GALVANIC CORROSION PREVENTION OF COMPLEX ASSEMBLIES THROUGH MODELING

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ABSTRACT

Corrosion impacts the value, safety, and readiness of many assets in almost all industries. The cost of maintaining and repairing runs into astronomical numbers.

The current approach to evaluate susceptibility to galvanic corrosion is by determining the relative position of metals in the galvanic series table valid for a given environment. However the potential difference between metals provides no information on the kinetics of galvanic or bimetallic corrosion. Additionally, there is a wide range of factors which affect the corrosion severity like surface area ratio, flow rate, temperature, dry-wetting cycle, inhibiting effects, etc. Moreover, in most mechanical assemblies the overall effect of multiple material components and the complexity of the geometry make corrosion prediction difficult.

In this article a unique 3D simulation technology to predict galvanic corrosion will be presented. Potential distributions and corrosion rates are calculated based on electrochemical characterization of the different materials in lab conditions. Corroded areas are visualized by the software tool and are compared with real-life observations on assemblies. The examples show cases where engineers select different material combinations of complex assemblies in a virtual environment during the design process and assess the corrosion behavior of the complete system under various environmental conditions. The technology provides quantitative information on the corrosion risk as well as the corrosion rate. Thus, ensuring target performance and safe operation.

Keywords: galvanic corrosion, prediction, simulation technology

INTRODUCTION

Corrosion impacts the value, safety, and readiness of many assets in almost all industries. The cost of maintaining and repairing runs into astronomical numbers. When looking at the Department of Defense (DoD) alone, an estimated annual cost of $22Bn is corrosion related[1].

Galvanic corrosion occurs when there is a potential difference between two different metals connected through an electrolyte, and current is running from the more active metal to the more noble metal. Complex mechanical assemblies comprised of components made of dissimilar metals and exposed to wet environmental conditions (such as immersion in water or a thin film of moisture) have galvanic couples designed inadvertently into their components.

Galvanic corrosion is well known, yet a significant proportion of corrosion incidents can be traced back to galvanic issues in a subsystem, resulting in unexpected, high rates of corrosion. There have been some well-publicized failures, even with the newest platforms.

For example, the F-22, experienced severe corrosion of the skin and aluminum airframe structure within six months of entering service. The source was determined to be galvanic corrosion between noble metal flakes in the gap filler and the aluminum substructure that occurred with the ingress of rainwater. $238M has been allocated[2] to rectify this problem, and even now there is no guarantee that the proposed solution will work. There are also well-known problems in legacy systems. F-18 wing fold actuators, for example, have always been a major galvanic corrosion challenge because they use high strength steels in close proximity to Ni-based alloys in a system where protective coatings are quickly damaged and the actuators are exposed to salt spray for prolonged periods, resulting in a large number of lug failures due to galvanic corrosion[3].

With new designs and legacy system upgrades, the galvanic corrosion problem has become orders of magnitude more difficult. Legacy systems primarily comprised chromated Al frames and skins, and high strength steels that were Cd plated and chromated, all protected with chromated primer. Modern systems contain many more materials and finishes driven by requirements for minimization of environmentally unacceptable materials such as cadmium and chromates. Many materials include carbon fiber composites, titanium, specialty coatings, and metal flake-filled gap fillers, all of which must operate without benefit of chromate conversion coatings and chromated primers. Cd may be replaced with CRES alloys and coatings such as Al, ZnNi, Zn/Al flake, and even electroless Ni; numerous Cr^{3+} and non-Cr alternatives are used, while primer inhibitors include organics and inorganics, as well as Mg particles. The number of potential galvanic interface conflicts is growing exponentially and galvanic design can no longer rest on rules of thumb; in fact we do not even have valid galvanic data for most of today's materials and finishes.

State-of-the-art structural, thermal and aerodynamic engineering software tools are used by industry to design and assess systems. Many characteristics of a complex assembly, including metals used, selected surface finishes, and operational conditions such as moisture, humidity, and temperature, can impact its galvanic corrosion resistance. Clearly, a reliable computational method is required to avoid designing galvanic corrosion into modern systems, as well as for correcting galvanic corrosion problems in legacy systems, especially as new materials are adopted to meet mandates.

Working in close collaboration with a major automotive supplier, a simulation software[1] has been developed that predicts where galvanic corrosion will occur on mixed metal assemblies and calculates the corrosion rate.

The software provides designers with the means to see how materials will interact with each other. The user identifies the materials, selects the operational environment, and the software produces a simulation model that illustrates areas of galvanic corrosion as well as the corresponding predicted corrosion rates. It helps designers avoid making design decisions that result in components in the field with galvanic corrosion issues that affect their service life. The software doesn't just calculate areas of anodes and cathodes and make a judgment as to whether or not the assembly will corrode; it also calculates the corrosion rates on each and every point on that geometry.

In the following section the basics of the galvanic corrosion simulation platform are explained.

