

CP SYSTEM VALIDATION OF OFFSHORE STRUCTURES THROUGH MODELING

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ABSTRACT

Nowadays offshore structures are typically equipped with a sacrificial anode cathodic protection system (SACP). Design and application of SACP systems is well documented and most owners of marine equipment rely on this traditional approach. SACP systems for big structures result in a large amount of anodes increasing the mechanical load on the structure, installation cost (welding) and the release of soluble metals into the environment. Moreover, monitoring of the CP performance requires access to the anodes in order to verify the material consumption resulting in expensive ROV inspections.

An innovative and more economical way to protect such offshore structures is by fitting these structures with an impressed current system (ICCP). This relatively new approach makes use of a restricted amount of insoluble Mixed Metal Oxide (MMO) anodes positioned at strategic locations on the structure. Monitoring and adjusting of the ICCP system can easily be performed from an accessible control panel. Most of the ICCP installations are even less expensive than SACP systems. The difficulty, however, is to find a correct design in order to guarantee an adequate protection level for the complete structure and to avoid local overprotection around the MMO anodes.

In this article case studies will be discussed where a 3D simulation technology was used to evaluate the two different CP system designs for a semi-submersible oil rig. Long term effects like polarization behavior and consumption rate of sacrificial anodes is provided and simulation results are compared to current standards.

Keywords: corrosion protection, CP design, simulation technology, CP validation, offshore

⁽¹⁾Det Norsk Veritas

INTRODUCTION

Marine structures are protected against corrosion by passive coatings and/or cathodic protection systems. Historically, the majority of CP systems consist of sacrificial anodes (SACP) like the Al-Zn-In type. Sacrificial anodes have a proven performance and the amount of required anodes can be calculated from standards like DNV RP B401:2005⁽¹⁾. However, the use of sacrificial anodes has its limitations:

- assures protection only locally around the anode in a high resistivity medium
- no adjustment to changes in environmental conditions due to the fixed current output
- limited life time leading to expensive retrofit programs for extending the service life of the structure to be protected
- high installation cost due to involvement of skilled dive teams/welders.

As an alternative, impressed current cathodic protection (ICCP) systems have many benefits over SACP systems:

- adjustable current output
- no need for retrofit
- drastically lower installation and maintenance cost
- possibility for continuous monitoring so that the protection level is safeguarded at all time
- limited weight keeping the mechanical load of the structure low

However, ICCP systems have the danger of overprotecting the structure which can lead to hydrogen embrittlement for high-strength steels and to coating disbonding. Correct positioning of the anodes and reference electrodes is therefore crucial. Current standards like DNV RP B401:2005 do not include design rules for ICCP systems however. In the past such systems could not be accurately and confidently designed. Today, with Elsyca's 3-D simulation technology^{1,2}, a proper design is modeled and gives the owner full confidence in the corrosion protection of the asset.

First the behavior of a sacrificial anode is simulated taking into account its shape change during operation. The shape change is simulated by a unique Finite Element Method (FEM) 3D modeling approach. The most important anode parameters like current output, anode potential and anode resistance are simulated and the results are compared with the DNV standard.

Secondly the simulation technology is used to validate an ICCP design of the semi-submersible oil rig Opti-Ex⁽²⁾ from Exmar Offshore Company (Houston, Texas). Simulations are performed for different CP conditions like decommissioning, maintenance regime, and gradually aging of protective coating. Based on the results a redesign is proposed in order to guarantee longevity of the asset.

Finally the ICCP system is replaced by an SACP system that is designed according to the DNV standard. A comparison of performance between both CP systems is made.

⁽²⁾Trade Name

SIMULATION OF SACRIFICIAL ANODE BEHAVIOR

Sacrificial anodes will dissolve and material will be consumed over time. The galvanic protection current flowing from the sacrificial anode towards the steel structure is not uniformly distributed over the complete anode surface. It is well known that the current density is higher at sharp edges than at flat surfaces and that material loss will be more important at the edges. In order to calculate the dissolution of the anode the total process time is divided in a sequence of discrete time steps. The FEM approach used in this paper has been widely described by Purcar et al³. The anode shape is found at each time step by displacing the mesh nodes proportional with, and in the direction of the local current density according to Faraday's law. In order to avoid mesh distortions the new anode surface is re-meshed and a volume mesh is generated in the computational domain at each calculation time step.

As an example a rectangular stand-off anode of 80 kg net weight with dimensions of 2360x114x114mm (LxWxH) is considered. The stand-off distance from the structure to be protected is 350 mm.



Figure 1: rectangular sacrificial Al-Zn-In stand-off anode

Simulation of bare steel surface

In a first series of simulations the SACP system is calculated for a bare steel plate of 50x50 m. The results are compared with the DNV RP B401 design rules for assets in tropical seawater at 0-30 m depth. A seawater resistivity of 0.20 ohm-m is considered and a lateral seawater flow of 0.1 m/s is assumed. The cathodic current demand of steel is mentioned in Table 1.

Table 1
Design current densities according DNV RP B401

J (A/m²)		
initial	mean	final
0.150	0.70	0.100

The initial resistance of a stand-off slender anode ($L > 4r$) is calculated according to equation (1) and (2).

$$R_{ai} = \frac{\rho}{2.\pi.L} \left(\ln \frac{4.L}{r} - 1 \right) \quad (1)$$

Where,

$$r = \frac{c}{2\pi} \quad (2)$$

In equation (1) ρ is the seawater resistivity, L the length of the anode and r the equivalent radius of the anode. For a rectangular shape an equivalent radius is calculated based on the cross sectional periphery, c equals 456 mm. The equivalent radius r becomes 73 mm and the initial anode resistance R_{ai} results in 0.052 ohm. The initial current output I_{ai} is determined by the potential difference between the anode E_a and the protected structure E_c , and the anode resistance R_{ai} .

$$I_{ai} = \frac{E_c - E_a}{R_{ai}} \quad (3)$$

Where

$$E_a = -1.070 \text{ V}$$

$$E_c = -0.800 \text{ V}$$

The initial current output of the anode is 5.2 A.

