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Application of Cathodic Protection Simulations in Hydrogen Embrittlement Risk Assessment

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ABSTRACT

Cathodic protection (CP) systems are widely employed to prevent corrosion in metallic structures. Despite their effectiveness in corrosion risk mitigation, overprotection can result in hydrogen embrittlement (HE)—a phenomenon where hydrogen atoms penetrate metal, causing brittleness and potential failure. This study explores advanced cathodic protection simulation techniques for geometrically complicated structures, with a specific focus on their application in HE risk assessment.

Through advanced computational modeling, we simulate the behavior of CP systems under various environmental conditions and material configurations. These simulations enable a deeper understanding of the interactions between cathodic protection and hydrogen absorption, diffusion, and trapping within metallic lattices. The study examines how different levels of CP current density, environmental factors, and metal types influence the risk of hydrogen embrittlement.

The study highlights the challenges of overprotection, which can inadvertently exacerbate hydrogen evolution and uptake, leading to increased embrittlement risks. The findings demonstrate that optimized CP systems can significantly reduce the likelihood of hydrogen embrittlement by controlling hydrogen evolution rate at the metal-electrolyte interface and its ingress into the metal.

This research provides valuable insights into the design and application of cathodic protection systems for critical infrastructure, offering guidelines to balance corrosion protection with the prevention of hydrogen embrittlement.

INTRODUCTION

Hydrogen embrittlement results from hydrogen atoms infiltrating the metal lattice, causing a decline in ductility and load-bearing capacity. This is particularly evident in high-strength steels and alloys. Cathodic Protection is an electrochemical technique used to control the corrosion of a metal surface by making it the cathode of an electrochemical cell. The integration of simulation techniques aids in optimizing CP systems to reduce the risks of HE.

CATHODIC PROTECTION (CP): A BRIEF OVERVIEW

CP involves shifting the electrochemical potential of a metal to prevent or reduce corrosion. The two main types are galvanic (sacrificial anodes) and impressed current CP. Both systems work by supplying electrons to the metal surface, reducing the metal ion formation that contributes to corrosion. The major issue is above certain potential, hydrogen evolution and hydrogen absorption may take place that may cause HE in high strength steels and high performance alloys in aggressive environments such as corrosion acidic soils, subsea environments.

HYDROGEN EMBRITTLEMENT (HE)

HE is exacerbated by environments that facilitate hydrogen uptake, particularly under high stress. Hydrogen atoms penetrate the metal surface, leading to crack formation and propagation. It is imperative to balance CP potential to protect against corrosion while minimizing hydrogen generation.

CATHODIC PROTECTION AND HYDROGEN EMBRITTLEMENT (HE)

CP is a widely used method to prevent corrosion of metals, particularly in harsh environments such as pipelines, acidic soils, and subsea structures. However, a critical issue arises when CP potentials exceed a certain threshold. In high-strength steels and high-performance alloys, excessive cathodic potential can lead to the evolution of hydrogen gas. This hydrogen, once generated on the metal surface, can be absorbed into the material.

When hydrogen enters the microstructure of metals, it can cause HE, a detrimental process where the material becomes brittle and loses its ductility. This is particularly problematic in high-strength steels and alloys used in aggressive environments, as they are more susceptible to HE. In such cases, the presence of absorbed hydrogen can lead to premature failure through cracking or fracture, significantly impacting the integrity of infrastructure such as pipelines and subsea equipment.

In aggressive environments, especially where CP is applied (e.g., to prevent corrosion in subsea very low oxygen environments), the interaction of high-performance alloys with hydrogen can lead to serious consequences. It is crucial to carefully control the CP potential to avoid conditions that promote hydrogen absorption and minimize the risk of embrittlement.

Our research has shown that it is now possible to determine the hydrogen concentration which causes hydrogen embrittlement. We can also show how that content depends upon cathodic potential that each portion of the component “sees”. Having this ability greatly magnifies the value of FEA CP simulations. We can with confidence predict the risk of HE and where it is anticipated.

This is a complex issue that must be managed through appropriate monitoring and selection of materials, as well as ensuring that CP systems are properly designed and maintained to mitigate the risks of hydrogen embrittlement while providing adequate corrosion protection.

Another breakthrough, which we discuss in other papers, is the ability to measure hydrogen content real time. So, with FEA CP simulation showing us danger zones and in-situ hydrogen concentration of the component, hydrogen embrittlement becomes manageable.

USING FINITE ELEMENT ANALYSIS (FEA) AND POTENTIAL SIMULATION TO IDENTIFY HYDROGEN EMBRITTLEMENT (HE) RISK AREAS

FEA and potential simulation techniques are powerful tools in predicting and managing corrosion and hydrogen embrittlement (HE) risks, especially in complex systems like pipelines, subsea structures, and other metallic infrastructure. When cathodic protection (CP) is applied to these structures, the key concern is ensuring that the potential stays within the safe limits to prevent excessive hydrogen evolution, which can lead to hydrogen embrittlement, especially in high-strength steels and high-performance alloys.