GALVANIC CORROSION SIMULATION PLATFORM

The galvanic corrosion simulation platform presented here comprises a materials database and engineering software that utilizes the database to calculate galvanic corrosion risks.

The software does not calculate surface areas nor uses look-up tables of metals and corresponding corrosion potentials to identify corrosive areas.

Instead an FEA (Finite Element Analysis) method is employed to solve the fundamental electroche-mical equations that govern the corrosion phenomena taking into account:

- Laplace's equation which calculates the potential distribution (U) in the electrolyte with a given conductivity (σ)
- Ohm's law linking the electrolyte potential (U) with the current density (J)
- Polarization behavior linking the electrolyte potential (U) and metal potential (V) with the current density
- Faraday's law which calculates the corrosion rate (CR) for a given time period as a function of the local current density

Acquisition of polarization data

The materials database consists of polarization curves for each material and environment under consideration. Polarization is the change in potential on a metal surface due to current flow, and a polarization curve is the measurement of the polarization characteristics of a particular material in a particular electrolyte. Basically, the curve describes the corrosion behavior of the material in a given environment. Polarization curves are not standard. They have to be measured and input into the database.

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[1] GalvanicMaster by Elsyca (www.elsyca.com)

In order to predict galvanic corrosion rates by employing a physics-based approach, it is essential to have reliable polarization data from the materials involved, including alloys, coatings, surface treatments, and of course the wetting electrolytes – whether they are salt solutions or mixtures of water and di-icing fluids etc. The substrates can comprise bare metals or alloys, but in most cases a surface treatment will be present (e.g. anodized layer, Cd or hard chrome plate, composites, or a variety of chromate conversion alternatives).

Basically, there are two different methodologies for obtaining polarization data. Linear Sweep Voltammetry (LSV) is a fast method for obtaining polarization curves, but it does not allow for a proper characterisation of long-term polarization behavior that is influenced by film formation (corrosion products, compact oxide layer leading to passivation, etc.). Hence simulation results that are obtained based on these polarization data only allow for a qualitative determination of the corrosion risk, which may still be of benefit to a designer early in the design project.

Potentiostatic point-by-point measurements on the other hand are more elaborate and allow for obtaining simulation results with more quantitative accuracy. These experiments typically expand over a time period that extends at least to 30 minutes. The current response is recorded over time. The coupons are examined after the experiment for roughness (using a Surface Roughness Tester) and morphology (SEM), in order to check for the appearance of pits or other anomalies.

This allows for a more detailed understanding of the corrosion speed as a function of current density. Also, due to the extensive duration of each experiment, the film formation (including passivation) is fully accounted for.

Qualitative prediction of galvanic corrosion

The software uses a new and unique thin film approach comprising an analysis based on a constant film thickness (d) and constant conductivity (σ) (derived from the environmental parameters) and a potential method approach that models the gradient of the electrolyte potential in relation to the distance to the surface. The software automatically calculates the overlap between thin films on different bodies to ensure ion transfer between neighboring bodies with overlapping films.

The environmental parameters leading to the automated selection of the polarization curves are derived from a (customized) wizard interface. The thin film approach is much more suited to solving corrosion problems in automotive and aerospace systems, as opposed to submersed marine systems and structures[2].

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2 For fully submersed systems a dedicated simulation tool based on the bulk electrolyte approach has been developed as described in detail in references[4-7]. The latter approach currently requires the user to be more skilled in FEA and CAD technologies.

The software is being developed with user-friendliness in mind. The features embedded into this tool form a strong foundation for a dedicated galvanic corrosion prediction tool:

- Pre-processor
  - Generic and flexible CAD-import tool (STL-based[3])
  - Automatic high quality surface mesh
  - Automated polarization curve selection
- Solver
  - Robust and fast
  - Supports multi-body configurations and external current sources
- Post-processing
  - Fully automated and configurable reporting
  - Powerful visualization tool available throughout the organization

The input for the high quality surface re-meshing is a low quality STL triangulation which can be generated by any CAD package. This STL triangulation is only used within the CAD package to represent the CAD model, it can as such not be used to perform numerical simulations due to the bad quality of the mesh. The STL remesher that has been developed within this platform automatically replace the low quality STL mesh with a high quality surface mesh needed for the thin film simulations. This will become clear in the example.

The typical process workflow is indicated in Figure 1:

- Starting with the 3-D model of the system on the left, the materials and coatings are identified by clicking on the components and assigning the materials to them
- Next the environment is defined in terms of the corroding liquid (usually saltwater) and thin film properties (thickness and conductivity)
- The model is then meshed for FEA, which is done automatically by the software
- The software then goes on to solve the electrochemical equations subject to the boundary conditions established by the materials, the model and the environment
- The software produces a 3-D rendering of the model showing corrosion rates by color on a model that can be rotated, expanded, and evaluated in detail by the user
- The software simultaneously produces a customized report that includes pictures, and summary tables with relevant corrosion related information (such as predicted corrosion rates)

If the resulting corrosion rates in the simulation are excessive, the user can go back and adjust the materials selection, run the processing step again, and within a few minutes obtain the corresponding corrosion rates for the new materials selection. From the results, the user can determine which material combinations offer the best corrosion resistance.

