



# AMPTIAC

**QUARTERLY**

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**Special Issue**



## **Corrosion Conscious DESIGN**

**A Roadmap to Life-Cycle Cost Reduction**

**Material**  
E A S E

**Material Failure Modes**  
*Part 3*  
**Corrosion**

**Rules of Thumb**  
Material Selection and Design Considerations



AMPTIAC is a DOD Information Analysis Center Administered  
by the Defense Technical Information Center

## Editorial: The Key to Reducing Corrosion Costs Lies in Material Selection

This Special Issue of the *AMPTIAC Quarterly* is something that I've wanted to do for quite some time. As you may recall from an earlier Special Issue (Vol. 7, No. 4), corrosion costs our country an unbelievable amount of money. A few years ago the US Federal Highway Administration commissioned a study to quantify corrosion's toll on the nation's economy - the result was a staggering \$276B annually across 26 sectors, with Defense accounting for \$20B of this cost. While some may question the accuracy of these estimates, the scale of the problem is beyond dispute as the amount of funding expended each year to repair or replace corroded assets is massive.

In response to Congressional direction, the DOD elevated the fight against corrosion to a department-wide level by establishing the Office of Corrosion Policy and Oversight. This new office was chartered to integrate the many corrosion activities of the Services under a unified banner by transcending the traditional organizational stovepipes and cultural boundaries. To implement its strategies, the Corrosion Office turns to its action arm, the Corrosion Prevention and Control Integrated Product Team (CPC IPT). This team is charged with developing and executing the plans, procedures, and roadmaps to address many of the larger corrosion issues facing the Department. By directing resources, the CPC IPT is attacking the difficult-to-solve problems affecting military systems and infrastructure; many of which have the potential for large returns on investment. Using guidance developed by the CPC IPT, new acquisition programs are now beginning to plan for corrosion prevention and control up-front. This measure will help reduce future life-cycle costs tremendously, however, more still needs to be done.

Some two decades ago, while working towards my Bachelor's degree in mechanical engineering at a major university, I was one of only three students from the ME department that took a formal corrosion course as an elective. All the students in the department had some exposure to corrosion, which was covered in a required elementary materials science course. However, the instruction we received in this class discussed *what* corrosion is, and not *how* to select materials and technologies to prevent its occurrence. Two and a half years ago, when AMPTIAC first joined the CPC IPT, I began to wonder if my

experience was indicative of how designers are trained today. I had my staff conduct a study to investigate the state of corrosion education at our top colleges and universities. Using US News and World Report's 2004 listing, we identified the ten top four-year engineering colleges and doctorate-granting universities. We examined their mechanical engineering curricula and found that my initial observations from twenty years ago remain true today. The overwhelming majority of colleges and universities teach designers, as exemplified by mechanical engineers, what corrosion is, not how to prevent it. Since designers make the vast majority of material selection decisions, I felt it important that AMPTIAC publish an entire issue of the *Quarterly* which targets the design community and other interested parties, and focuses on improving corrosion resistance by increasing its consideration during material selection.

While conducting research for this issue of the *Quarterly*, we may have discovered why corrosion prevention and control, from a material selection standpoint, isn't taught to designers. It's because material selection that focuses on corrosion prevention and control can follow many different paths. It's not a single process per se, but is more akin to a discipline, which creates a quandary: how do you teach an entire discipline to designers who will only use it sporadically throughout their careers? To help resolve this plight we developed this Special Issue of the *Quarterly* with the intent that it will become a designers' desk reference. For this issue, we have taken the major elements of corrosion analysis independent of path, and assembled a generic process that designers can consider during material selection. Moreover, we point to sources of data designers can use to make informed decisions, while also highlighting the major issues. While this template certainly can't replace the knowledge acquired through formal training, it does serve to improve awareness about the need to consider corrosion in design. It also provides a road map of the necessary considerations to make during a material selection activity. Taken as a whole, the body of knowledge within this publication will help designers reduce the impact of corrosion to future systems.

