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Predicting the impact of metallic coating and paint degradation on airframe corrosion

Alan Rose, Keith Legg, Corrdesa LLC
11 Jefferson Place, Newnan, GA 30263, USA
arose@corrdesa.com, klegg@corrdesa.com

ABSTRACT

The present approach for considering galvanic incompatibilities is simplistic and static. It is *simplistic* in that the only thing it takes into account is the galvanic potential difference between two adjacent materials. An estimate of the galvanic corrosion severity is usually based on some form of galvanic potential table, as in MIL-STD-889. However, in mixed material assemblies it is the galvanic *current* that determines the severity of corrosion, not the galvanic *potential*, and the two are not directly related. The design engineer needs a way to estimate the true corrosion risk based on both the explicit geometry and all the materials in an assembly.

The present approach is *static* in that it assumes that the condition of an assembly remains constant. However, from the moment that weapons systems are deployed, corrosion protection schemes become compromised over time due to physical and environmental damage. Sacrificial coatings and passivates become depleted, while paint systems become damaged and deteriorate. It is essential therefore, that the design engineer considers, upfront, not only how the factory-fresh finish system will perform, but the very real impact of environmental degradation and protective finish damage on the integrity of the weapon system over its lifetime.

This paper introduces a development where deterioration is simulated over time, accounting for the consumption of sacrificial metallic coatings. The insight provided by this approach is invaluable, for the first time giving the designer the tools to incorporate protection schemes that are more damage-tolerant, and appropriate for the intended operational environment of the weapons system.

Keywords: Computational Corrosion Analysis, Galvanic corrosion prediction, FEA, corrosion prediction, polarization data, coating degradation

INTRODUCTION

Aerospace structures are challenged by many corrosion mechanisms and one of particular severity is galvanic corrosion. This manifests as an acceleration of corrosion when two or more *galvanically incompatible* materials are used in close proximity. It is especially common in aircraft because of the preponderance of mixed metal assemblies. The aerospace and defense communities have, over time, gathered data and developed design guidelines and various tools to assess the risk of galvanic corrosion and guide material choice.

PRESENT APPROACH FOR ASSESSING GALVANIC CORROSION

Most of these design aids comprise two main components, namely, **Data** and **Practice**. The **data** is usually in the form of a galvanic series or table of materials with their open circuit potentials (OCP) and a working **practice** typically involves the use of guidelines that suggest designers avoid using materials with a difference in OCP beyond a certain threshold. The exact criteria for this potential difference varies according to the particular standard or practice.

➢ MIL-HDBK-729 [1] provides basic and fundamental information on corrosion and corrosion prevention of metals for the guidance of engineers and designers of military materiel. It describes factors that influence and control galvanic action, such as the electrical circuit (metals and conductive medium or electrolyte), the ratio of anode to cathode areas, and polarization of the materials. It points out that galvanic corrosion is greatest near the junction between dissimilar metals, and falls with increasing distance from the junction.

➢ MIL-STD-889B [2], on the other hand, requires that suitable protection against galvanic corrosion be applied when dissimilar metals are used in intimate contact. It contains a matrix of metals, with corrosion severities for sea water, marine atmosphere, and industrial atmosphere based on galvanic potential differences.

➢ MIL-DTL-14072E(CR) [3] sets out required finishes for ground-based electronic equipment. Even if the component under investigation is not electronic in nature, engineers still refer to its tables and information. It contains a galvanic chart of metals, alloys and platings arranged by groups which have common electro-motive forces (EMF), supposedly within 50mV. All members of a group regardless of metallurgical similarity or dissimilarity are considered *compatible*. Indeed, materials, from *different* groups are still cited as *compatible* if they are **within** a range of 250mV.

The common factor in all of these specifications is that they are based on galvanic potential differences between materials. Although the potential is the *driver,* in reality the *extent* of corrosion is determined by the corrosion current. They also tend to consider only metals that touch, whereas in reality incompatible materials only need to be electrically connected through the electrolyte. Nevertheless they do provide useful guidelines on avoiding galvanic corrosion couples and on minimizing the extent of corrosion.