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[3] STL is a file format native to the stereolithography CAD software created by 3D Systems[8]. STL files are widely used for rapid prototyping and computer-aided manufacturing[9].
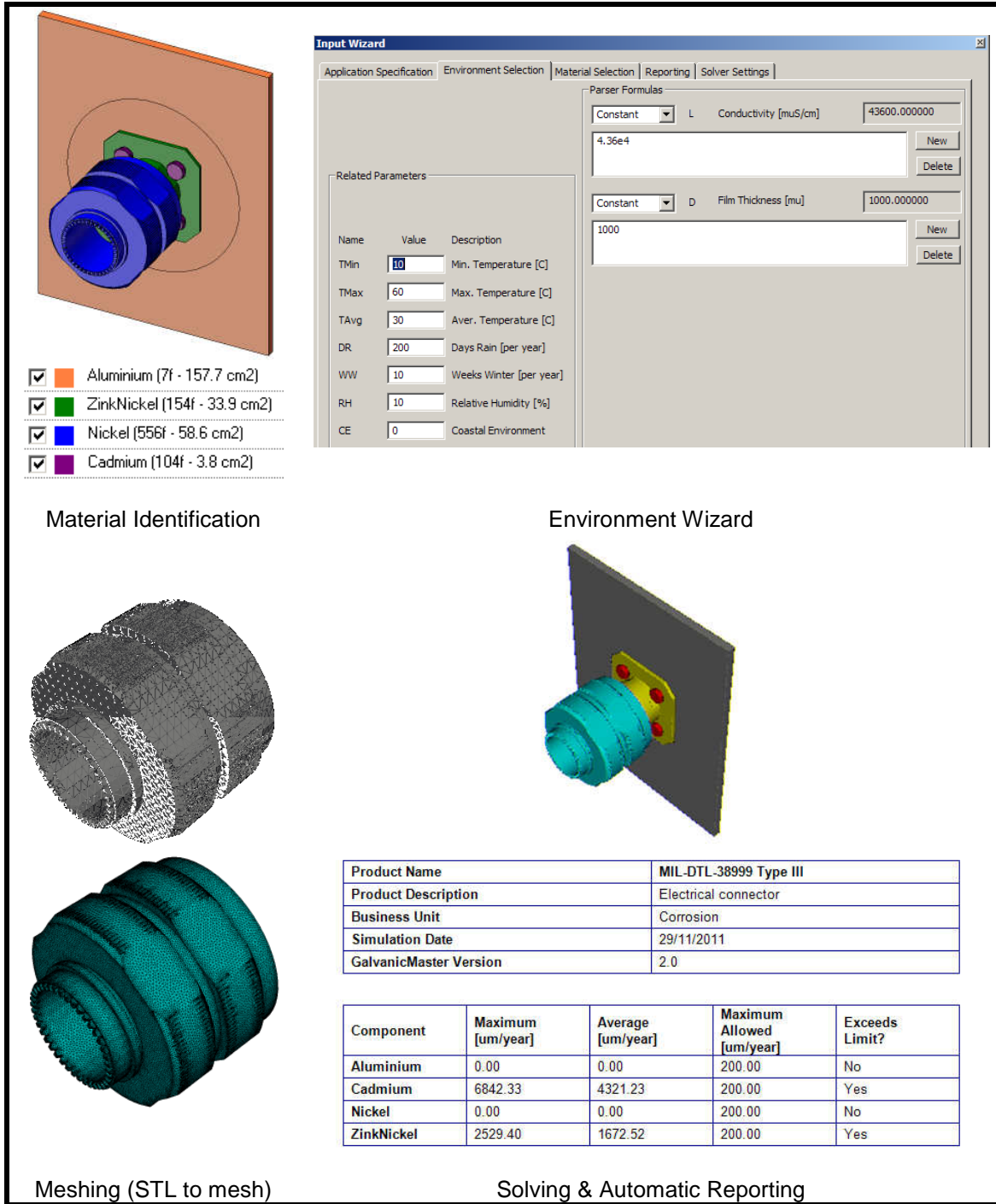
Material Identification

Environment Wizard

Meshing (STL to mesh)

Solving & Automatic Reporting

FIGURE 1. Simulation software process flow

CASE STUDY

The model studied here is the Ball Intake Valve[10] commonly used on fire engines to control the flow of water into the pump. The valve's lightweight aluminum design and patented waterway has proven ideal for use on mobile equipment. Fresh water inside the valve is drained from the valve between uses, leaving only stainless steel valve components exposed to the residual water inside the pump manifold. This combination has a reputation for excellent corrosion protection.

It's no wonder that firemen are trying this valve in new applications and harsher operating environments like exposure to 24/7 water, and bolted on exterior piping in the hot sun. The aluminum doesn't fare as well in this situation, but it can have an acceptable service life.

