2017 Award Nomination

Title of Innovation:

Corrosion Djinn™ – Galvanic Corrosion Risk Prediction

Nominee(s)

Alan Rose, Corrdesa LLC

Category:

(select one below)

Coatings and Linings	Instrumentation
Cathodic Protection	Testing
Materials Design	Integrity Assessment
Chemical Treatment	Other—fill in

Dates of Innovation Development:

July, 2015 to August 2016

Web site:

www.djinntools.com, www.corrdesa.com

Summary Description:

Corrosion Djinn is easy-to-use software available on-line and as an 'App' for IoS and Android, that helps engineers and designers make sound material choices in design and maintenance by predicting and quantifying galvanic corrosion risk at material interfaces. Galvanic corrosion is the primary corrosion mechanism in multi-material systems such as aircraft, especially Naval aircraft, where 80% of structural failures result from cracks initiated at corrosion pits.

Recent R&D clearly demonstrates that galvanic corrosion rate is determined by corrosion current (kinetics), not by the potential difference, ΔE, between members of the galvanic series. Yet the presently accepted method of estimating galvanic corrosion severity, called out in industry and military specifications, is based on ΔE. We have found that the galvanic potential approach sometimes *reverses* the expected galvanic corrosion severities, leading engineers to choose the *worst* galvanic couple rather than the best, even in quite common assemblies. The resulting poor choices of materials, coatings and sealants, creates billions of dollars of unnecessary maintenance cost in the Department of Defense

alone.

Corrosion Djinn™ calculates self-corrosion and galvanic corrosion current/rate using a new curated, consistent Electrochemical Database of qualified material polarization curves. It can be used with little or no training, and takes only a minute or two (quicker than looking up ΔE in tables, and orders of magnitude faster than making complex finite element calculations). While galvanic tables contain only generic materials, the Corrosion Djinn™ Electrochemical Database provides data from specific modern alloys, coatings, and surface treatments, and can be readily updated with any specific material or coating that users need.

This is a new paradigm for the industry that will significantly reduce corrosion damage and maintenance cost, while improving system safety and time-on-wing. Although developed for aircraft, it is already being used in general industry, electronics and automotive.

Figure 1. Airframe galvanic corrosion around F-18 wing-attach bushing.

Full Description:

1. What is the innovation?

Corrosion Djinn™ is a software tool for galvanic corrosion prediction and mitigation, available as an online web application, and an app for Apple and Android devices. The tool comprises a fast and easy-to-use corrosion current/rate calculator based on an underlying database of modern, curated and accredited electrochemical data.

Corrosion Djinn™ is a simple, usable solution to the perennial problem of galvanic corrosion that is a constant source of failure in aircraft, and in any other multi-material equipment.

The software and initial aerospace material database were developed for the Sea-Based Aviation Team under an SBIR contract from the Office of Naval Research (ONR).

2. How does the innovation work?

With just a few taps on any smart device the user can, on the fly, predicts corrosion risk and rate between modern material interfaces, including the new light alloys and composites that are increasingly taking the place of steels and other alloys in modern aircraft, vehicles and machinery.

Modern corrosion analysis shows that galvanic corrosion rate, and hence corrosion risk, is determined by the galvanic current between two objects, NOT their galvanic potential difference. Using modern electrochemical data, Corrosion Djinn™ can calculate the corrosion current, and from it the corrosion rate. When we showed this approach in a meeting of aircraft maintainers at one of our Navy depots, they immediately recognized it as a paradigm shift that could greatly reduce the time and money spent on corrosion repair.

Corrosion Djinn™ uses a well-known electrochemist's approach, but brings it into the 21st century with a modern digital database of modern materials. It is well-established that the electrochemistry of all corrosion involves simultaneous metal dissolution in one location coupled with oxygen reduction and hydrogen evolution in another. At equilibrium the consequent current traveling from anode to cathode equals that from cathode to anode. The location of the equilibrium point is determined by the galvanic current and voltage at which the cathodic current (oxygen reduction/hydrogen evolution) from the cathode is equal and opposite to the anodic current (metal dissolution/pitting) from the cathode. These currents and voltages are defined by the current-voltage characteristic of the surface beneath the electrolyte, that is, its polarization behavior. In practical terms, when the polarization curve is plotted in the standard absolute current versus potential graph, equilibrium is the point where the cathode and anode curves cross. What Corrosion Djinn™ does is to find this crossing point automatically.