At the end of the service life the initial anode mass m_{ai} of 80 kg decreases to a final mass m_{af} . Taking into account a utilization factor $U = 0.9$ the final mass is 8 kg.

$$m_{af} = m_{ai}(1 - U) \quad (4)$$

New dimensions must be calculated for this end of life situation. The remaining anode length L becomes then 2124 mm (equation 5).

$$L_{final} = L \cdot U \quad (5)$$

The equivalent radius r_f , is calculated based on the remaining mass m_{af} and the density d of the material. For Al-Zn-In this is 2750 kg/m³. The equivalent radius becomes 20.9 mm.

$$r_f = 1000 \sqrt{\frac{m_{af}}{1000 \cdot d \cdot L_f \cdot \pi}} \tag{6}$$

The final anode resistance, R_{af} is calculated according to equation (1) given the new dimensions L_f and r_f . The same potential difference between the anode and the structure is assumed. The final anode resistance is 0.075 ohm. The final current output becomes 3.6 Amps.

The service life of the anode can be predicted from the consumption rate (3.8 to 3.4 kg/A/y). Given the initial current output of 5.2 A, a net anode mass of 80 kg and a consumption rate of 3.8 kg/A/y, the total life time of the anode becomes 4.04 years. In case of a consumption rate of 3.4 kg/A/y the total life time is 6.53 years. The lifetime cannot be predicted accurately since the resistance and potential difference between anode and the structure changes over time.

Therefore 3-D simulation technology is proposed where the dynamic change of the system is taken into account. The seawater resistivity and the (anodic and cathodic) polarization data are the only input parameters necessary to feed the model.

The polarization data for bare steel under different conditions is constructed based on the work of Hack⁴ and scaled for the design current requirements according to the DNV standard in Table 1. The resulting cathodic polarization data for bare steel are given in Figure 2. The anodic polarization data for the Al-Zn-In anode is taken from Munoz et al.⁵ as shown in Figure 3.

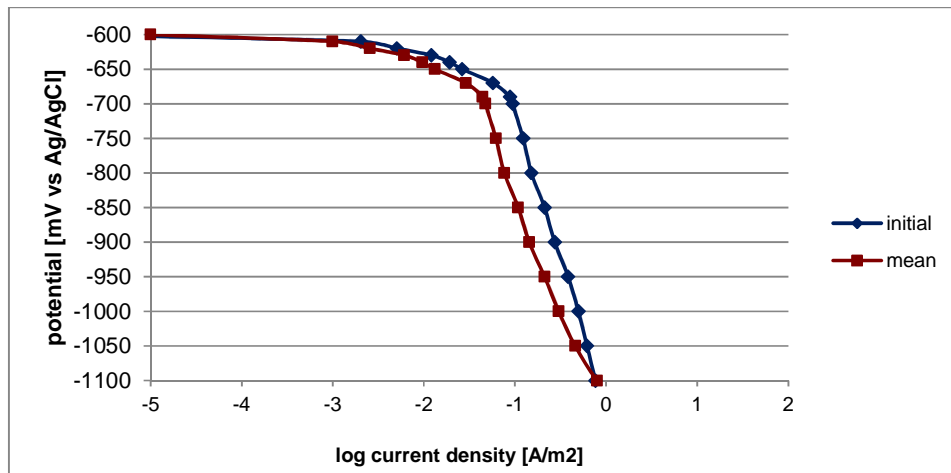


Figure 2: cathodic polarization data of bare steel in seawater after decommissioning (initial) and after calcareous film formation (mean)

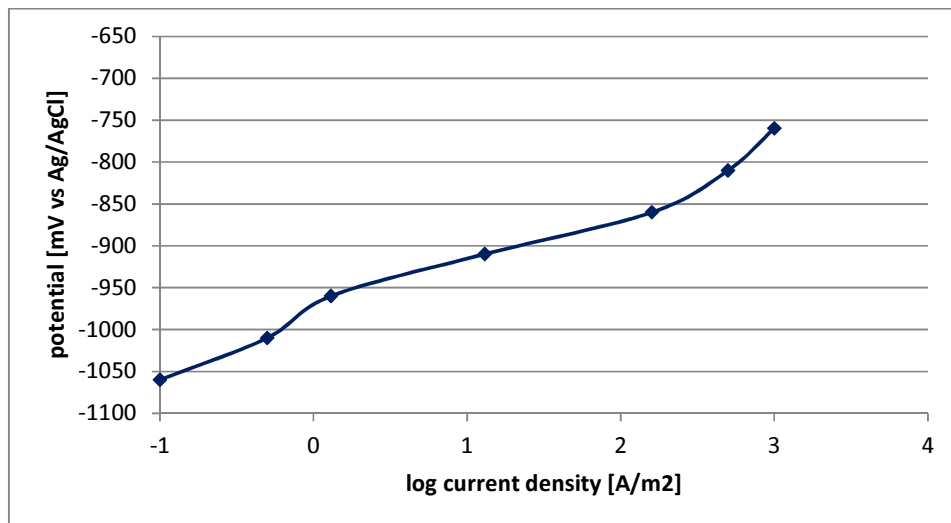


Figure 3: anodic polarization data of Al-Zn-In anode in seawater

The anode consumption is simulated for several small time steps of approximately 2 months. Figure 4 shows the anode shape after 1 and 4 years of activity. The legend refers to the amount of material reduction (μm) which is higher at the extremities of the anode.