However, the results can be far different when coupled to brass or when filled with salt water. Salt water is harsh by itself but brass just takes away aluminium's natural corrosion resistance. Brass contains a lot of copper, it conducts a lot of electricity, it has a high voltage potential against the aluminum within the galvanic series. Put it all together and it's a problem!

Sure, corrosion could be stopped by just making everything out of solid tantalum. But with budgets tightening a cost effective solution needs to be found. This case study shows how the use of dedicated software and reliable polarization data can be used to find suitable alternatives and take into account side effects from material changes that may not have been accounted for up till now.

Figure 2 presents the wetted part of the ball intake valve with on the left the complete assembly followed by some detailed views on different components. A complete overview of all components and materials is presented in Table 1.
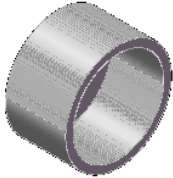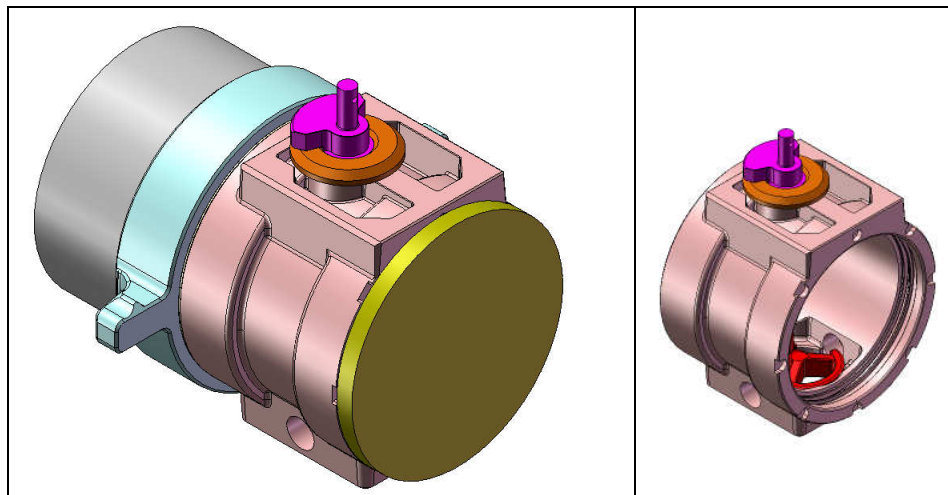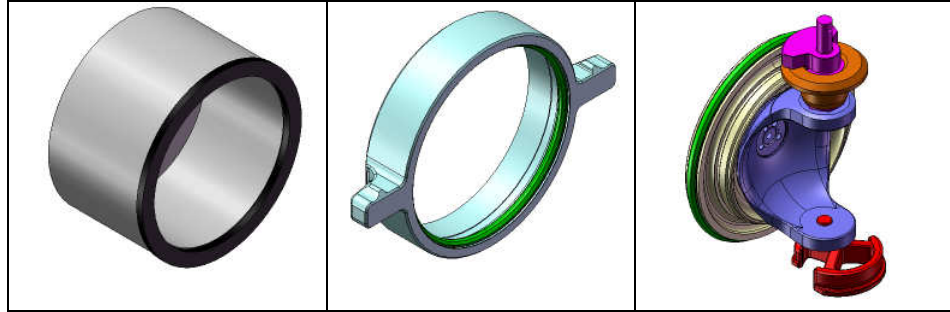
FIGURE 2. Ball intake valve – assembly and components

TABLE 1 - BALL INTAKE VALVE – COMPONENTS AND MATERIALS

Components	Name	Material
	Valve body	Aluminum Alloy A366-T6
	Back ring	Stainless Steel Alloy 316
	Retaining ring	Polymer - Nylon 6
	Coupling	Aluminum Alloy 6061-T6
	Upper trunnion	Aluminum Alloy 6061-T6
	Bushing	Polymer; acetal
	Valve ball	Stainless Steel Alloy 316

	Lower trunnion	Stainless Steel Alloy 316
	Coupling (simplified)	Brass
	Pump inlet (simplified)	Ductile Iron
	Hose gasket	Rubber

For all materials listed in Table 1 above the polarization data have been recorded in lab conditions for tap water and seawater at 30 ºC according to the details as listed below.

In a first stage, simulations haven been done for the materials listed in Table 1 without any finishing (anodizing or coating) added. Corrosion rates in tap and seawater have been compared.

Acquisition of polarization data (lab tests)

The electrochemical corrosion behavior of the bare metal samples is investigated by LSV. The LSV polarisation measurements are performed with an Autolab PGSTAT30[4] potentiostat equipment, based on a typical 3 electrode system: Working Electrode (WE), Reference Electrode (RE) of type Ag/Ag/Cl and a Pt mesh Counter Electrode (CE). The RE is connected to the electrolyte solution by means of a KCl salt bridge, in order to prevent contamination.