ROLE OF FEA IN PREDICTING CRITICAL AREAS

FEA allows engineers to model the distribution of electrochemical potentials across the entire surface of a metallic structure under cathodic protection. By inputting material properties, environmental conditions, and the geometry of the system, FEA can simulate how electric fields and potentials are distributed across various regions of the structure.

Steps Involved in FEA and Potential Simulation:

1. **Modeling the System Geometry:**
    - Complex geometries, such as pipelines, welds, and subsea structures, are accurately represented in a 3D model.
    - The model accounts for all relevant features, including metal surfaces exposed to aggressive environments, coatings, and weld joints.

2. **Defining Material Properties and Boundary Conditions:**
    - High-strength steels and high-performance alloys used in subsea or industrial applications often have known electrochemical properties. These properties, including the potential ranges where hydrogen evolution may occur, are defined within the simulation.
    - Environmental conditions such as temperature, pressure, salinity (for subsea applications), and pH are also input to ensure accurate representation of real-world conditions.

3. **Simulating Cathodic Protection (CP) Systems:**
    - The CP system is modeled by placing anodes and defining the current distribution across the structure. This simulation shows how the applied CP potential changes across different regions, and FEA predicts where potentials may drop below the critical threshold, causing hydrogen evolution.
    - The simulation identifies areas where the potential is overly negative, indicating regions where the risk of hydrogen evolution and subsequent embrittlement may be high.

4. **Analyzing Hydrogen Evolution Zones:**
    - FEA provides detailed maps of potential distribution across the entire structure, allowing engineers to pinpoint areas where the potential is negative enough to cause hydrogen evolution (typically below -0.8 V vs. Ag/AgCl in seawater).
    - High-stress areas such as welds, bends, or other discontinuities in the structure are of particular concern since these are often the initiation points for hydrogen-assisted cracking.

5. **Predicting Hydrogen Absorption and Embrittlement:**
    - The potential maps generated from FEA are cross-referenced with material properties, such as hydrogen diffusion rates and critical thresholds for embrittlement.
    - Areas where the local potentials are overly negative, combined with high stress, will be flagged as regions at high risk for HE.

Benefits of Using FEA for HE Risk Assessment:

1. **Accurate Prediction of Risk Areas:**
   - FEA allows for a precise mapping of at-risk areas where hydrogen generation is most likely to occur, enabling better-targeted inspections and maintenance strategies.

2. **Optimization of Cathodic Protection Systems:**
   - By understanding the potential distribution across the structure, the CP system can be optimized to avoid over-protection, reducing the likelihood of hydrogen evolution.
   - FEA helps determine the ideal placement and sizing of anodes, minimizing the risks of excessive negative potentials.

3. **Informed Material Selection:**
   - The results from FEA simulations can guide the selection of appropriate materials for different areas of the structure, ensuring that materials less susceptible to HE are used in high-risk zones.

4. **Proactive Maintenance and Monitoring:**
   - By predicting high-risk areas for hydrogen embrittlement, operators can implement monitoring systems such as hydrogen sensors, strain gauges, and periodic inspections at targeted locations to detect potential failure before it occurs.

Challenges and Considerations:

- **Model Complexity:** Accurate simulations depend on the detail of the model and the precision of input parameters, including environmental variables and material properties.

- **Potential Gradients:** High gradients in potential distribution can occur near coatings and welds. FEA helps map these gradients and assess their impact on hydrogen generation.

- **Environmental Factors:** Variables such as seawater chemistry, temperature, and flow rates can affect hydrogen generation and absorption rates, making it crucial to incorporate these into the simulation for more accurate results.

Discussion:

Using FEA and potential simulation in conjunction with cathodic protection systems is an advanced approach to prevent hydrogen embrittlement in high-strength steels and alloys. It allows for the proactive identification of at-risk areas where potentials are sufficiently negative to cause hydrogen generation, providing valuable insights for design, optimization, and maintenance of critical infrastructure.

1. **Design Optimization**: Simulations help design optimal CP systems, ensuring adequate protection without overprotection that might promote hydrogen uptake.

2. **Material Selection**: By simulating different environmental and operational scenarios, materials less susceptible to HE under CP can be identified.

3. **Environmental Impacts**: Simulating varying environmental conditions allows for predictive analysis of CP performance, tailoring systems to specific locations.

Simulation Techniques:

Advanced computational methods, including FEA is employed to simulate CP and its interaction with materials. These simulations incorporate chemical, electrochemical, and mechanical factors to understand the comprehensive effects of CP on hydrogen embrittlement.

Applications and Case Studies:

1. **Pipeline Protection**: Simulations can assess the CP system's impact on pipeline materials, ensuring protection against both corrosion and HE in varying soil and fluid environments.