Dave Rose  
AMPTIAC Director

*About the Cover: An MV22 Osprey rising into the salt-laden atmosphere above the Atlantic Ocean illustrates the need to consider the intended operating environment during system design in order to maximize long-term corrosion prevention. US Navy photo by Photographer's Mate Airman Zachary L. Borden.*

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From Our Viewpoint:

# Designers take Note!

## Improved System Corrosion

## Resistance Reduces Life-Cycle Costs

David H. Rose  
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### THE DESIGN PROCESS: CORROSION STARTS HERE

A serious but often overlooked problem that has enormous cost and safety implications is corrosion. Each stakeholder in the design, development, sustainment, and system operation communities likely has a different perspective on the implications of corrosion. From the standpoint of a system operator, corrosion often results in excessive maintenance time and reduced readiness rates, while a maintainer views corrosion as an issue that can require substantial financial and personnel resources. A program manager may worry about the cost of planning for corrosion prevention and control and see it as an issue that competes for budgetary resources with other technical considerations such as reliability or manufacturing. In contrast, a manufacturer may experience reduced profits due to poor reliability and associated warranty problems. A few years ago Congress commissioned a study to investigate the costs of fighting corrosion. The results of this study were astounding: corrosion was estimated to cost the US \$276B per year or 3.14% of the US GDP. In the Defense sector alone, corrosion was estimated to cost approximately \$20B per year.[1]

**Corrosion was estimated to cost the US \$276B per year or 3.14% of the US GDP**

When considering these enormous costs one might ask, can't corrosion be eliminated or at least minimized to reduce the burden that consumes so much of the Government's budget

**Design engineering students are not adequately taught corrosion prevention and control**

and our own paychecks? From my perspective, one of the reasons that corrosion costs are so high is because of the lack of coordination between different engineering communities. In particular, poor communication between materials/corrosion specialists and the design community contributes to the inadequate consideration of corrosion during the design process. I firmly believe that the overriding factor responsible for this communication barrier is the fact that design engineering students (e.g. mechanical engineers) are not adequately taught corrosion prevention and control (CPAC) while learning their craft. Upon leaving college and entering the workforce, many engineers know little about corrosion and fail to see it as a critical design issue.

Undergraduate studies in mechanical engineering, for example, often offer students little more than a brief introduction to corrosion. The introductory coursework typically focuses upon the forms of corrosion themselves, not the process of designing corrosion resistant components or structures. The result of this educational deficiency is that practicing designers typically have some understanding of the galvanic and uniform (traditional rust) forms of corrosion, but little or no awareness of the mul-

titude of other forms that are far more difficult to detect and prevent. Many of these other forms are localized and may be hidden such that they can go undetected until failure occurs. Design practices that incorporate corrosion prevention and control during material selection is the most effective way to develop components and/or systems that possess the desired attributes to ensure reasonable life-cycle costs and acceptable readiness rates.

### A MULTIDISCIPLINARY CALL TO ACTION

Reducing the cost of corrosion requires engineers, and particularly designers, to break out of their comfort zones and more fully consider the technology and knowledge resources available to them from other technical communities. Designers need to think outside their own discipline and reach out to the materials community; in essence they need to *pull* the corrosion solutions to them. But in order to do so, they must realize that a problem exists in the first place. Reaching this level of understanding alone will be a breakthrough.

The United States Government has spent billions of dollars on research and much of the information generated can be used by designers to help reduce risk on current projects. Available are hundreds of thousands of materials-related technical reports and other information resources that cover a broad range of subjects including various applications, environments, as well as system performance under various conditions. Over the years, the materials community has tried to *push* this technology and information to users, especially designers, but have had only limited success. The recent study on the cost of corrosion should be a wake up call to the entire engineering community. We must change the way we design new systems, so that the products we develop are made to be more durable and resistant to corrosion. This is the one sure way we can strategically reduce corrosion costs.

Reducing the cost of corrosion is not something that any one individual or group can do on their own. As mentioned earlier, the most important aspect is for the design community to recognize the problem and subsequently take steps to rectify it. One of the steps that must be taken is to update undergraduate engineering curricula to ensure that engineers coming out of college are armed with the tools and knowledge needed to fight the corrosion battle during design, rather than having to mitigate the problem later when it becomes a costly sustainment issue. Likewise, the materials community needs to interact more directly with designers and provide them with the technology solutions and data needed to produce corrosion resistant equipment, systems, and structures. By working

**The materials and design communities can convert the existing technology push into a technology pull.**

together, the materials and design communities can convert the existing technology *push* into a technology *pull*, thus streamlining the process of implementing new technologies, which currently takes decades.

Breaking down the institutional and professional barriers responsible for the inadequate consideration of corrosion prevention and control during design can only occur with the support of the engineering professional societies. If the design-related societies, such as ASME, IEEE and SAE, and the societies that produce material selection type products, such as ASM International and NACE International, would work together in a cooperative enterprise, each of their individual constituencies would

benefit from the activities, resources, and knowledge available from the others. If this cooperation were to happen, then we will have put into place the processes needed to help

minimize the corrosion problems we currently face. Establishing the necessary coordination between the participating societies will not be easy. Furthermore, successful coordination will only occur if the senior management from each society understands that it's in their best interest to cooperatively work together with the common goal of solving a National problem.