However, if that was all it did, then it would not be particularly useful because the user would still have to find the relevant polarization curves in the literature, hope that they were taken in a similar, robust manner, and enter the data into the application, all of which would make looking up galvanic potentials on a table a much more appealing proposition. What makes Corrosion Djinn™ fast and accurate is a database of polarization data consistently measured by the ONR team, using Best Practices that we have developed.

The user simply chooses the two combinations of material, coating and surface treatment from the database (Figure 2), presses a button and sees the resulting galvanic current density (corrosion rate) and mixed potential (Figure 3). In order to minimize corrosion, other materials/coatings/treatments can immediately be chosen and compared to find the most cost-effective and safest option with the lowest corrosion rate. The evaluation takes less than 2 minutes (see the demo at http://www.screencast.com/t/XNCfzmTDq, http://youtu.be/H6jgF15glMo). This is less time than it takes to find and look up a table (which is inaccurate anyway), and far less time than the hours or days needed to create an electrochemical Finite Element Analysis (FEA) model and input all the relevant data.

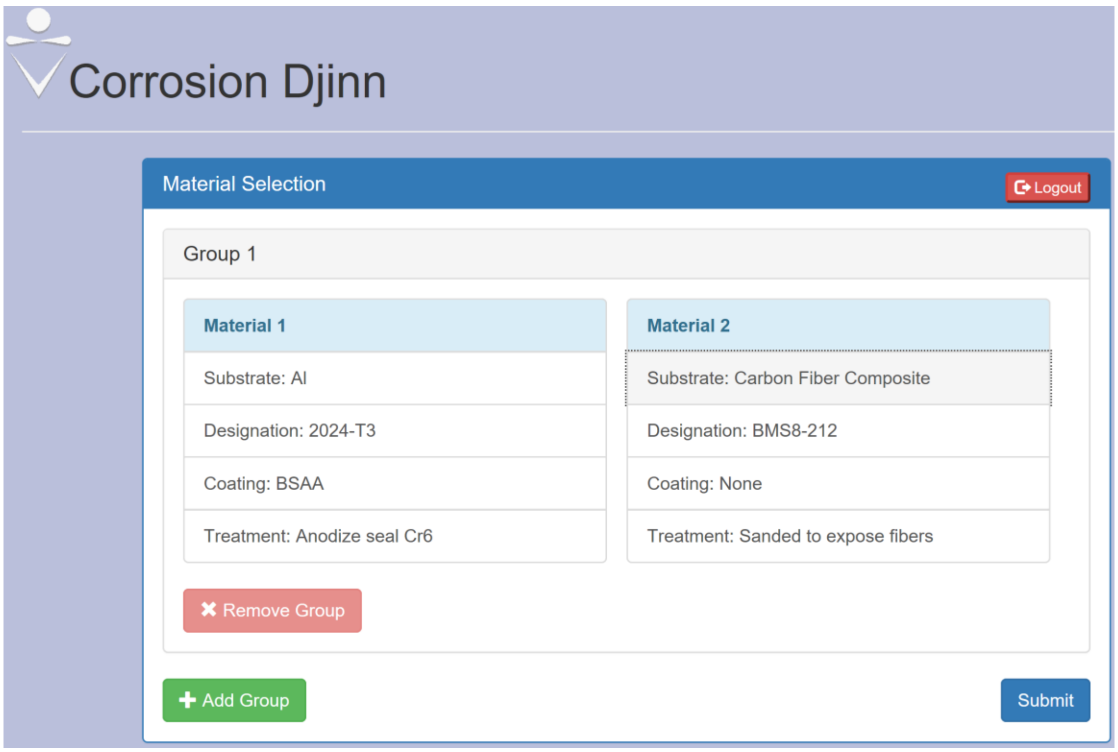

Figure 2. Corrosion Djinn input screen.