2. **Subsea Platform Components**: For subsea components exposed to corrosive environments, CP simulation informs design choices for enhanced HE resistance.

3. **Aerospace Applications:** CP simulation is critical for protecting aircraft components susceptible to high-altitude moisture induced HE.

CASE STUDY:
CP SIMULATION FOR X-TREE IN DEEPSEA APPLICATIONS

In this study high-resolution finite-element analyses are performed to investigate effectiveness of a sacrificial anode arrangement on cathodic protection of a Subsea X-tree structure, including a high strength Collet Connector made of F22 (105 Ksi). A three-dimensional CAD model of the X-tree structure is shown in Figure 1. As shown in the CAD model, twelve aluminum-alloy anodes are attached to the X-tree for cathodic protection purpose — ten anodes attached to the structure frame and two smaller anodes mounted on top of the pipe assemble. It is important to mention the X-tree geometry is modified to reduced unnecessary geometry features such as bolts, nuts, threads, small holes, etc. Also, additional components of the structure were deleted/modified during FEA analysis due to presence of overlapping surfaces and tiny gaps (manufacturing tolerance) that prevented construction of a computational mesh.

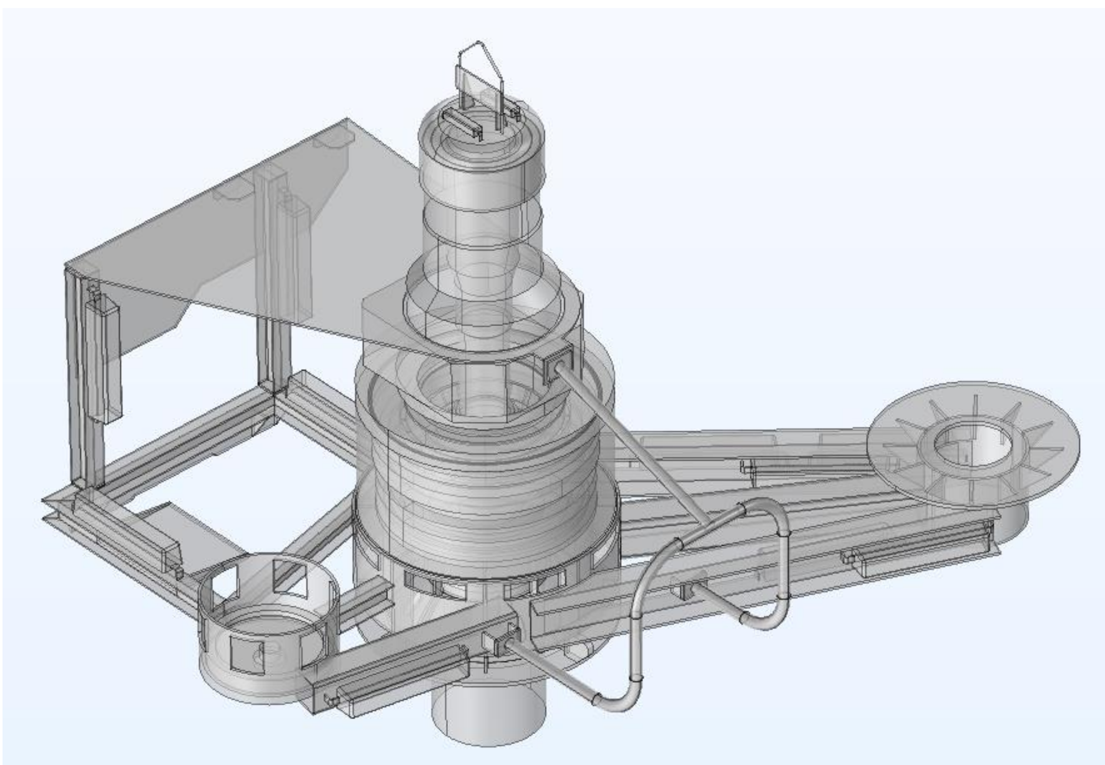

Figure 1: Three-dimensional CAD model of X-tree structure

The ultimate objective of simulations is to investigate whether the current anode arrangement provides protection to *internal surface* of the assembly in service; meanwhile cathodic protection potential distribution on *external surface* is also evaluated.

A cross-section of the X-tree assembly is shown in Figure 2 where surfaces of interest are highlighted inside yellow boxes.