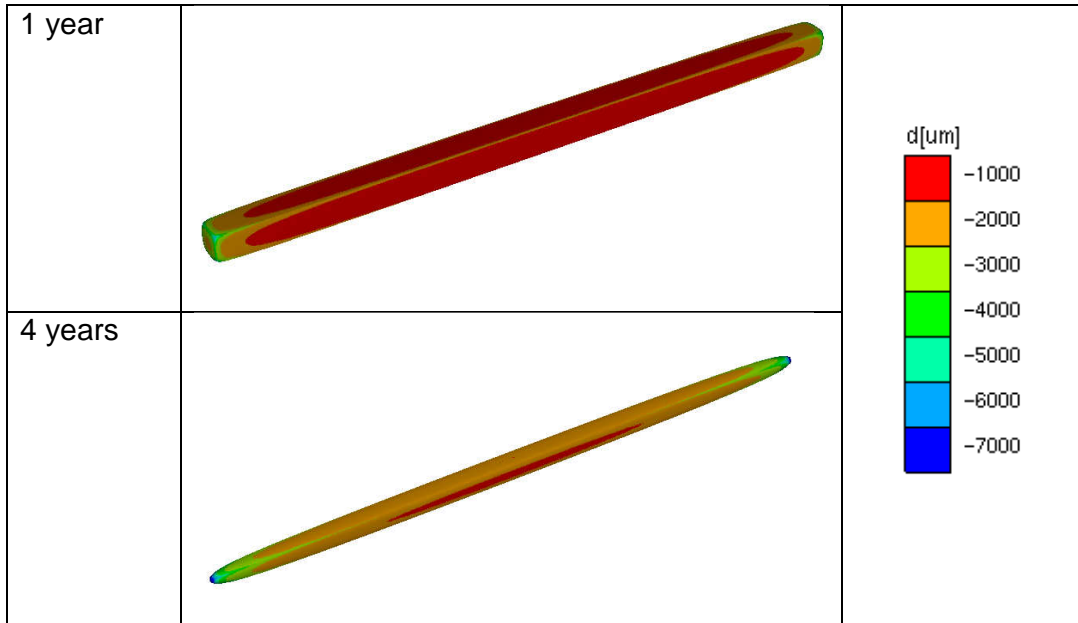


Figure 4: anodic polarization data of Al-Zn-In anode in seawater

At each time step the volume of the anode, the current output and the anode resistance is determined. The anode has an initial volume of 0.030671 m³ (2360x114x114mm). The inserts in the shape of cow horns are not included. Figure 5 shows the results for the volume and current output. The current output starts at 6.1 Amps. The volume reduces linearly with time.

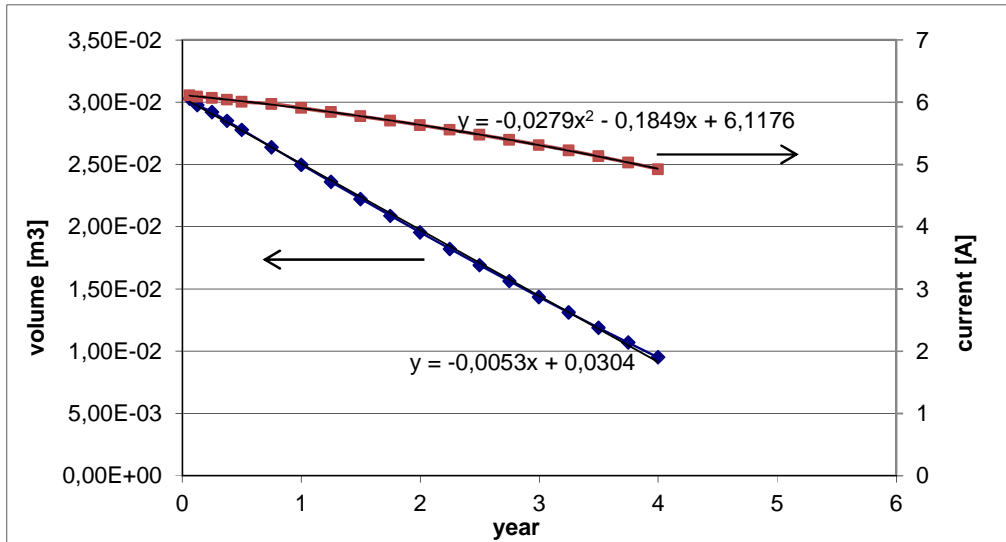


Figure 5: current and volume change of Al-Zn-In anode protecting bare steel

The consumption rate for each time step can be calculated from the material density (2750 kg/m³), the volume loss and the current output. The averaged value is 2.76 +/- 0.16 kg/A/y for the bare steel plate. The time necessary to reach a mass of 8 kg (or volume of 10%) can be calculated based on the trend line equation in Figure 5. Given the initial volume of 0.030671 m³, a remaining 10% means a final volume of 0.0030671 m³. Using the trend line equation in Figure 5, a life time period of 5.15 years is calculated for 90% utilization. The final current output is then 4.42 A.

After each step the anode resistance is determined by applying a current of 1A from a virtual point to the isolated anode (no inserts, nor steel plate). The potential at far field is measured and the anode resistance is calculated by Ohm's law. Figure 6 shows the increase of the anode resistance in function of time. The resistance starts at 0.059 ohm. After 5.15 years the resistance will increase to 0.077 ohm according to the equation in Figure 6. The results are in good agreement with the DNV standard.

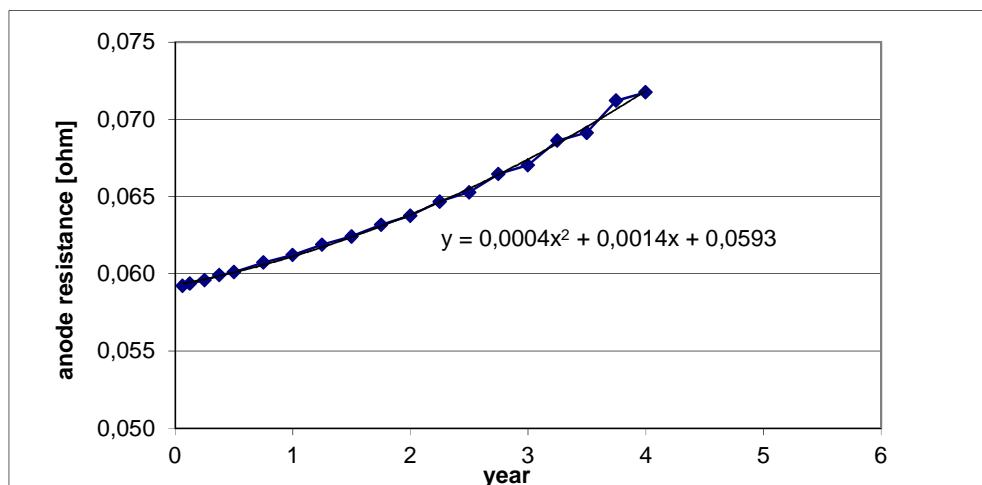


Figure 6: change in resistance of Al-Zn-In anode protecting bare steel

Simulations have been performed with the same input parameters as used for the DNV RP B401 standard. With the simulation technology a 3D configuration is calculated and the shape change of the anode is taken into account. Table 2 shows the results from the design rules and the simulations. The anode resistance from the simulations is in good agreement with the DNV standard. The current output however is higher and the consumption rate is lower. The discrepancy can be due to the fact that the formulas in the standard do not take the shape change into account. From the simulation results the anode will last longer and has a higher performance (delivers more current).