Although all of the data in the database at this point is for 3.5% NaCl, corrosion behavior under any electrolyte can be added, from DI water to acids and alkalis. In fact, the data also makes it possible to predict the self corrosion rate of alloys, as well as the galvanic corrosion between them.

	Material 1	Material 2
Group 1		
Substrate	Al	Stainless steel
Designation	2024-T3	304
Coating	BSAA	None
Treatment	Anodize seal Cr6	Passivate
OCP (V_{SCE})	-0.555	0.0554
Mixed potential (V_{SCE})	**-0.4957**	
Corrosion current density (Am^{-2})	**6.757174E-2**	

Corrosion severity	
Low	<1E-03 Am^{-2}
Moderate	<1E-3 <1E-2 Am^{-2}
High	>1E-02 Am^{-2}

Figure 3. Corrosion Djinn output.

3. Describe the corrosion problem or technological gap that sparked the development of the innovation? How does the innovation improve upon existing methods/technologies to address this corrosion problem or provide a new solution to bridge the technology gap?

Until now engineers have relied on a galvanic series arranged by galvanic potential, using data that is mostly generic and at least half a century old. For

Figure 4. Corrosion in F-18 wing.

military aircraft and vehicles, where galvanic corrosion is particularly common and severe, there are military specs (MIL-STD-889B and MIL-DTL-14072) with somewhat more comprehensive (but still generic) tables.

The idea of Corrosion Djinn™ grew from a visit we made to one on the US Navy's aircraft repair depots. As we passed wing upon wing with the carbon fiber composite top skin removed and the inside looking like Figure 4, the conversation went something like this:

"I see you get corrosion around all the bolt holes."

"Yes they always come in that way after a few years."

"So how do you repair them?"

"We grind out the corroded material, which opens up the bolt hole, so we usually have to drill the hole out and repair it with a bushing. That is a pretty common type of repair."

"Looks like a huge amount of work for every single one of those hundreds of holes! "

"It sure is. And when they come in again in a few years the corrosion will have expanded and we will have to remove the bushing, grind it out some more and probably have to put in a bigger bushing."

"Which sounds like twice as much work as the first time around. What do you make the bushings out of?"

"Usually stainless steel to minimize the corrosion. If you look in MIL-STD-889 you will see that is the best bet." (Figure 5)

"Why not use titanium? It would give you much less corrosion."

"Not according to MIL-STD-889. And anyway titanium is much more difficult to machine."

"Umm…. Let us tell you what the latest data shows."

We discussed this with the maintenance team, showing them the output from our FEA models to clearly demonstrate that stainless steel is one of the worst materials to use for a bushing in this situation and titanium one of the best. Their reaction was "That is a completely new paradigm! It could make a big difference to our workload." At that point we realized that people understood the importance of what we were saying, but had no good way of making evaluations themselves unless they were FEA experts. What was needed was a galvanic corrosion prediction tool with modern materials data that anyone could use with little or no training.

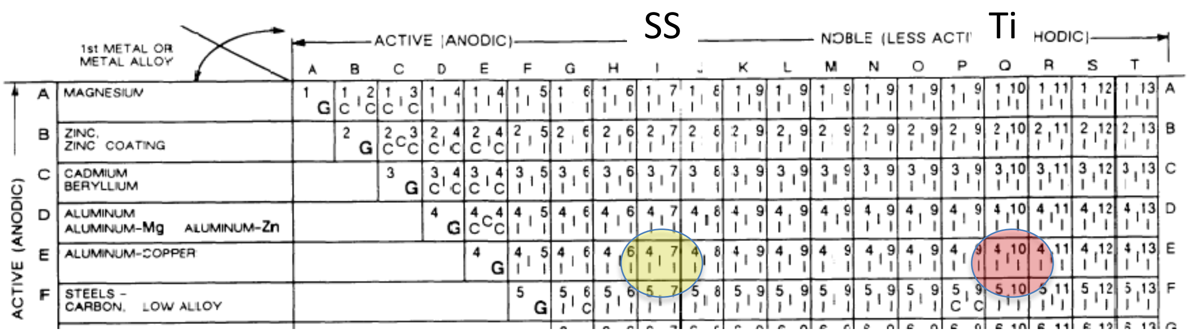

Figure 5. MIL-STD-889 table showing stainless steel creating lower corrosion than Ti with aluminum.