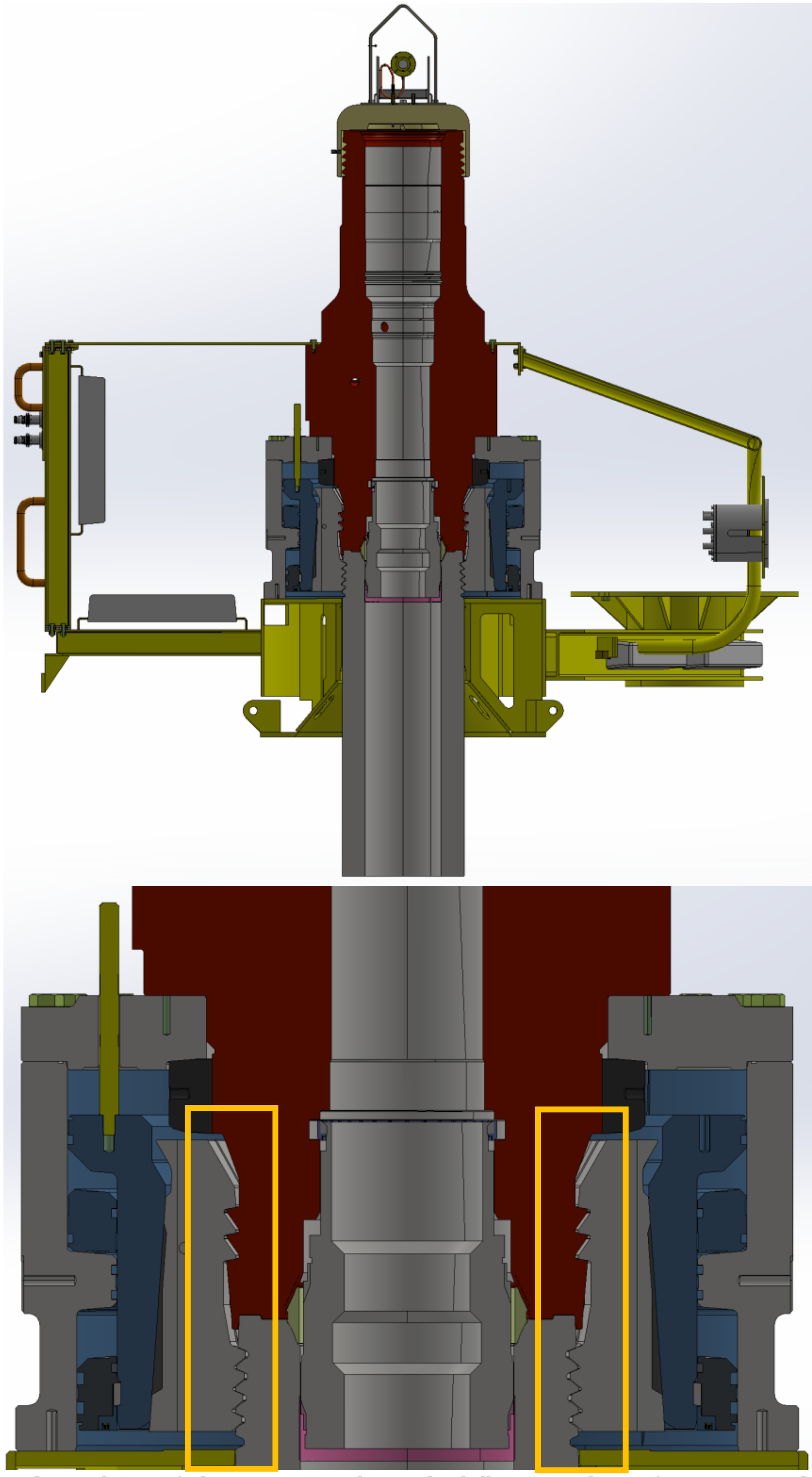

Figure 2: Cross-section view of the X-tree. Threaded (internal) surfaces are shown inside yellow rectangles.

Electrochemical Model Assumption

It is understood that the structure is fully coated, and different types of high-strength steel alloys are used for the components; however, in the initial stage of this study effects of protective coating are neglected. Furthermore, it is assumed that all surfaces in contact with seawater are made of carbon steel, thus a constant equilibrium potential is prescribed to all surfaces of the X-tree structure in contact with seawater.

Anodic and cathodic Tafel equations are used as kinetic boundary conditions to relate the current density at anode-seawater and structure-seawater interfaces to potentials of the anodes and the structure.

The assumed kinetic parameters used in simulations are listed in Table 1. Since accuracy of simulation results strongly depend on Tafel parameters (i.e., Tafel slopes and exchange current densities) it is highly recommended to experimentally measure these values to achieve realistic potential distribution. The assumed kinetic parameters can be easily updated with actual values once potentiodynamic measurements (three electrode setup) are completed to evaluate Tafel parameters for the following materials:

- Carbon steel
- LAS F22
- Pipe X65
- Inconel 718
- Super Duplex 2507
- Anode material (aluminum alloy)
- Coating material

All potentials are reported with respect to Ag/AgCl-seawater reference electrode (solid junction).