Table 2
Comparison of results for design of SACP system

	DNV RP B401	Simulation
R_{ai} , [ohm]	0.052	0.059
R_{af} , [ohm]	0.075	0.077
I_{ai} , [A]	5.2	6.1
I_{af} , [A]	3.6	4.4
Consumption rate, [kg/A/y]	3.8-3.4	2.76

Simulation coated steel surface

The current demand and hence the CP design and performance depend on the coating condition. The current demand will slowly increase due to aging of the coating. The long term coating deterioration behavior can be predicted by calculating the coating breakdown factor as mentioned in the DNV standard. The standard classifies coating systems according to the dry film thickness (DFT) and the coating type. As an example, the paint system of the Opti-Ex™ hull belongs to Category II (epoxy, DFT <350 μm) while the coating system of the splash zone belongs to Category III (epoxy, DFT > 350 μm). The category determines the parameters “a” and “b” in the equation for the coating breakdown factor f_{cf} .

$$f_{cf} = a + b t_f$$

Considering a service life t_f of 10 years the coating breakdown factor f_{cf} for the different paint systems is easily calculated. Results are given in Table 3.

Table 3
Results of the breakdown factor for different coating type

	a	b	f_{cf}
Hull	0.05	0.025	0.30
Splash zone	0.02	0.012	0.14

A coating breakdown factor f_{cf} of 0.30 for the hull coating means a 30% increase in bare steel after 10 years of operation. The same calculation method is applied for the remaining coating system. This means a total bare steel active surface area of 19% and 35% for respectively the splash zone and the hull.

The cathodic polarization curve of the coated steel is achieved by scaling the polarization data of the bare steel from Figure 2 by the coating breakdown factor. This is done for different time steps (years). Figure 7 shows results at the decommissioning of the system (5% bare steel no calcareous film formation), after calcareous film formation and after 10 years of service life for respectively a coating in Category II and Category III.

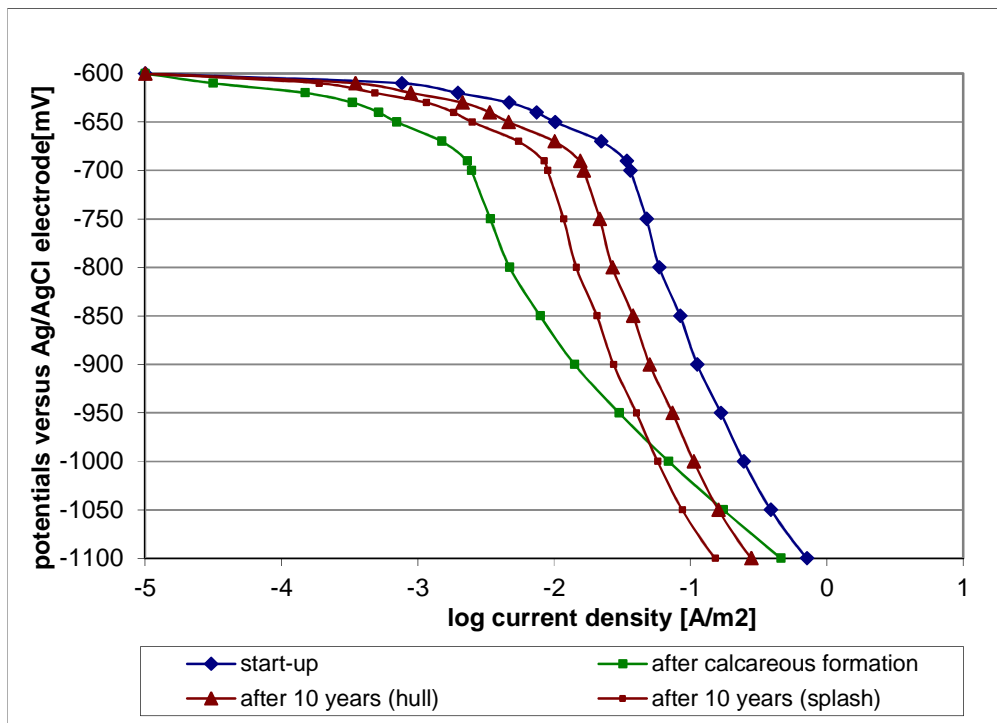


Figure 7: cathodic polarization data for coated steel at different time scales

According to the DNV standard the anode consumption rate and anode current output are not influenced by the presence of a coating system. A painted surface offers a higher coverage range that can be achieved with a single anode if compared with a bare steel surface. Figure 8 shows the simulation results for the same set-up as in previous section but with the difference that the steel plate is coated and coating breakdown factor is gradually increased. If Figure 5 and 8 are compared one can see that there is a slightly lower anode dissolution rate (slope of volume curve) if a coated steel plate is considered. The effect is rather minor. Based on the trend line equation in Figure 8 the time to reach 90% utilization is 5.83 years.