Navy evaluation has shown that more than 80% of structural failures are initiated from corrosion pits[1]. Because they use so many disparate materials, the most serious corrosion in aircraft (and Naval aircraft in particular) is due to galvanic corrosion. Periodically aircraft corrosion makes headlines, such as the $238 million F-22 airframe corrosion problem caused by galvanic coupling between the gap filler and the aluminum airframe[2], but mostly it is accepted as a perennial, insoluble problem

Present DoD acquisition requirements perpetuate the problem because they require corrosion analysis based on the existing mil specs, which are founded on galvanic potential, not galvanic current. Recently, for example, because of changes in operating theaters from desert to maritime environments, one UAV maker was asked to carry out a galvanic corrosion evaluation identifying as potential problems all interfaces with a galvanic potential difference greater than 250mV. We are presently working with ONR to change the galvanic corrosion specification MIL-STD-889 into a specification based on galvanic corrosion current generation in place of galvanic potential.

4. Has the innovation been tested in the laboratory or in the field? If so, please describe any tests or field demonstrations and the results that support the capability and feasibility of the innovation.

Both our FEA analysis and our Corrosion Djinn™ analysis are built on the same electrochemical database (which we think of as the "Corrosion MMPDS" – the electrochemical equivalent of MMPDS, the standard aerospace alloy mechanical properties database), with modifications to

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[1] William Nickerson, ONR "Sea-based Aviation Experience with Combined Mechanical and E nvironmental Loading", International Workshop on Stress Assisted Environmental Damage in Structural Materials (2015).

[2] "Defense Management: DoD Needs to Monitor and Assess Corrective Actions Resulting from Its Corrosion Study of the F-35 Joint Strike Fighter". GAO-11-171R, 16 December 2010.

optimize the different computational methods. Corrosion Djinn™ has been verified and validated in several independent ways:

Lug	Lug OCP	Bushing	Bush OCP (mV SCE)	Finite Element J (Am^{-2})	Corrosion Djinn J (Am^{-2})
Al 2024 bare	-601	Stainless 316 bare	-117	$2.3x10^{-2}$	$2.3x10^{-2}$
Al 2024 1200S	-615	Stainless 316 bare	-117	$2.3x10^{-2}$	$2.3x10^{-2}$
Al 2024 SAA	-617	Stainless 316 bare	-117	$2.3x10^{-2}$	$2.3x10^{-2}$
Al 2024 bare	-601	Stainless 316 1200S	-181	$6.2x10^{-3}$	$6.1x10^{-3}$
Al 2024 bare	-601	Ti6Al4V bare	-146	$3.9x10^{-3}$	$3.8x10^{-3}$
Al 2024 bare	-601	Ti6Al4V 1200S	+68	$7.6x10^{-5}$	$8.0x10^{-5}$

Figure 7. Corrosion current comparison between FEA and Corrosion Djinn calculations.

1. The underlying curve crossing methodology is a well-known electrochemical technique that has been shown to agree with analytical calculations of simple geometries.

2. Corrosion Djinn™ calculations of corrosion current agree with FEA calculations, and both agree with analytical calculations and laboratory measurements and weight loss (Figure 6).

3. FEA analysis shows the same corrosion pattern as B117 and beach exposure of NAVAIR Al specimens with stainless steel and titanium screws (Figure 7). Corrosion Djinn™ calculates the same galvanic currents as the FEA model.