Table 1:
Electrochemical model input parameters

Parameter	Value	Unit
Seawater resistivity	0.2	[Ohm-m]
Seawater conductivity	5	S/m
Structure equilibrium potential	-0.6	[V]
Cathodic Tafel slope, Structure	-110	[mV]
Cathodic exchange current density	0.001	[A/m^2]
Anodes equilibrium potential	-1.1	[V]
Anodic Tafel slope, Anodes	50	[mV]
Anodic exchange current density	0.1	[A/m^2]
Limiting current density, aluminum alloy	100	[A/m^2]

Seawater Ingress Path

Based on the provided CAD model for the X-tree assembly, it was a challenging task to confirm a continuous path for seawater penetration from open seawater into the threaded assembly. Since all components are designed with a manufacturing tolerance, formation of very small voids and gaps between assembly parts are expected, nonetheless, it is not known if all these voids are actually connected.

After consulting with the end user, and to address this issue, two sub-assemblies which are in contact through the threads are modified to exaggerate the tolerance between assembly parts and construct an apparent path for seawater ingress.

The modification includes size scale-up for the external sub-assembly by 5%, and size scale-down for the internal sub-assembly by 7%. In Figure 3, the external and internal sub-assemblies are highlighted with yellow and blue colors, respectively. In Figure 4, a cross-sectional view of the scaled sub-assemblies is shown. The areas with gray color correspond to seawater. This confirms that these components are electrolytically connected to anodes through seawater; thus, a cathodic protection simulation is feasible.

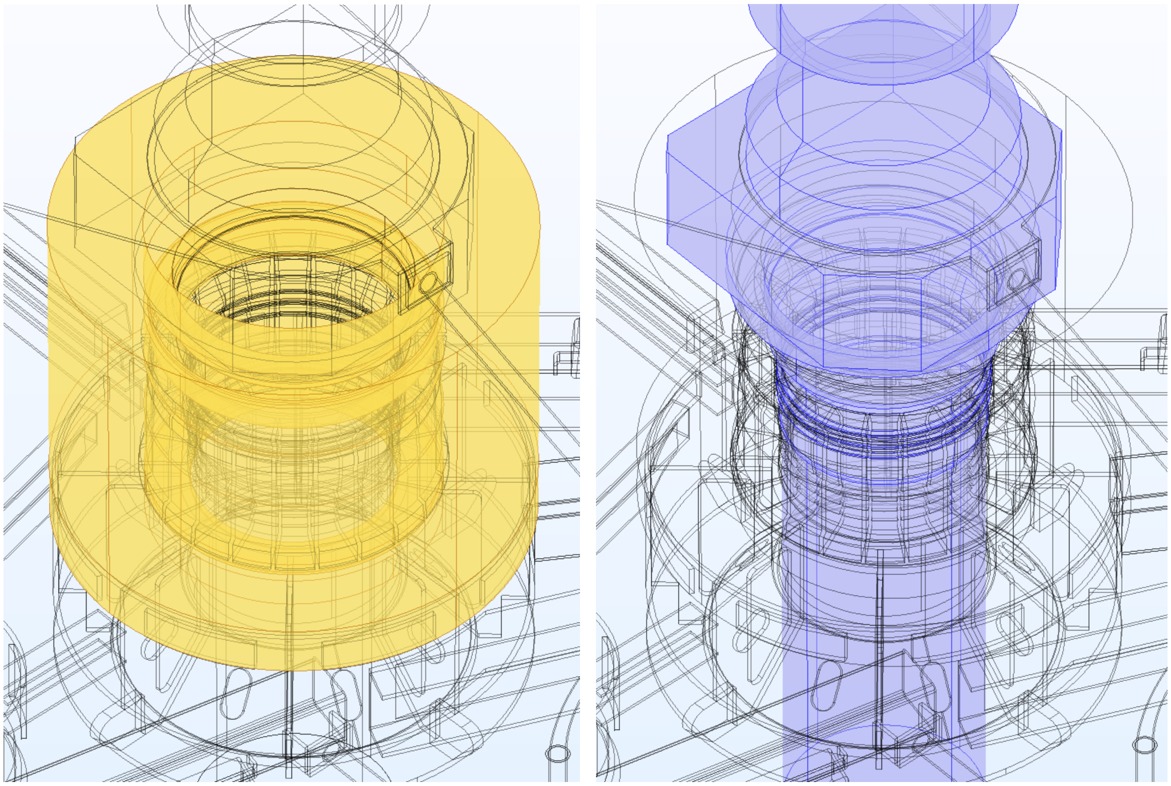

Figure 3: Scaled sub-assemblies to assure seawater ingress.