**Professional Societies need to work together with the common goal of solving a National problem**

**PROPER MATERIAL SELECTION: THE KEY TO REDUCING LIFE-CYCLE COSTS**

Unlike other design considerations such as fatigue, conducting a corrosion analysis isn't a straightforward process and it may be a costly one since each form of corrosion is essentially a separate failure mode that needs to be considered individually. The challenge that designers face is balancing the degree of detail put forth in the analysis against their available resources including time and budgetary concerns.

One might wonder why a practical, design-based material selection process that considers corrosion prevention and control hasn't already been developed and subsequently taught to new design engineering students. The following list identifies many of the factors that contribute to the difficulty in developing a simplified, readily understood process.

- There are multiple and often competing forms of corrosion that need to be considered for every design.
- There are a vast number of material/operational environment combinations, and each can form the basis for potential corrosion problems to occur.
- Corrosion data are overwhelmingly empirical, often widely scattered, and come in a variety of forms. Since some data are tabular, other types are graphical, and still others are entirely qualitative, it makes it somewhat difficult to evaluate and compare them with each other.
- Corrosion data are specific to the material and the environment from which it was taken. The corrosion form and rate at which it occurs varies with slight changes to the material's composition/processing history or the environment it's exposed to. Thus, corrosion data can be easily misapplied.
- Laboratory test data are not always reflective of how a material will behave in an application.
- Data may not be available for all potential forms of corrosion

that might pertain to a specific application/environment combination.

- Corrosion data often cannot be easily used to predict corrosion rates in field applications.

Because of its complexity, corrosion analysis is really more of a practice or discipline, like reliability engineering, than a process such as that used when designing fatigue resistance into a structure. Since designers are routinely pressed for time and operate under a strict budget, they don't often have the luxury of consulting with corrosion specialists to verify many of the decisions they make. The impact of improper consideration of corrosion is exactly the same as improper consideration of reliability: unanticipated problems that result in reduced readiness and increased life-cycle costs.

**Corrosion analysis is more of a practice or discipline than a process**

Unanticipated corrosion problems will always occur, and correcting them requires a reactive approach using the services of a trained specialist to determine the best way to mitigate the problem. Corrosion can be minimized if the design community proactively considers corrosion resistance early during system design when material selection has not been 'locked in'. Improving material selection practices to fully consider corrosion prevention and control will reduce total ownership costs and enable affordable life extension – two important attributes that DOD program managers and their prime contractors should consider. One critical issue to understand when selecting materials is that

**Improving material selection practices to fully consider corrosion prevention and control will reduce total ownership costs**

you will seldom find the 'perfect' material, since most materials will corrode when exposed to corrosive conditions. Rather the goal is to identify the

best material and associated corrosion prevention and control practices that meet your expected budget for material acquisition and life-cycle costs.

This issue of the *AMPTIAC Quarterly* is devoted to the subject of corrosion prevention and control with a special emphasis on material selection. We are currently writing a book entitled "Corrosion Prevention and Control: A Program Management Guide for Selecting Materials." Included in the book is a chapter on material selection, which the following articles are largely based upon. The book will be available in the Spring of 2006. The following article on material selection and the others on corrosion-related failure modes (*MaterialEASE*) and corrosion rules of thumb form the basis for improving consideration of corrosion during design. By reading all of these articles a designer will gain a better appreciation for the corrosion analysis process and where they might go to get the data needed to ensure they develop corrosion resistant designs.

**REFERENCE**

- [1] G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, and J.H. Payer, *Corrosion Costs and Preventative Strategies in the United States*, Federal Highway Administration, FHWA-RD-01-156, September 2001

# Selecting Materials for Improved Corrosion Resistance

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## INTRODUCTION

In a perfect world, materials engineers and corrosion specialists would always assist designers with material selection tasks to ensure that components and systems are designed with longevity in mind. In the real world, however, this is not always the case. Designers typically select the materials of construction themselves, with these decisions based on meeting critical performance requirements. Other factors, such as corrosion prevention and control, are often given minimal consideration.