Typically polarisation curves are obtained in potentiodynamic mode. A potential sweep at fixed scan rate between WE and RE is imposed and the current response between WE and CE is recorded over time. The working electrode (WE) is a circular coupon that is installed in a customized Rotating Disc Electrode (RDE).

The double walled laboratory cell is thermostatised by a water circuit that is connected to a Lauda E100 immersion circulator. Before each experiment, the bare metal samples are degreased in aceton and rinsed with demineralized water to ensure a clean surface.

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[4] The AUTOLAB PG STAT30 is a general purpose electrochemical workstation, a modular high current potentiostat/galvanostat with a maximum current of 1A, a compliance voltage of 30V and the possibility to do IR-compensation.

In order to obtain the 'pure' polarization behavior, all polarization curves have been corrected for the ohmic potential drop around the RDE.

The conductivity of the tap and salt water are measured at 30 ºC and are equal to 0.12 and 4.36 S/m respectively.

Pre-processing

Figure 3 presents a screenshot of the pre-processing step in which the CAD model is loaded and the material selection is done. It presents on the left an overview of all material groups that have been defined, with each material group its own color attributed. The total surface area for each group is listed as a reference.

In a second step the thin film conductivity and thickness need to be entered. These values can be automatically calculated by using formula's in which environmental parameters can be entered.

For this specific test case the conductivity of the film has been measured (0.12 and 4.36 S/m for tap and seawater respectively). The thin film thickness is taken to be 1 mm (1000 microns) as can be seen from Figure 4.
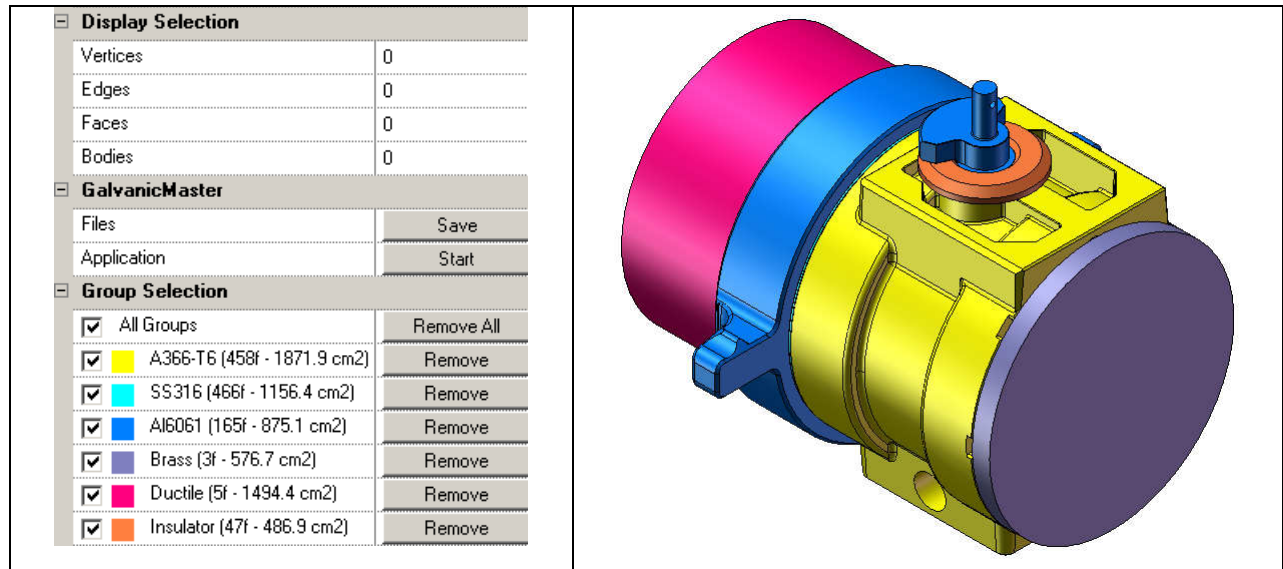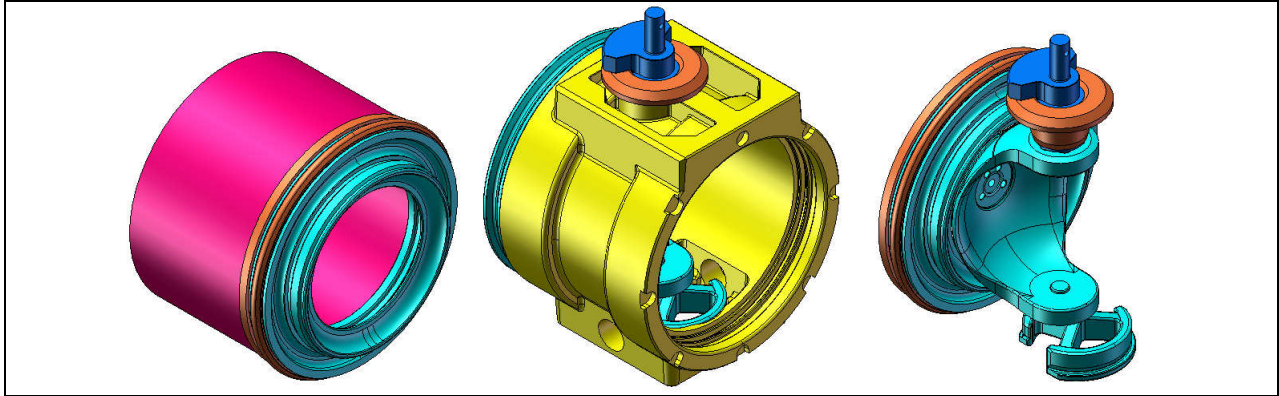
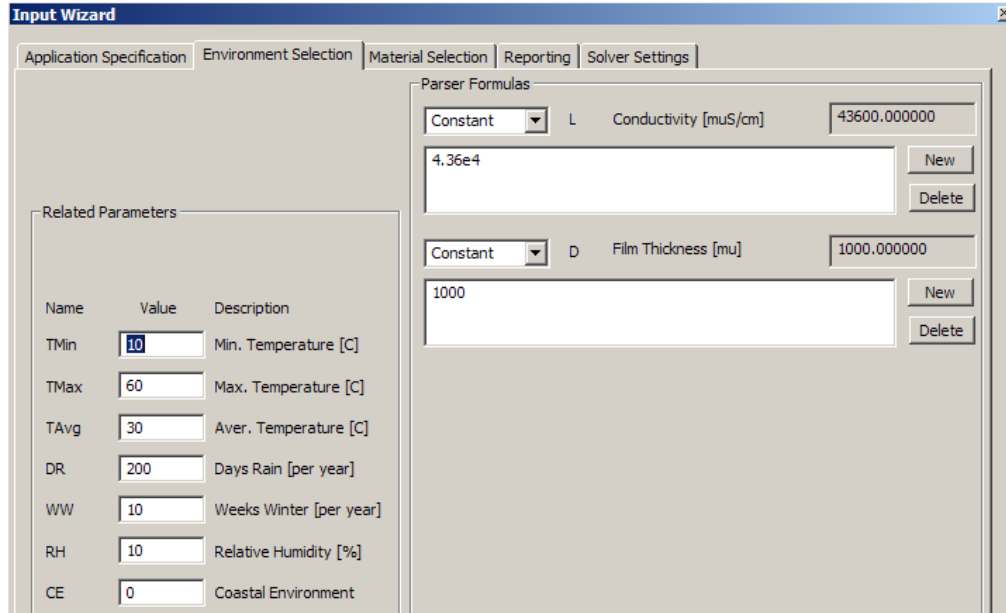FIGURE 3 - Pre-processing: CAD import and definition materials