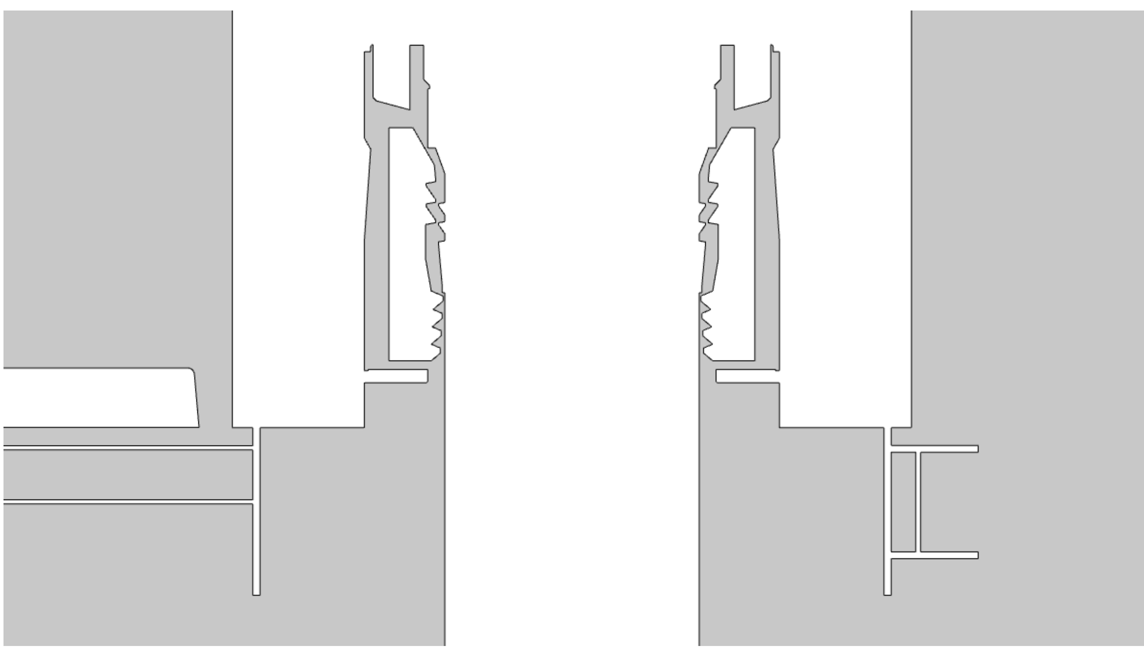

Figure 4: Cross-sectional view of the scaled assemblies to show seawater ingress.

Potential Distribution

A shown in Figure 5, free tetrahedral mesh generation technique in spherical coordinate is utilized to generate the computational grid inside seawater domain (dome) and on the surface of the X-tree structure in contact with seawater. Some peripheral components of the structure are deleted to facilitate mesh generation process; compare Figure 5 to Figure 1.

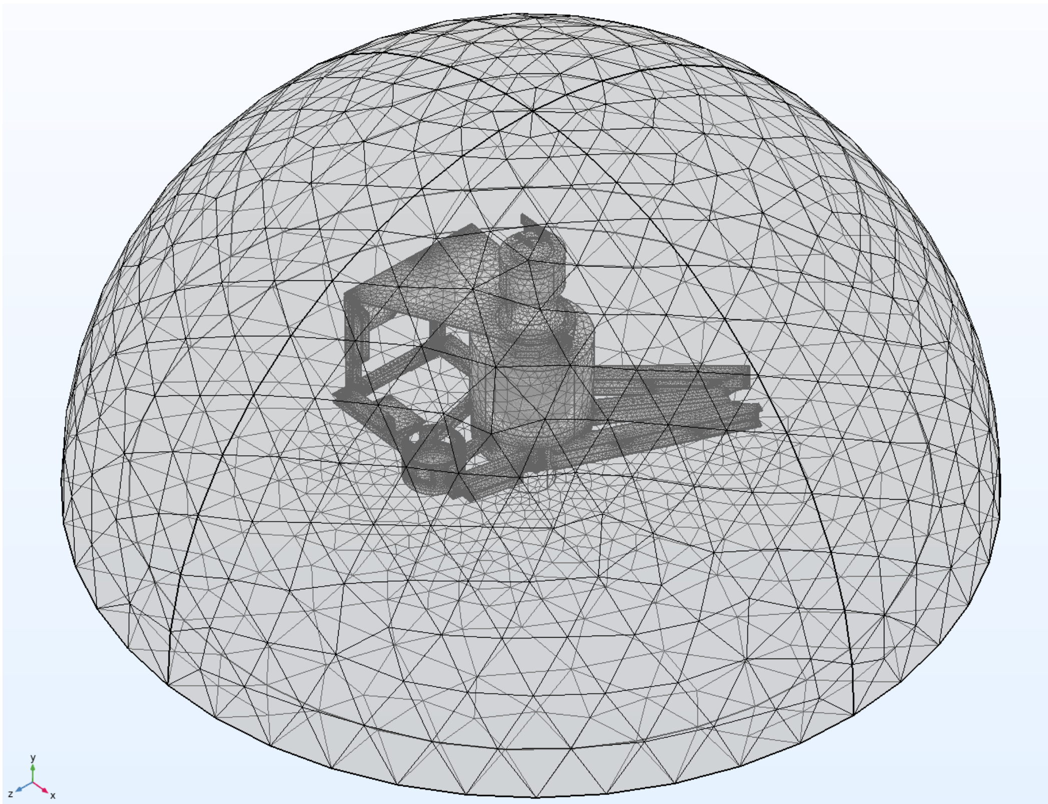

Figure 5: Computational domain with high-resolution tetrahedral mesh; dark areas represent mesh refinement zones.