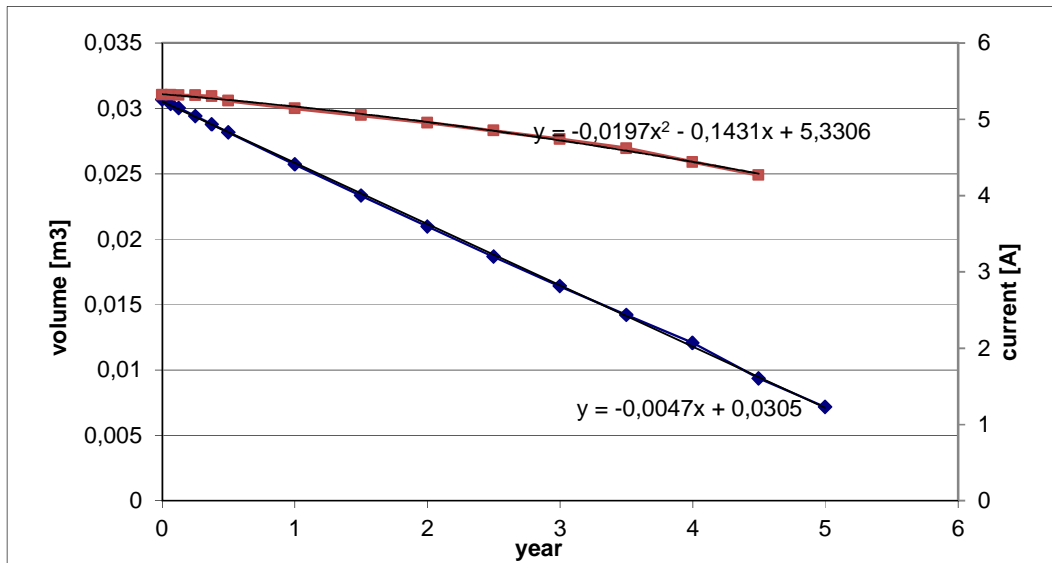


Figure 8 current and volume change of Al-Zn-In anode protecting coated steel

DESIGN COMPARISON FOR OPTI-EX™ RIG STRUCTURE

The Opti-Ex™ semi-submersible rig is operating in the Mississippi Canyon 547 in the Gulf of Mexico and is kept in place by 12 mooring chains of 150 m length in direct contact with the hull. Umbilicals and flexible risers connect several subsea structures at 944 m depth to the rig.

The rig has a length of 76.8 m, a width of 76.8 m and a height of 42 m. Once in operation at open sea the rig will be partially submerged up to 26 m above the baseline (ABL). For numerical simulations only the wetted parts will be considered. The total wetted surface is 11876 m² for the hull while the mooring chains have a total surface area of 526 m². Piping systems are considered as perfect insulators.

The structure is coated by two different marine coating systems of International Paint (AkzoNobel). The coating systems belong to Category II and Category III according to the DNV standard.

- o Hull (0 to 20 m ABL):
2x 125 mm DFT of aluminum pure epoxy coating Intershield 300
Category II
- o Splash zone on hull (20 to 36 ABL):
2x 375 mm DFT of high build glass flake reinforced epoxy coating Interzone 505
Category III

At open sea the rig is submerged for 26 meters with the upper 6 m of the column having a splash zone specific coating and the remaining 20 m has a hull specific coating. Figure 9 shows the computational CAD model.



Figure 9: CAD model of Opti-Ex™ (submerged parts) with initial ICCP system

The structure is initially designed with an ICCP system containing 12 MMO anodes with dielectric shield of 2 m diameter. Four of them are mounted on the columns and eight of them on the pontoon. Four zinc reference electrodes are positioned in the middle of the pontoon pointing outwards. Remark that hidden surfaces like hull structures behind fair leaders and latching heads are critical areas for cathodic protection. Current cannot easily reach those places and the risk for corrosion will increase. These locations are also difficult to survey by the permanent reference electrodes or during deep cell measurements and hence the hot spots cannot easily be detected. Figure 11 on the right shows the position of the reference electrode on the pontoon.

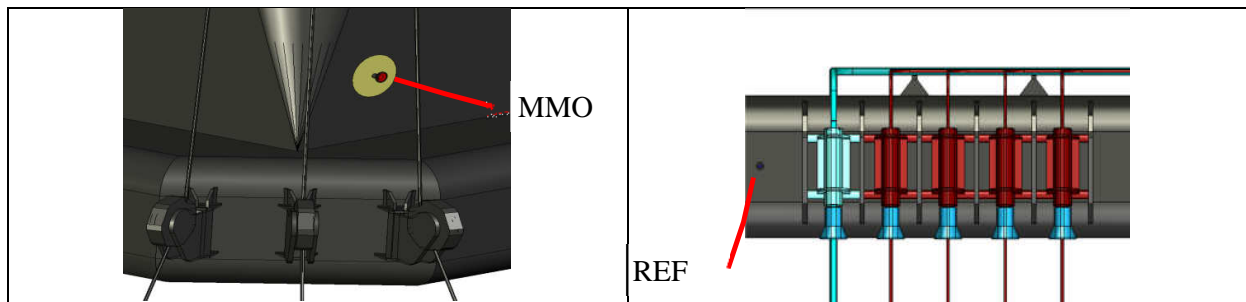


Figure 11: CAD model of Opti-Ex™ (submerged parts)

During simulation a fixed current output is applied on each individual MMO anode. An appropriate amount of current is determined in an iterative way so that a maximum cathodic protection level at all locations is reached but at the same time overprotection near the MMO anodes is avoided. Overprotection will lead to hydrogen embrittlement of high strength steels (especially weldings) and coating disbonding.

As a result the IR free potential is given for the complete surface of the structure. In fact thousands of virtual electrodes are made available through simulation. Exploring the simulation results of the protection potential in 3D allows the owner of the rig to assess protection level of the structure and to localize hot spots. Moreover measured field potentials by the reference electrodes can easily be compared with the calculated values.

Simulation initial ICCP design

Simulations are performed for three different life time scenarios, namely just after decommissioning, after calcareous film formation (typically 1 year) and after coating degradation (10 years). An initial coating defect of 5% is considered. The value is based on the current demand of the structure during docking (pontoon half submerged). After 10 years of operation the coating breakdown factor is added to the initial coating defect resulting in 35% and 19% bare steel for respectively the hull and splash zone coating systems. Table 4 summarizes the total applied current, the simulated averaged current density and the IR-free potentials. The potentials at the reference electrodes are within the standard deviation of the IR free potential on the rig and are thus representative for the overall protection level of the rig.

Table 4
Simulation results for initial ICCP design

	Applied Current I_{tot} [Amps]	IR-free potentials [mV _{Ag/AgCl}]			Ref. pot. [mV _{Ag/AgCl}]
		averaged	max	stdev	averaged
0 years	240	-659	-1080	37	-643
1 year	180	-854	-1161	28	-839
10 years	240	-709	-1186	42	-688

From Table 4 it can be concluded that the protection level is not achieved after 10 years of operation due to aging of the paint systems. Figure 12 gives a mapping of the IR free protection potentials on the structure. The critical zones between the anodes become apparent.