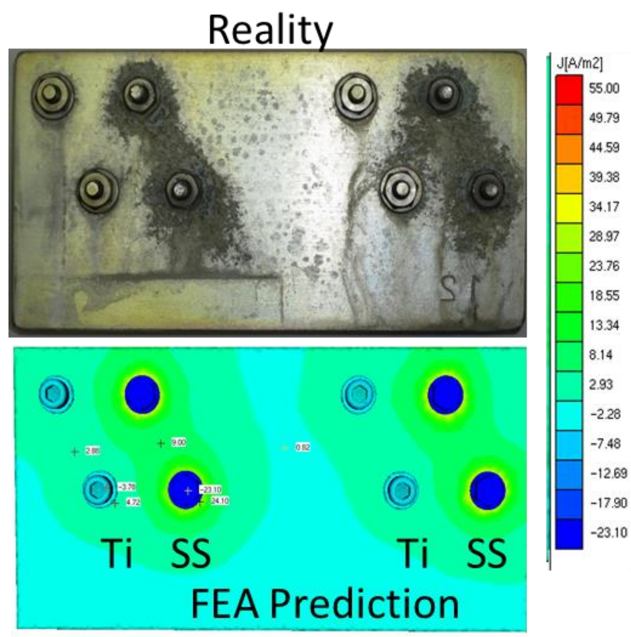

Figure 6. Comparison between test data and FEA showing galvanic corrosion of Al by Ti and stainless steel.

4. **How can the innovation be incorporated into existing corrosion prevention and control activities and how does it benefit the industry/industries it serves (i.e., does it provide a cost and/or time savings; improve an inspection, testing, or data collection process; help to extend the service life of assets or corrosion-control systems, etc.)?**

The Corrosion Djinn™ approach is easily incorporated into existing CPC activities at the Material and Process (M&P) engineering level. It is presently being used on a test basis by several aerospace and general manufacturing companies. It is particularly useful as a way to decide which of various options can best replace sacrificial coatings such as Zn and Cd in existing products, as well as to evaluate alternatives for replacing chromates as required by the European REACH and RoHS regulations. Whenever materials or coatings need to be replaced, it is a quick and easy way for the design engineer to evaluate the corrosion consequences of a change. We just recently used it to evaluate suggested replacements for tin plating in an industrial sensor plagued by tin whisker issues.

The technique is being incorporated into an update of MIL-STD-889B. In this case, Djinn enables the designer to use the new standard to make better and more reliable material choices for new design, design changes, or repair.

In a time when materials and industrial finishes are constantly and rapidly changing in response to regulations and customer demand for higher performance and reduced energy usage, the benefits to industry are reduced time, cost, and most importantly risk when transitioning new materials and making changes to existing products. Improved corrosion performance and better maintenance methods in turn reduce cost of ownership, safety, durability and, for aircraft components time-on-wing.

The improved database that lies beneath Corrosion Djinn™ is itself a big step forward for the industry. Whereas the old galvanic series provided nothing more than the galvanic potentials of various generic materials, the new digital Electrochemical Database provides the complete current-voltage characteristics, not of generic materials, but of specific alloys, carbon fiber composites, modern coatings, passivates and other surface treatments, for various service environments. This database is no longer a static table or galvanic series, but a constantly updated and expanded database of curated materials electrochemical data, all taken in a consistent manner, following an established protocol in order to be suitable for computational corrosion evaluation and prediction using modern computational tools.

6. Is the innovation commercially available? If yes, how long has it been utilized? If not, what is the next step in making the innovation commercially available? What are the challenges, if any, that may affect further development or use of this innovation and how could they be overcome?

Corrosion Djinn™ and the Electrochemical Database are commercially available and are already being used by some companies, with one company having been using Corrosion Djinn™ for the past year.

The next step will be to incorporate relative anode/cathode areas, corrosion rate estimates, and a more graphical user interface to clearly show the severity and extent of corrosion damage. The major challenge will be to embed Corrosion Djinn™ in a commercial CAE environment. This will allow the designer to seamlessly employ corrosion analysis at the design stage, to eliminate the major design errors that lead to long-term failures and increased maintenance costs. This will require partnering with CAE and CAD software companies to incorporate directly into design tools both Corrosion Djinn™ and links to the essential electrochemical database.

7. Are there any patents related to this work? If yes, please provide the patent title, number, and inventor.

Since the software and database are both built on existing principles, they have not been patented. However, the database and software are copyrighted and as a result of the SBIR funding source, the US Government accords them SBIR data rights.