FIGURE 4 - Pre-processing: thin film parameters

For each of the materials defined above the proper polarization curves need to be selected as presented in Figure 5.
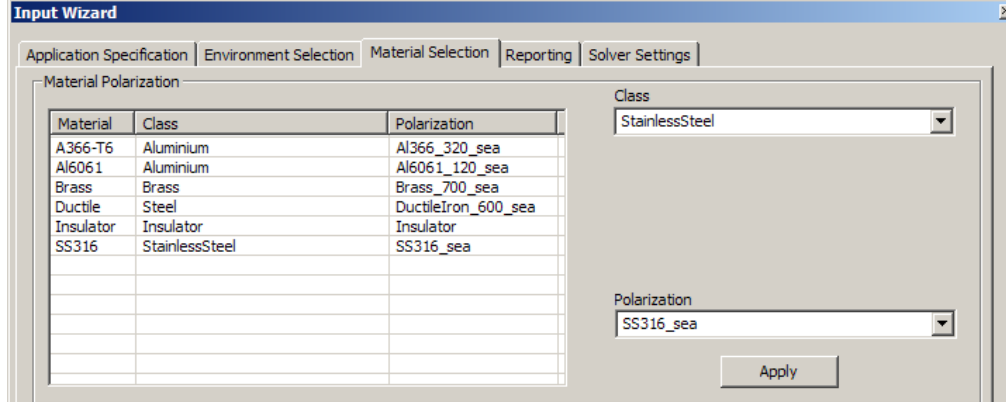
FIGURE 5 - Pre-processing: polarization curve selection