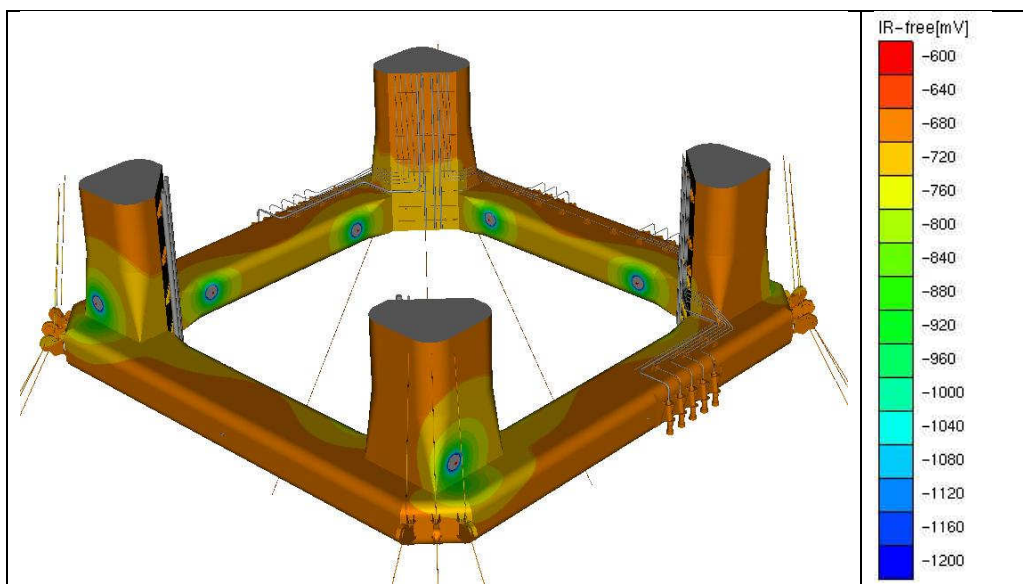


Figure 12: IR free potentials vs Ag/AgCl for initial ICCP design (situation after 10 years)

A redesign was necessary in order to guarantee long term cathodic protection. The amount of MMO anodes was increased from 12 to 20 pieces. They were positioned on specific target locations indicated by Exmar and additional anodes were added on top of the columns and on top of the pontoon. Figure 13 shows the resulting CAD model. The surface area of the dielectric shield around the new anodes was enlarged (diameter of 4 m instead of 2 m). This allowed applying more current on the additional anodes with less risk of overprotection.

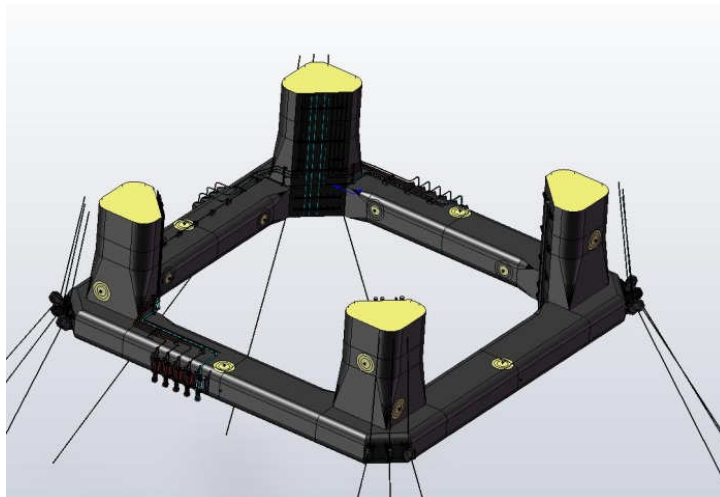


Figure 13: CAD model of Opti-Ex™ (submerged parts) after redesign of ICCP system

Table 5
Simulation results for ICCP redesign

	Applied Current I_{tot} [Amps]	IR-free potentials [mV _{Ag/AgCl}]			Ref. pot. [mV _{Ag/AgCl}]
		averaged	max	stdev	averaged
0 year	640	-720	-1156	62	-722
1 year	260	-899	-1131	27	-902
10 years	540	-859	-1150	54	-859

As could be seen in Table 5 proper protection is achieved except at start-up. This is due to the fact that a calcareous film needs to be formed on the surface. This occurs within a relatively short time of approximately 1 year. From then on, proper protection is guaranteed as can be seen in Figure 14. Through simulation suspicious locations can be studied more into detail like areas around fairleaders, latching heads and MMO anodes (Figure 15).