Since it is galvanic *current* that determines the severity of corrosion, not the galvanic *potential*, an improved method should make use of both the galvanic potential, to indicate possible incompatibility and the galvanic current to quantify the extent or severity of the corrosion. Even then, the method would only be placed on the initial (time = 0) properties of the materials. In reality, however, materials degrade and change over time. As soon as weapons systems are deployed, corrosion protection schemes begin to degrade. Coatings become compromised over time due to physical and environmental damage. Sacrificial coatings and passivates become depleted, while paint systems become damaged and deteriorate. It is essential therefore, that the design engineer considers, upfront, not only how the factory-fresh finish system will perform, but the very real impact of environmental degradation and protective finish damage on the integrity of the weapon system over its lifetime.

NEW APPROACH FOR ASSESSING GALVANIC CORROSION

Computational methods, offer a way to build upon the approaches presented above and also to incorporate the change of material properties over time while bringing additional advantages:

- By incorporating the actual CAD model of the system under analysis the explicit geometry (size, shape, location) can be considered, whereas galvanic tables in the standards refer to couples with equal anodic and cathodic areas
- A complex system of several materials and multiple coatings can be analyzed in one computational model rather than looked at as a series of couples
- Specifying the electrolyte of interest: Many standards or guidelines refer to 'seawater' as the electrolyte. However, as input, computational methods can use polarization curves of materials with other electrolytes or NaCl concentrations.
- The thickness of the electrolyte film has an impact on the corrosion rate. For example, the hull of a ship may be considered to be in a 'bulk' electrolyte whereas an internal aircraft structure may have a very thin film of electrolyte due to condensation. This can be accounted for in how the polarization data is measured and used
- A computational method can simultaneously assess the galvanic potential **and** the current

In this paper galvanic corrosion is assessed by using *Elsyca CorrsosionMaster[1]* a commercial software tool for predicting the locations and severity of corrosion on complex assemblies of mixed materials. Using Finite Element Methods (FEM) the software solves the fundamental electrochemical equations that govern the corrosion phenomena, taking into account the CAD model of the assembly, the polarization behavior of the substrate and coatings, and the thickness and resistivity of the electrolyte film. The electrolyte is modeled as a thin film with defined thickness (microns to millimeters). Details on the software have been reported elsewhere [4,5]. This software tool was used to study the corrosion issues on wing lug bushings of a military aircraft.

CORROSION PREDICTION OF WING-FUSELAGE ATTACHED BULKHEADS

Bushed aluminum wing lugs are commonly found in aircraft. A typical lug attachment consists of a bushing through which a connecting lug pin passes. Figure 1 illustrates the set-up.
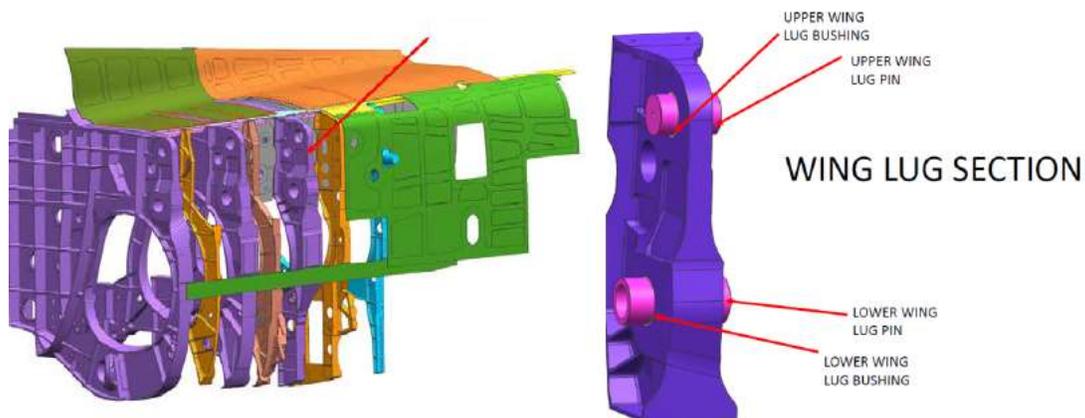