Potential distributions on external surface of the X-tree is shown in Figure 6. The data confirms all external surfaces are protected but the internal threaded assembly receives the lowest level of protection — and can be completely unprotected if sizes of the gaps are reduced to their real values (i.e., manufacturing tolerance).

Results and Discussions

For a better illustration, a cross-sectional view of potential distribution in seawater is shown in Figure 7. The results clearly show a significant potential drop in vicinity of the threaded assembly. It is important to mention that geometry modification, i.e., size scale-up and scale-down of threaded components, has created a significantly large channel for water penetration and ionic current. In the real assembly the CP current must travel a long much smaller channels that can result in much lower cathodic polarization.

It concludes that in an assembly with small manufacturing tolerances, externally installed anodes will not provide sufficient cathodic polarization to the internal components due to lack of electrolytic connectivity.

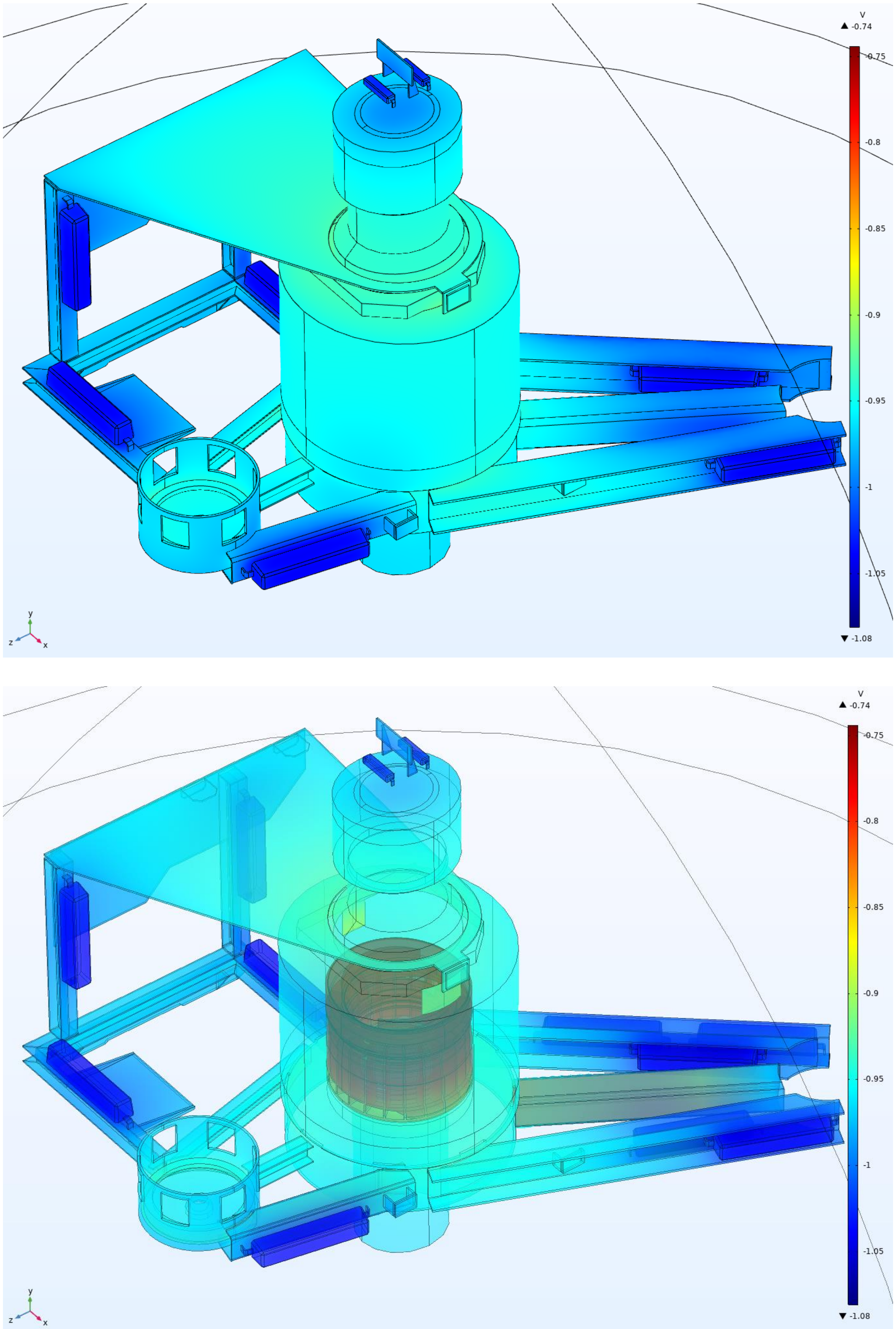

Figure 6: Potential distribution on external and internal surfaces of the X-tree structure (transparency of surfaces are increased in the bottom figure to show the potential drop inside the assembly)