Before the calculation starts, the input STL meshes are automatically re-meshed as can be seen form Figure 6. The overlap between the thin film on neighboring bodies is calculated to allow ion transport between bodies.
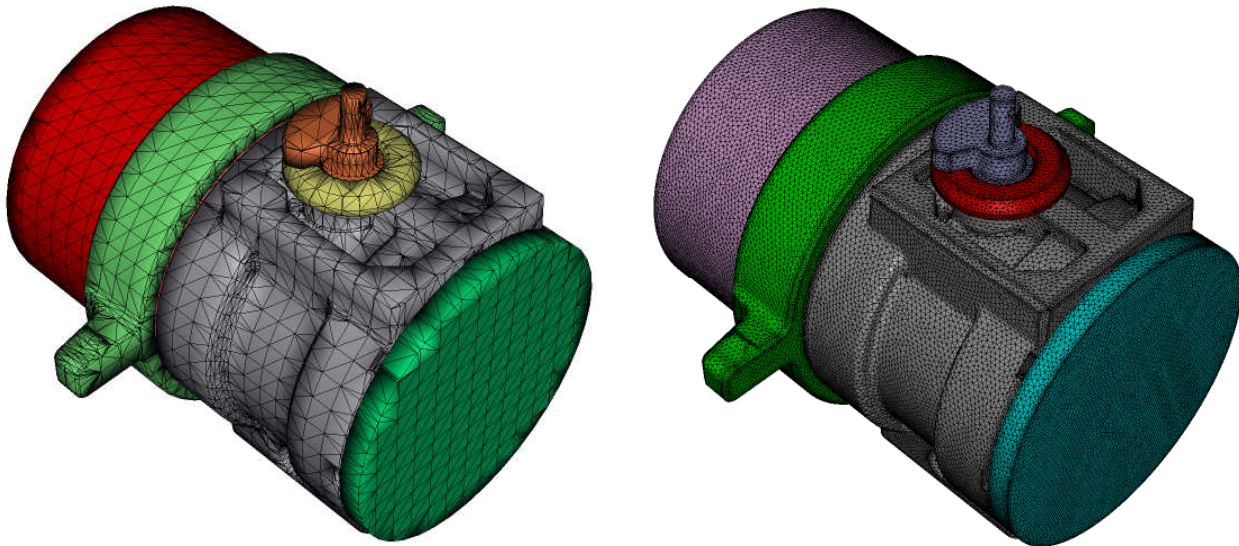

FIGURE 6 - Pre-processing: STL remeshing

Figure 7 shows the comparison between the calculated corrosion rates for tap and seawater. The brass coupling has been removed to look "inside" the model. The largest corrosion rates can be found on the valve body where the aluminium is in contact with the brass and on the tip of the upper trunnion where aluminium is close to stainless steel of the valve ball.

It can be observed that in general the corrosion rates in seawater are about 20-30 times larger than in tap water.
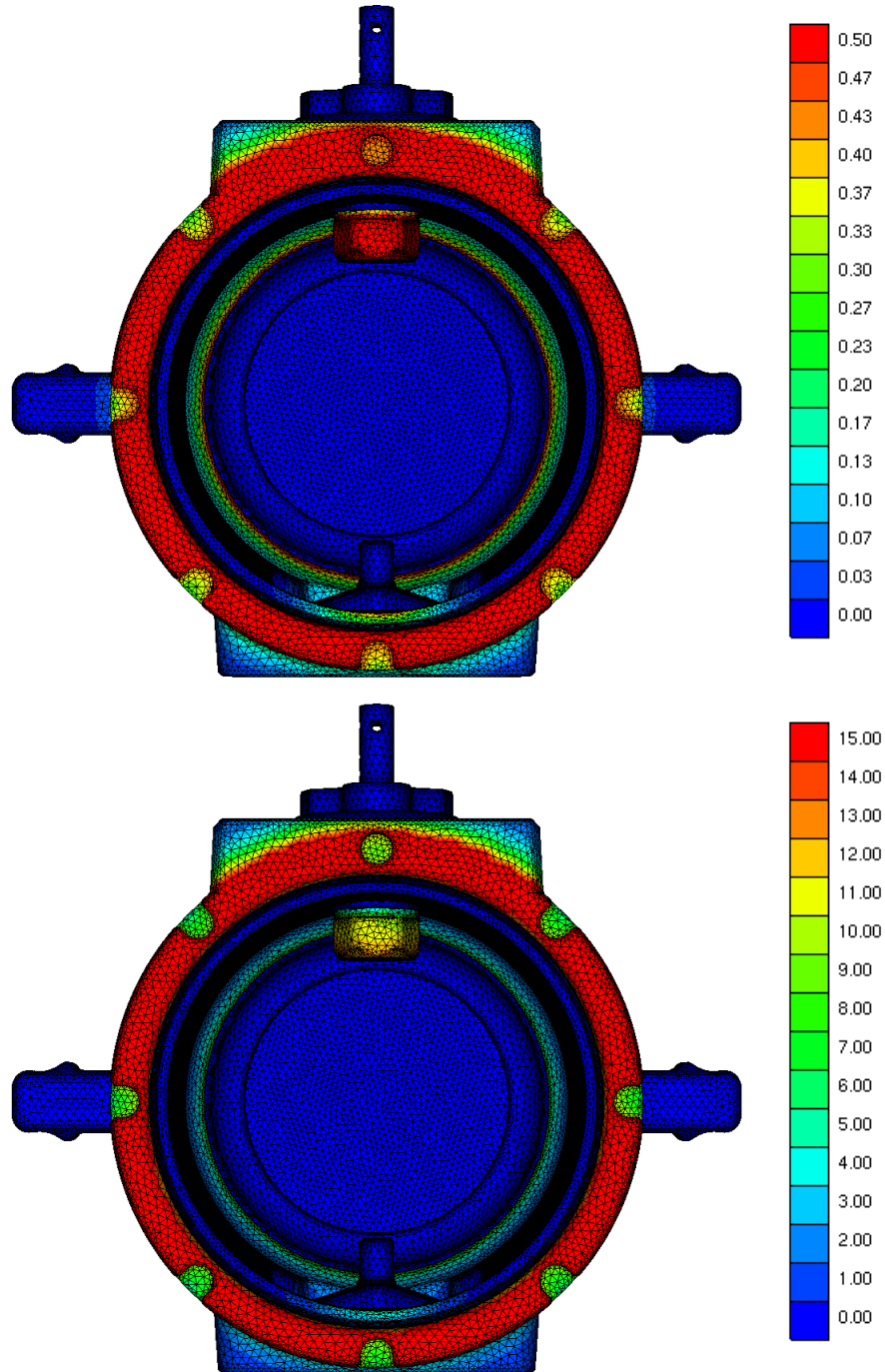