Figure 1: Position of the bulkhead wing lug with bushing and pin

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[1] Tradename

A schematic of the fuselage bushing is given in Figure 1, and material details _used in this example case_ are summarized in Table 1. *Note that the materials in Table 1 are not the actual materials used in practice, but electrochemically similar materials for illustrative purposes.*

In principle the Cu-Be bushing and stainless steel pin are Cd plated, and the aluminum alloy UNS A92024[2] lug is anodized. The bushing ID and OD are Cd plated but are not painted. However, the exposed surfaces of the lug are anodized and chromate sealed, while both bushing and lug are chromate primed and painted. Typically the bushing face and the lug area adjacent to it are usually also sealed with a chromated sealant. In practice however, due to movement between wing and lug, and aging of the organics, the paint system will always degrade and absorb water. Galvanic currents between bushing and lug will eventually corrode the aluminum. Consequently in service the periphery of the aluminum around the bushings always shows corrosion attack.
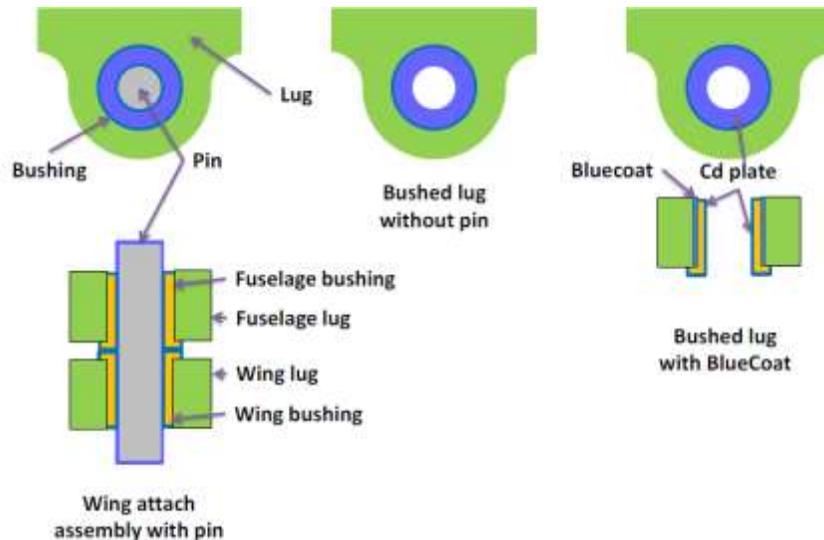

Figure 2: Schematic of wing lug/bushing system

Table 1 Materials specification used in the bushed wing lug simulation – at T=0

Item	Material/ substrate	Coating	Note
lug	UNS A92024	Anodize, unsealed	Anodize undamaged
bushing	Cu-Be Heat treated to HRC 34-36,	Cd plated, 5µm thickness	Model as Cd, then when consumed, the Cu-Be polarization data will automatically be used
pin	stainless steel UNS S31600	Cd plated, 5µm thickness	Model as Cd, then when consumed, the stainless steel UNS S31600 polarization data will automatically be used

In order to find the corrosion hotspots the sealant and paint system are ignored. Corrosion begins in any case where the coating breaks down. Figure 3 identifies the materials and coatings.