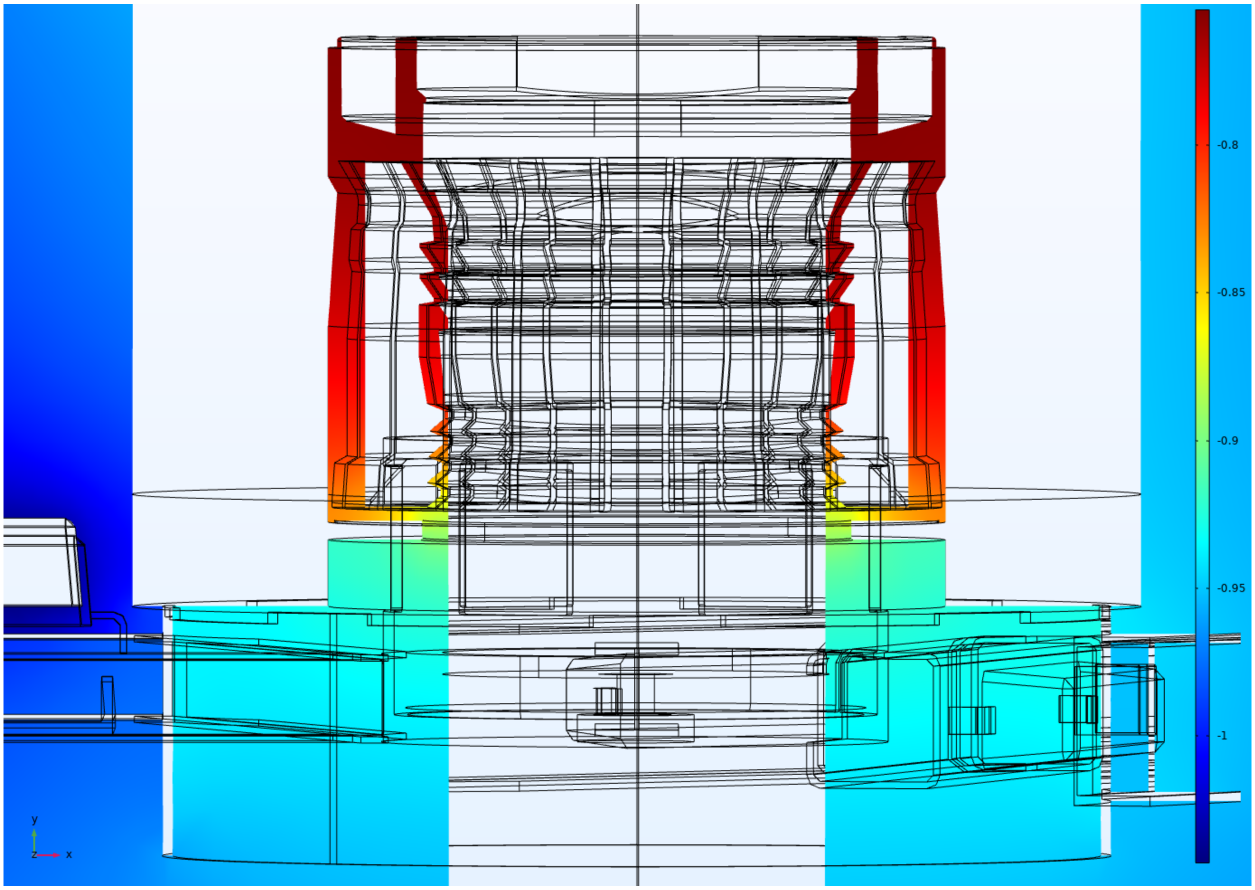

Figure 7: Cross-sectional view of potential distribution in seawater (electrolyte). Seawater potential inside and outside the threaded assembly is shown.

Conclusion

Cathodic Protection simulation offers invaluable insights into balancing corrosion protection and hydrogen embrittlement mitigation. By leveraging computational models, industries can enhance material longevity and safety. As simulation technologies continue to advance, the integration of predictive analytics will further refine CP strategies.

Future Work

Ongoing research into integrating multi-scale modeling with real-world monitoring data will provide a more comprehensive understanding of CP and its effects on hydrogen embrittlement, paving the way for smarter and more efficient materials protection strategies. Hydrogen sensors will provide real time feedback to FEA CP models to fine tune real time risk assessment.

A further level of sophistication in both FEA and hydrogen measurement involves accounting for different loading cycles. It is known that cyclic loads exacerbate hydrogen embrittlement. Cyclic loading is a magnifier of hydrogen embrittlement. But it too, can be analyzed through FEA. These can also be modeled, and the feedback from hydrogen content sensing will allow this more insidious form of HE to be quantitatively analyzed and avoided.