

t = 0 **t = 28 years**



SERVICE LIFE: 28.6 years

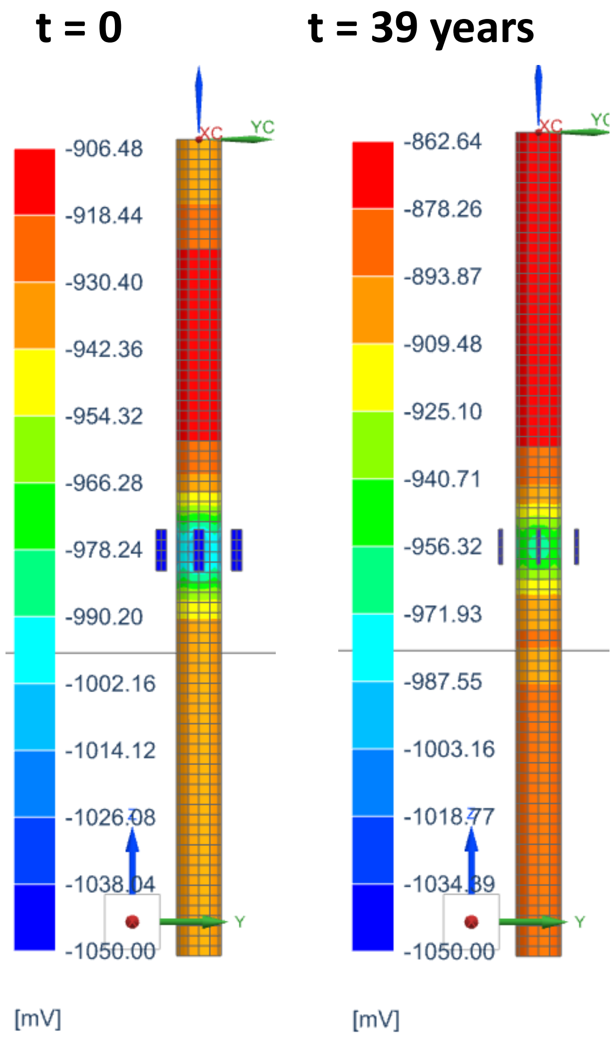
t = 0 **t = 28 years**



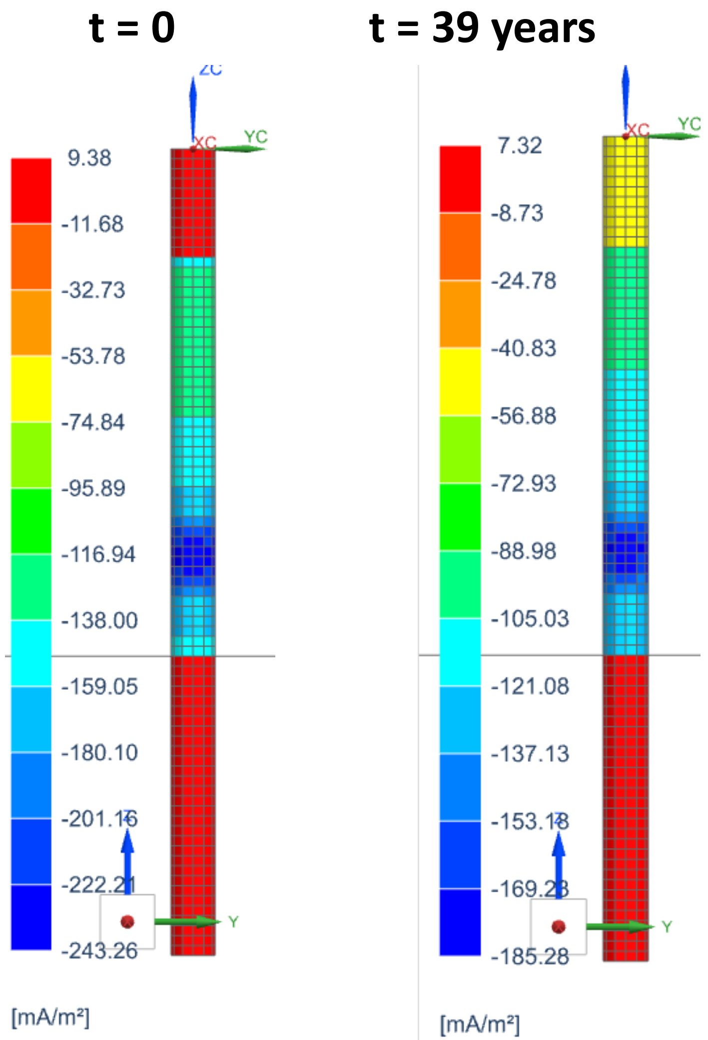
CASE STUDY:
PRELIMINARY DESIGN OF A SACP SYSTEM FOR A MONOPILE

Computer-based design based on modeling with BEM

Four (4) anodes (1.21x0.3x0.3) placed at z=-12m



SERVICE LIFE: 39 years



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Cathodic Protection Design
for
offshore Wind Turbines

End of the presentation

Thank you for your attention and patience!