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[2] Unified Numbering System for Metals and Alloys (UNS). UNS numbers are listed in Metals & Alloys in the Unified Numbering System, 10th ed. (Warrendale, PA: SAE International and West Conshohocken, PA: ASTM International, 2004).
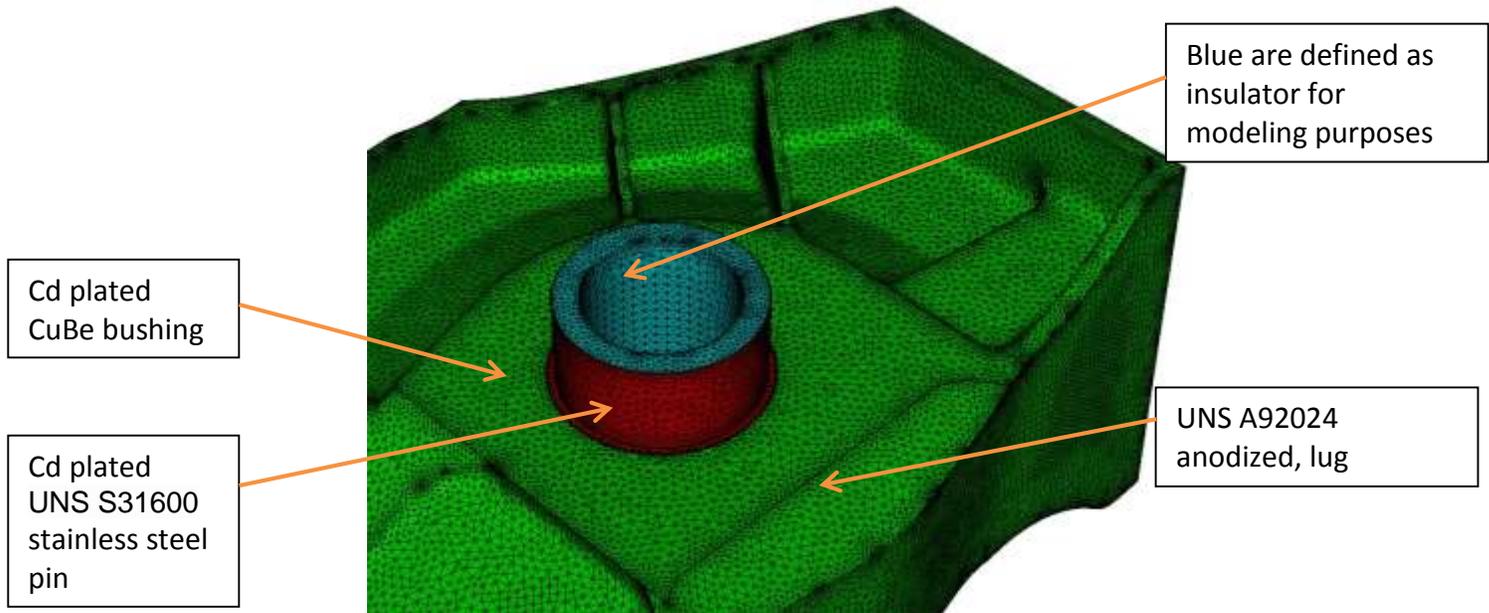
Figure 3: Mesh detail and material selections

Blue are defined as insulator for modeling purposes

Cd plated CuBe bushing

Cd plated UNS S31600 stainless steel pin

UNS A92024 anodized, lug

For this paper, the results of four simulations will be presented and discussed, two steady state and two transient in order to consider the impact of the two different, assumed thicknesses of electrolyte, which is considered to cover the entire assembly. The steady state simulations help to *scope* the problem and then the transient runs follow material consumption (the Cd plate) over elapsed time. It is anticipated that over time, the Cd plate will be consumed in some areas and eventually will reveal the underlying substrate, which of course will have significantly different electrochemical properties compared to the sacrificial Cd.
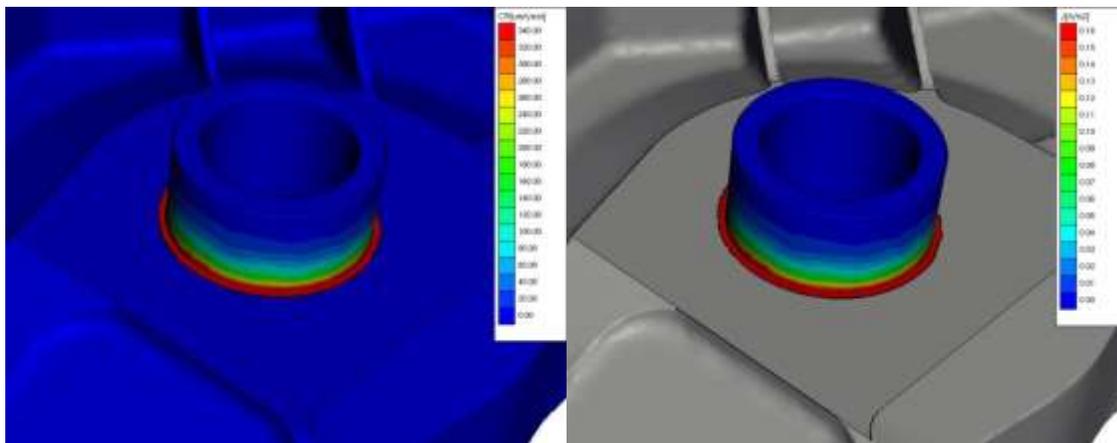