FIGURE 7 - Post-processing: corrosion rates in tap and sea water (microns/day wetted)

CONCLUSIONS

In this article a unique 3D simulation technology to predict galvanic corrosion has been presented. Potential distributions and corrosion rates are calculated based on electrochemical characterization of the different materials in lab conditions.

In a first test case the ball inlet valve model has been investigated. Conductivity data and polarization curves have been collected for in tap water and seawater Al6061, brass, stainless steel 316 and ductile iron under lab conditions. Based on these data and with a uniform thin film thickness of 1000 micron, the corrosion rates on the complete assembly have been calculated. The largest corrosion rates can be found on the valve body where the aluminium is in contact with the brass and on the tip of the upper trunnion where aluminium is close to stainless steel of the valve ball.

These simulations can be seen as the starting point for material selection optimization. This can be done by calculating the effect of finishes, coatings and alternative materials.

FUTURE DEVELOPMENTS

The long term aim is to develop an efficient, robust and easy to use software design tool that will pre-empt and avoid dangerous and costly design issues related to galvanic corrosion. There are two key ingredients to the success of such an objective, namely the technical capability of calculating corrosion rates on complex assemblies of mixed materials and how such a tool is accepted, delivered and implemented by the design community.

Consequently, the software design tool needs to be developed in such a way as to satisfy the needs of two different types of users, without a requirement that they learn the details of galvanic corrosion mechanisms, the electrochemical equations controlling corrosion rates, or FEA methods and meshing techniques:

- Designers of new/upgraded systems – These users would require any galvanic corrosion prediction solution to be fully integrated into their existing enterprise design environment. This would enable them to analyze their design for galvanic problems as part of their design workflow without leaving their preferred design software. This will make it easy to prevent galvanic corrosion from being designed into new or upgraded systems in the first place and will ensure that all analysis, materials and design information is correctly accessed and stored in a fully auditable condition. It also will make it possible for to upgrade materials and coatings without the risk of causing or exacerbating galvanic corrosion problems.

- M&P engineers evaluating legacy systems and needing to identify galvanic problems or substitute new materials, coatings or treatments. It is unreasonable for these users to purchase and learn to use major design software just to carry out a galvanic corrosion analysis and diagnostics. A more suitable tool for this audience of users would be a stand-alone analysis package that can easily import the 3-D model from the designer, and then allow the M&P engineer to assign materials, coatings and treatments to it in a simple manner, and execute a 3-D galvanic corrosion model in an intuitively understood graphical user interface.

The modeling approach must allow the impact of major influencers such as the effects of environment, stress, temperature, and surface condition. Further, an open architecture should be employed to leverage the pre-processing framework developed and available within the current software. This will enable the addition of other corrosion mechanisms into the same analysis environment, even if they are from third parties.

To develop a life cycle design capability, future phases of this work must address the following:

- The way that the polarization curves of the surfaces will change as a result of the build-up of corrosion products
- The effect of other corrosion mechanisms such as pitting corrosion and crevice corrosion
- The consequences of corrosion damage to the surface
- The effects of temperature and stress, including stress corrosion cracking
- The corrosion of different, layered surface coatings right down to the substrate as time evolves
- The effect of different 'environmental stresses' imposed by weather patterns, temperature and humidity, which will vary with basing location, such as polar, equatorial, desert, or rainforest climates

In addition, the models must use a common database of galvanic polarization data that will be available for use in any software. This should be complemented by a clear, peer-reviewed methodology outlined in a Best Practice Guideline to enable other organizations and agencies to capture polarization data with a well-defined, consistent methodology, and making it available via a trustworthy source with a clear and auditable stewardship and 'pedigree'.

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