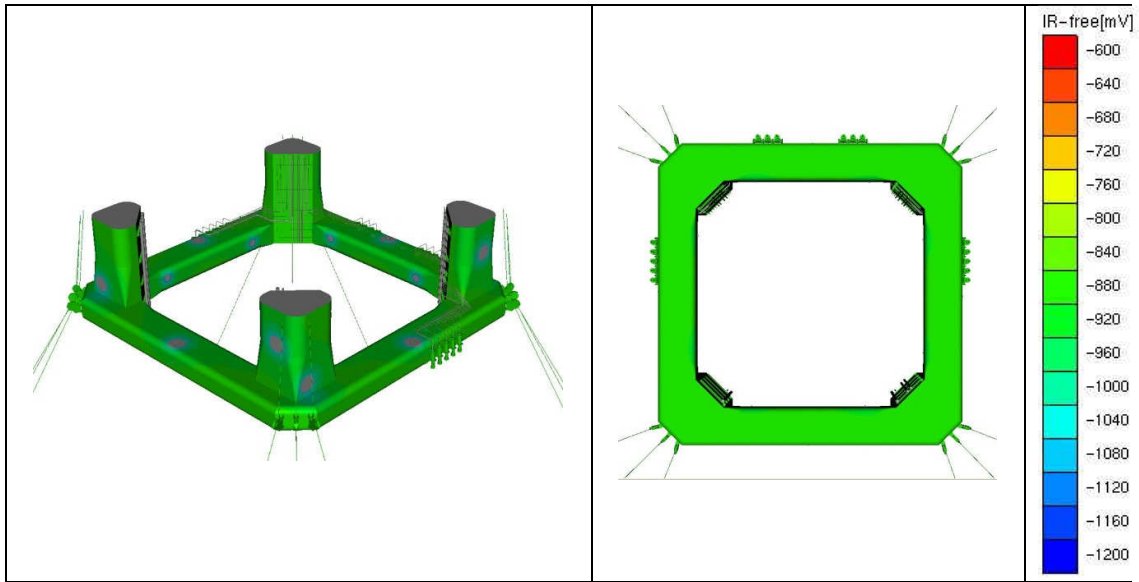


Figure 15: IR free potentials vs Ag/AgCl for ICCP redesign

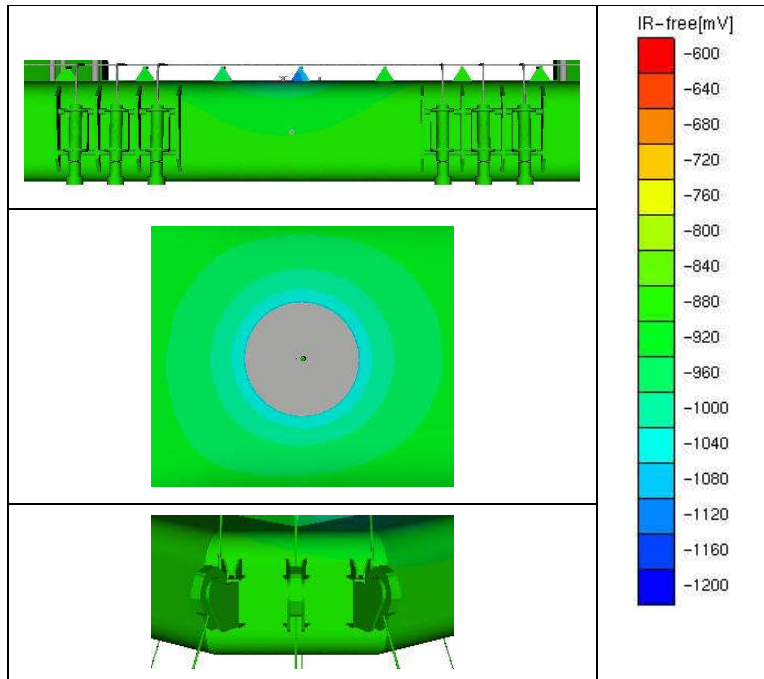


Figure 16: IR free potentials vs Ag/AgCl of hot-spots (ICCP redesign)

The initial current output is relatively high in all cases regardless of polarization effect and initial coating deficiencies of 5%. This is due to the fact that the mooring chains being bare metal are robbing current from the ICCP system. Given their surface area (526 m²) they could not be neglected and their effect should be taken into account when designing the cathodic protection system. As a consequence more current should be applied to protect the hull. The averaged current density *J* of the hull surface is given in Table 6. Remark that the current/potential relationship is given by the cathodic polarization curves in Figure 7. A much lower current density is expected for coated steel.

Table 6
Current density values of the hull at different life stages

	<i>J_{av}</i> [A/m ²]
Decommissioning	0.039
Calcareous film formation	0.016
After coating deterioration	0.042

Simulation of SACP design

The behavior of SACP anodes was simulated in the previous section. The amount of SACP anodes necessary for protecting the semi-submersible rig is estimated according to the DNV RP B401 standard. Sufficient anodes must be foreseen to polarize the structure initially, to maintain the calcareous film and to guarantee proper protection during operation and to re-polarize the structure if calcareous deposits are detached and rehabilitation of the film layer is required.

The required amount of anodes is estimated from the electrochemical capacity ϵ of the Al-Zn-In anode (2500 Ah/kg), the amount of bare steel surface *S* (35% coating breakdown after 10 years or 4156 m²) and the mean current density *J_m* (0.070 A/m²). The same anode types are considered as in the previous section.

$$\# \text{ anodes} = \frac{J_m \cdot S \cdot t_f \cdot 8760}{\epsilon \cdot U}$$

For a service life *t_f* of 10 years the number of 80 kg anodes is estimated to be 142 pieces. The ICCP system in the CAD model is replaced by the sacrificial anodes that are evenly distributed over the rig. Figure 17 shows the new model with the distribution of the anodes.