Figure 4: Initial corrosion rate (left) and current density (right), steady state, 1000µm film

Figure 4 shows the initial corrosion rate (left) and current densities (right) for a steady state model of the lug covered in a 1000µm electrolyte film of water containing 3.5% NaCl (this corresponds to the polarization curves used). Note, for visualization purposes, the color range for the current densities has been 'clipped' to show only positive current densities, that is, the gray areas correspond to negative or cathodic current densities.

As we would expect, the Cd plating on the bushing is corroding (sacrificing itself) to protect the more anodic, adjacent Al_2O_3 (anodized). This can also be verified by the positive current densities shown only on the bushing and pin. You can also see some of the corroding Cd plate on the pin.

Figure 5 illustrates the impact of a thinner electrolyte film. The corrosion is concentrated much more around the bushing and does not progress up the pin as far as that seen for the thicker film case.
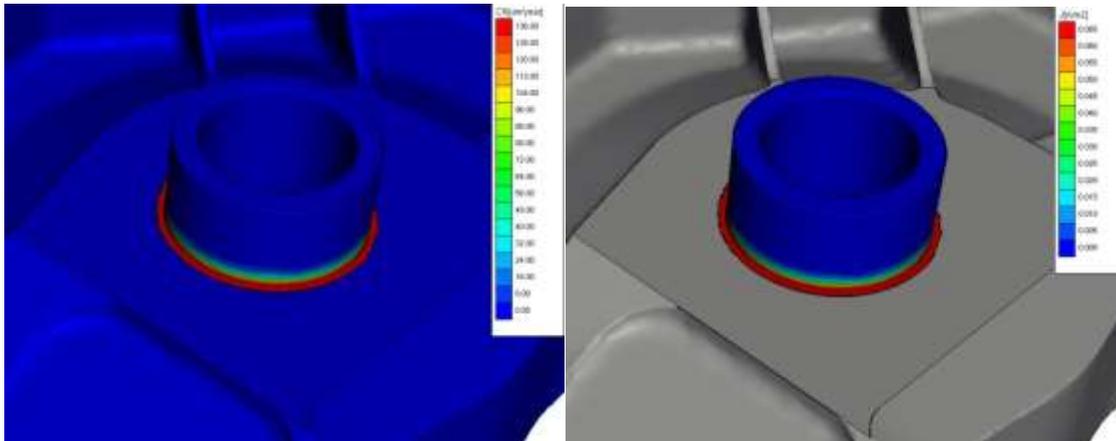

Figure 5: Corrosion rate and current density, steady state, 100μm film

Conclusions from such steady state results should be considered carefully, in line with the assumptions made:

- The assembly is considered 'wet' 100% of the time. In service there will be periods when the lug is dry, depending on humidity, temperature and geography
- No consideration is made for the impact of any corrosion products, which would likely reduce the corrosion rate
- Eventually the protective coatings will be consumed

We can start to take into account the above effects once we have a model within a time-dependent framework. Of course, this then demands more information, such as exactly how the wetting cycles vary etc.