A material's inherent corrosion resistance is largely determined by its elemental composition, but also by its processing history, surface morphology, geometry, and in some cases its size. Consequently, two very similar materials may have quite different resistances to corrosion. Selecting the 'best' material, from a corrosion standpoint, is not a cut-and-dried process. Numerous factors need to be considered and there is no single path to making an informed selection. Ultimately, designers must rely upon their best 'engineering judgment' to select the optimum material, considering corrosion resistance in balance with other performance requirements, as well as other tangible factors, including cost, availability, and maintainability.

It is important to realize that one will seldom find the 'perfect' choice, since most affordable commercial materials will corrode under the right set of conditions. Instead, designers should identify the material and associated corrosion prevention and control practices that meet the program's budgetary constraints, while also ensuring acceptable corrosion resistance over the system's life-cycle. This strategy will help to ensure that corrosion-related maintenance requirements are minimized and predictable, thus reducing overall life-cycle costs and increasing system readiness rates. Reasonable (and budgeted) life-cycle costs and high readiness rates (due to reduced maintenance requirements) are two of the most important contributions to lower operating costs, while ensuring long system service lives and increased safety.

## CORROSION PREVENTION AND CONTROL: THE RUST STOPS HERE

Most would agree that corrosion is a serious problem, but opinions differ greatly about how to address it. Many mistakenly believe that corrosion is a maintenance problem – an unavoidable part of doing business. The truth is more sobering: most corrosion that occurs in military and commercial systems could

have been avoided. While not the intent, many systems were inadvertently designed to corrode because little or no consideration was given to corrosion prevention and control (CPAC)\* during the material selection phase of the design activity.

One reason designers pay so little attention to CPAC is that they have minimal experience in considering corrosion issues. As mentioned in the previous article, "Designers Take Note! Improved System Corrosion Resistance Reduces Life-Cycle Costs," design engineers typically receive almost no training on the subject while in college. It is also true that corrosion science is a complicated matter that doesn't easily lend itself to the development of a simplified analysis process. Most material performance criteria can be expressed numerically, in terms of a threshold, a range, or even an equation. Choosing material candidates to meet these requirements is usually a straightforward process. Considering corrosion and CPAC strategies is a highly qualitative process that requires circumspection. Engineers must not only balance potential benefits against other performance parameters, but must also consider the longer-term attributes – service life, anticipated maintenance and repair, and disposal to name a few.

As these issues are complex and not in any way straightforward, it is easy to see why corrosion is overlooked in design, and is thus passively relegated to the operation and maintenance world. This article provides designers with a rudimentary 'road map' covering the major steps needed to assess whether a new design may be susceptible to corrosion and how potential problems can be effectively mitigated or eliminated. Following these steps during material selection, even without being an expert in corrosion, should help to reduce the instances and extent to which corrosion occurs. In critical situations where corrosion can't be tolerated at all, it's still best to involve a professional that has the credentials to ensure that all aspects of the design are thoroughly investigated.

The other articles published in this issue of the *AMPTIAC Quarterly* provide additional detail concerning the forms of corrosion and the approaches that can be used by designers to reduce future corrosion problems. Bear in mind that the information presented here is not exhaustive. More will be required before one can confidently conclude that a design will stand the test of time. For this reason we provide a listing of data sources that can be consulted to find the additional information needed to complete a corrosion analysis.