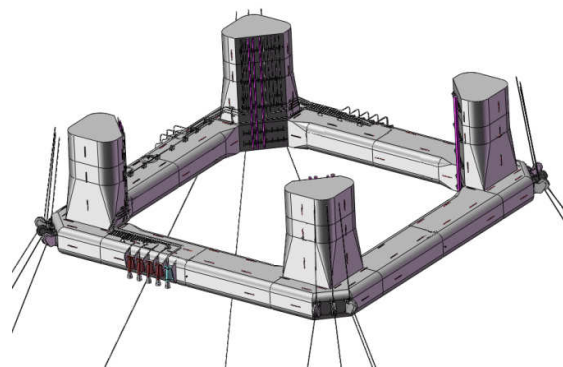


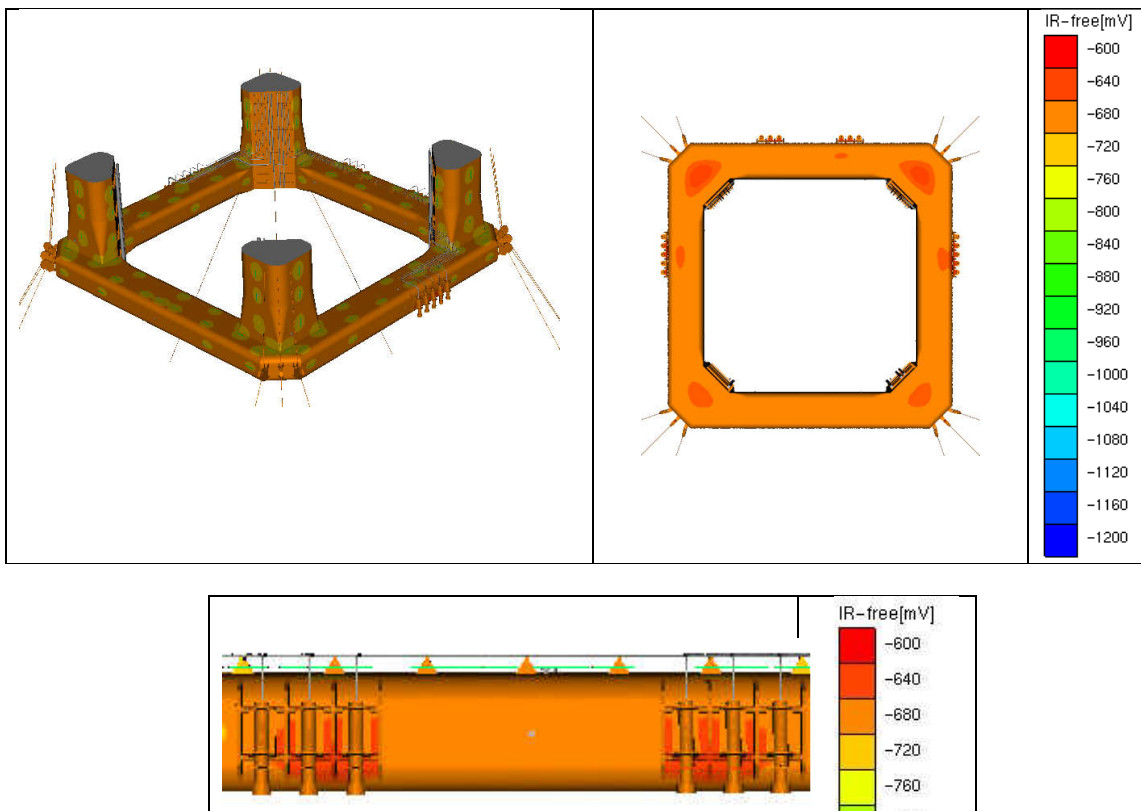
Figure 17: CAD model of Opti-Ex™ (submerged parts) with SACP system

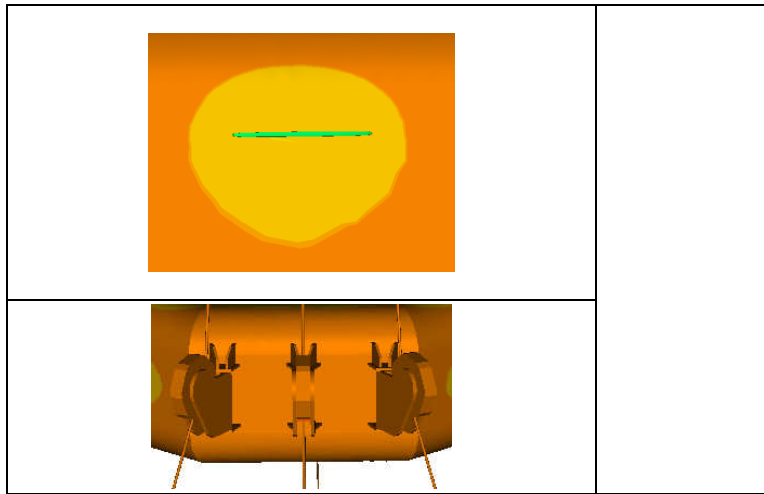
Table 7 gives the results for the situation after 10 years when coating deterioration has occurred. The total delivered current by the anodes is 181 A, 88% of which is consumed by the rig and 12% by the mooring chains. The current consumption by the mooring chains is less than with the ICCP system since sacrificial anodes act rather locally. The IR-free potentials at the surface of the structure show clearly that there is not sufficient protection after 10 years (35% and 19% coating breakdown for respectively hull and splash zone).

Table 7
Simulation results for SACP design

	Anode current I_{tot} [Amps]	IR-free potentials [mV _{Ag/AgCl}]			Ref. pot. [mV _{Ag/AgCl}]
		averaged	max	stdev	averaged
10 years	181	-690	-745	17	-680

Figure 17 shows the simulation results of the IR free potentials after 10 years. It is clear that the rig is underprotected and that corrosion can occur. When applying the DNV standard a proper cathodic protection cannot be guaranteed.





CONCLUSION

The DNV RP B401 standard was applied to design the sacrificial anode system of the semi-submersible rig Opti-Ex™. The dissolution behavior of a single sacrificial anode was simulated by Elsyca's 3D FEM technology taking into account the dynamic shape change of the anode and the polarization data of the anode and the steel in seawater. Simulation results show higher values for the initial and final current output but a lower value for the anode consumption rate compared to the design rules of the DNV standard. The anode resistance on the other hand is in good agreement. Simulations have also been performed for a painted steel plate with an aging coating system. The dissolution behavior of the anode doesn't change significantly compared to the bare steel plate.

The semi-submersible rig Opti-Ex™ from Exmar (Houston) is originally designed with an ICCP system. Through simulation it was clear that long term cathodic protection cannot be guaranteed. A redesign is proposed and proper cathodic protection is achieved. As a comparison a simulation is performed of a SACP system for Opti-Ex™ rig. The amount of anodes is estimated according to the DNV standard. After 10 years of operation the 3D anode shrinkage is calculated and the protection potential of the rig is validated. The results show however that, the Opti-Ex™ rig will be under protected after 10 years of operation. As a consequence expensive anode retrofit will be required if this design was maintained.

Based on Elsyca's simulation technology a proper ICCP system was designed. Long term cathodic protection and safe operation conditions with regard to coating disbonding and hydrogen embrittlement can be guaranteed in a cost effective way.

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REFERENCES

1. L. Bortels, B. Van den Bossche, M. Purcar, A. Dorochenko, J. Deconinck, "Expert 3D software simulations for cathodic protection in offshore and marine environments", Paper #07085, NACE Corrosion Conference 2007.
2. L. Bortels, "Expert 3D Software Simulations for Cathodic Protection in Offshore and Marine Environments", Paper #09516, NACE Corrosion Conference 2009.
3. Purcar M., Dorochenko A., Bortels L., Deconinck J., Van den Bossche B. and, "Advanced CAD integrated approach for 3D electrochemical machining simulations", J. of Material Processing Technology (2007) DOI:10.1016/J.JMATPROTEC.2007.09.082
4. H. P. Hack, "Atlas of Polarization diagrams for Naval Materials in Seawater", Naval Surface Warfare Center, Bethesda, Md. 20084-5000, Technical report 61-94/44, 1995.
5. A.G. Munoz et al., "Corrosion of an Al-Zn-In alloy in chloride media", Corrosion Science 44 (2002) 2171.