Figure 6 shows the evolution of corrosion over time for the case with the 1000μm electrolyte film and Figure 7 shows the results for the case with the 100μm electrolyte film. The images on the left hand side show the consumption of Cd over time, revealing the CuBe bushing and the UNS S31600 stainless steel pin. The images on the right hand side show the corresponding current densities – positive values highlighting the corroding/anodic surfaces.

In both cases, at the start of the simulation we see the Cd corroding. However, in the 1000μm case it is not until almost all the Cd has been consumed that we then see the corrosion 'switch' to the anodized lug, which is adjacent to the more electropositive CuBe. The 1000μm film is thick enough to allow current from the depleting Cd to 'protect' the anodized aluminum.

In the 100μm case however, we can see that as soon as the Cd starts to be consumed up the pin, we already see the anodized aluminum starting to corrode. The thinner electrolyte layer, with its higher impedance, does not allow the Cd to protect the lug.
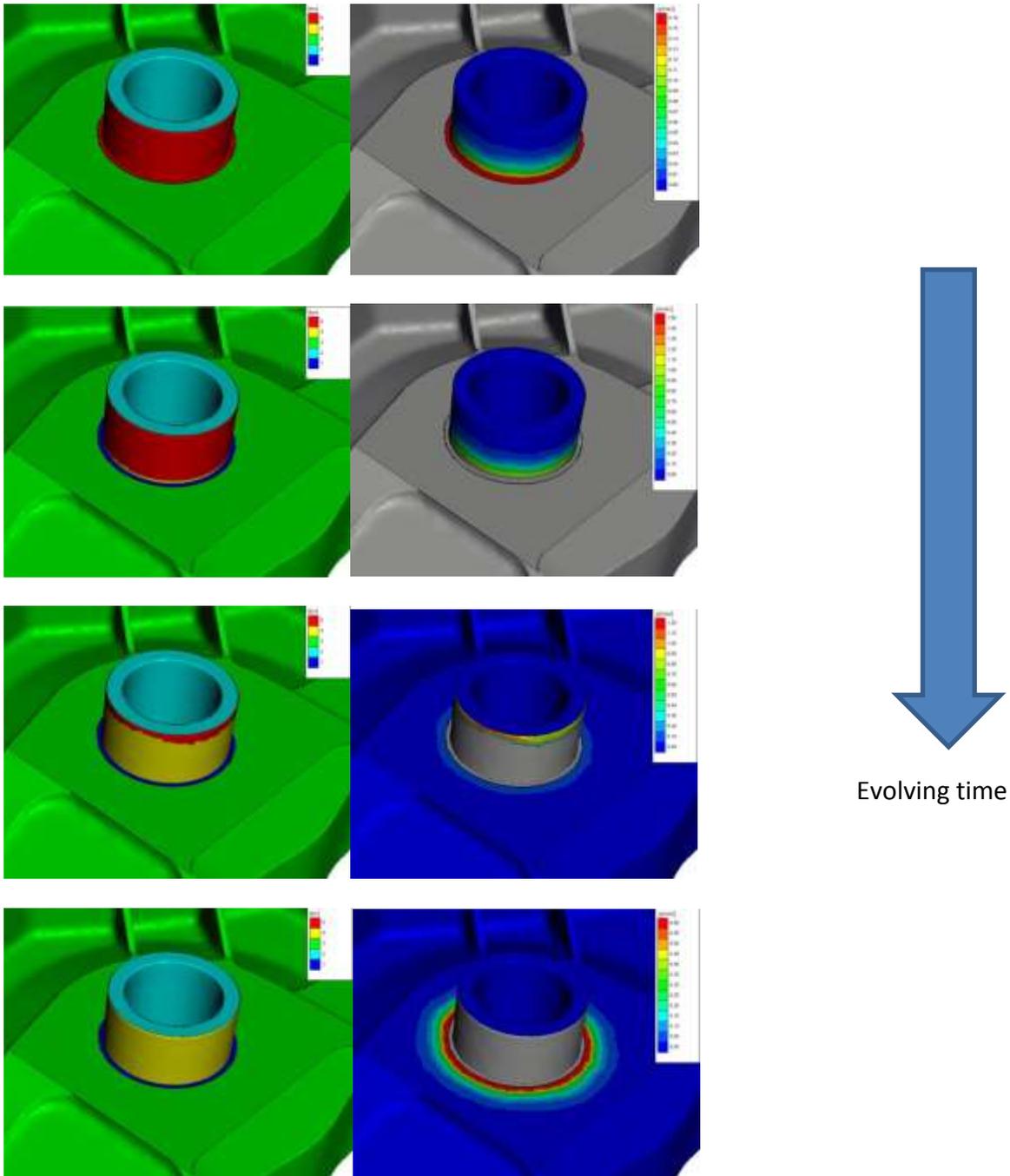
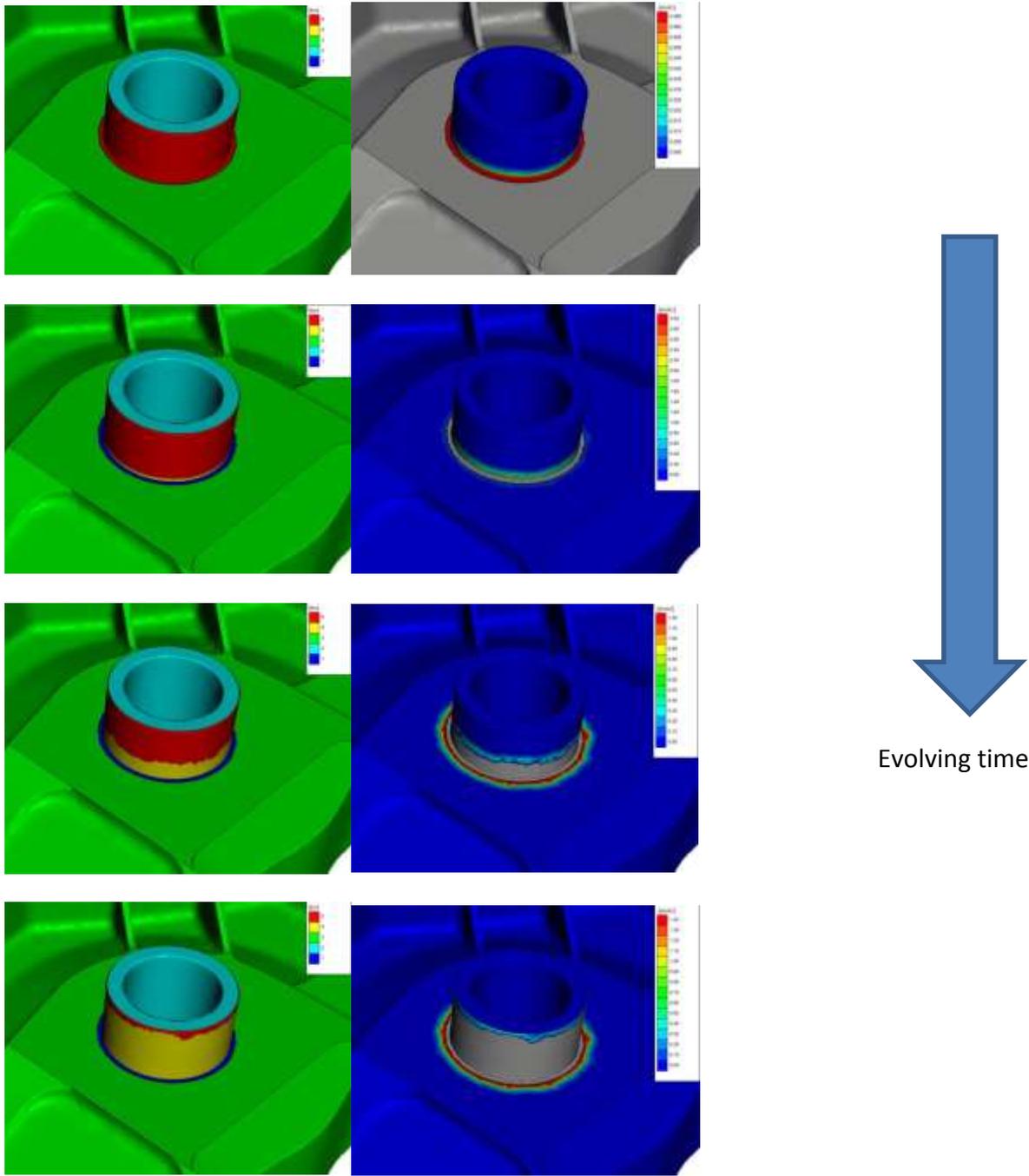**Figure 6: Exposed materials and current density changing with time - 1000µm film**

Figure 7: Exposed materials and current density changing with time - 100μm film

The progress of corrosion that we see in Figure 6 and Figure 7 shows something fundamental about the design of protective systems. Each coating is designed to protect its substrate or adjacent components: Cd on the bushing and pin is designed to make these cathodic alloys galvanically compatible with the Al airframe to prevent galvanic corrosion, while the anodized layer on the lug is designed to protect the lug from galvanic and general corrosion. These work adequately at first, but the anodized layer is more cathodic than the Cd, so that over time it corrodes the Cd away. That exposes the highly cathodic CuBe and stainless steel, causing the Cd to corrode faster. Once enough cathode area is exposed relative to the area of the sacrificial Cd, the cathodic steel and CuBe now attack the anodized Al. Thus what our protection system has actually become is a self-corroding system that will inevitably fail over the long term unless it is refreshed during sufficiently frequent periodic depot maintenance (PDM).

What this tells us is that either

- We need a better protection system for longer life, or
- We must establish the correct PDM cycle to protect the airframe between maintenance actions

The computational method allows us to evaluate any number of combinations of coatings and treatments to find the optimum treatment. Accurately predicting optimum PDM cycles is a more difficult matter, for which the computational method has not yet been demonstrated. In principle one should be able to predict average long term corrosion rates by taking into account how polarization curves change over time (or more accurately how they change with integrated corrosion current), and combining this with geographical basing location, mission profiles, wash cycles, and even average damage, to run the aircraft through a virtual life.

CONCLUSION

Present methods for assessing galvanic corrosion issues have been discussed and it has been shown that they depend simply on the potential difference between the coupled materials by referring to a published galvanic table. This approach may only highlight a potential issue but does not help the user to quantify the corrosion rate, which depends on the current, not the potential.

A computational approach has been presented which can take into account important factors such as explicit geometry, potential and current, and of course the evolution of the environment or consumption/degradation of protective coatings over time.

Several simulations were presented and it was shown that this approach can be very illuminating. The thickness of the electrolyte film is very important, and when the progress is tracked with time, the user can see the impact of the sacrificial coatings being consumed and 'suddenly' exposing other substrates which can then significantly change the character of the corrosion.

What the computational assessment also shows is that protective coatings should not be chosen individually, but designed to operate as a system if they are to provide optimum protection for the air system itself.

ACKNOWLEDGEMENTS

REFERENCES

1. *Corrosion and Corrosion Prevention – Metals.* MIL-HDBK-729, 21 November 1983.
2. *Dissimilar materials,* MIL-STD-889B., 17 May 1993.
3. *Finishes for Ground Based Electronic Equipment,* MIL-DTL-14072E(CR), 31 May 2007.
4. *Galvanic Corrosion Prevention of Complex Assemblies Through modeling*, J.-M. Dewilde, L. Bortels, C. Baeté, B. Van Den Bossche, R. Steingass, NACE paper 0001660 , Salt Lake City 2011
5. *Innovative Approaches for Predicting Galvanic Effects of Dissimilar Material Interfaces*, A. Rose, K. Legg. SBIR Phase 1 Final Report, Contract N00014-12-M-0075.