## Identify Initial Slate of Candidate Materials

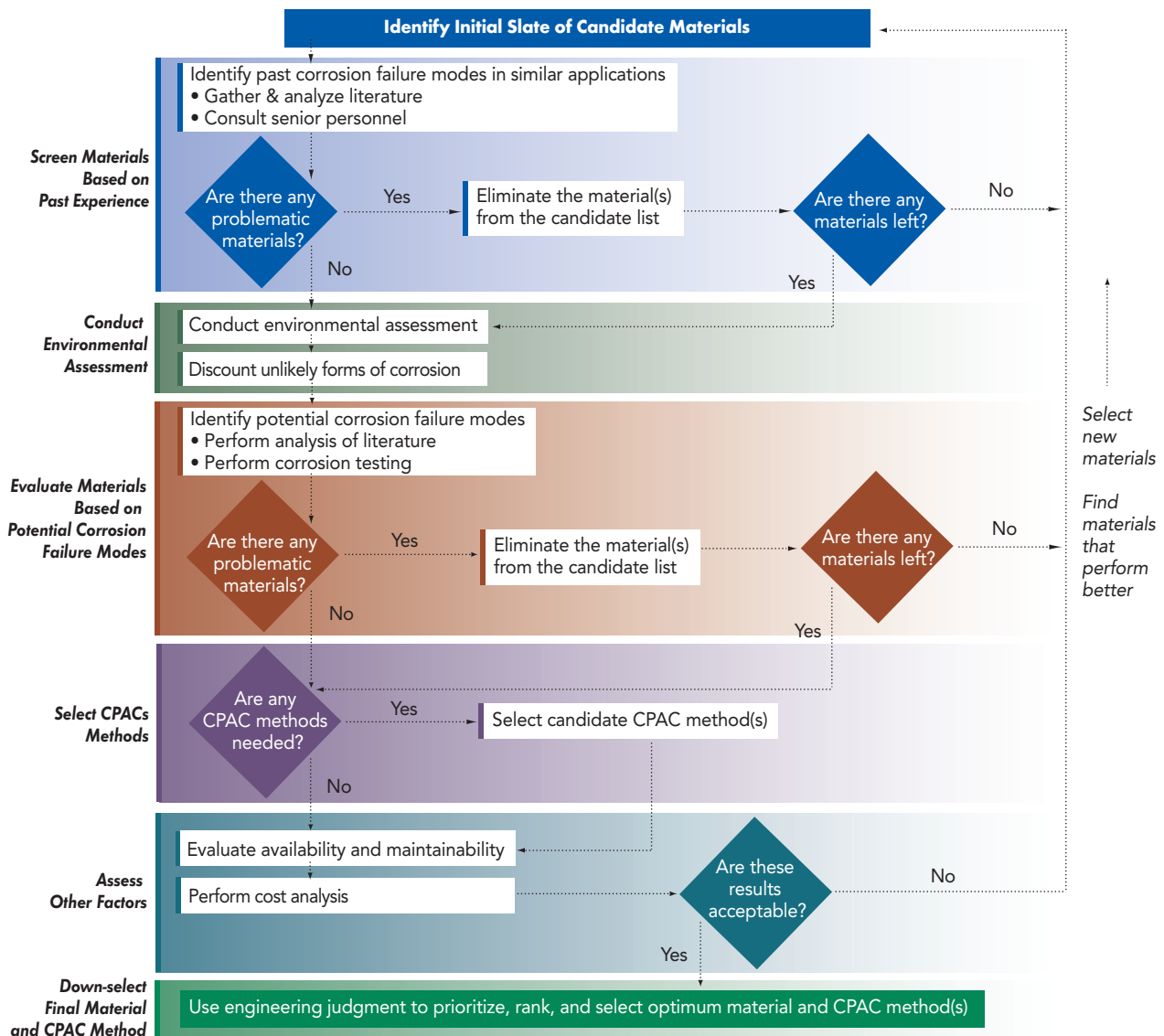
Figure 1 is a generic process for screening materials in a representative design situation. The body of this article parallels the steps in the flowchart, from developing a list of candidate materials through final selection. Via a host of traditional means, designers can readily identify a slate of candidate materials possessing the necessary physical, mechanical, thermal, and/or electrical properties to meet requirements. The challenge comes in ensuring that these candidates are scrutinized for their corrosion resistance as well when selecting the best overall candidate (Figure 2).

Depending upon the criticality of the application and the design process being employed, the number of materials chosen as initial candidates will vary. The advantage of considering more materials is that it would be more likely that an appropriate candidate could be identified to meet traditional requirements as well as provide some level of corrosion resistance. The disadvantage is that such an analysis could be more costly. For highly important decisions with strict deadlines, analyzing multiple materials simultaneously would be the most efficient approach as

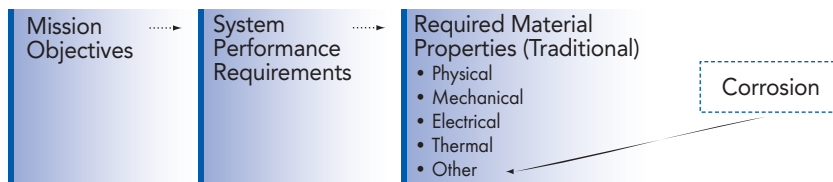
it would minimally impact the project schedule. For less critical applications it may be more practical to perform a comprehensive corrosion analysis on just a single material instead.

## Screen Materials Based on Past Experience

After determining the material(s) to be considered, the next step is to look at whether there have been corrosion problems in similar applications to that being designed, and to ascertain what caused those problems to occur. The cheapest thing to do (from a life-cycle cost standpoint) is to eliminate from consideration any material that has caused corrosion problems in a similar application in the past, especially those problems that couldn't be controlled using affordable CPAC practices and associated maintenance procedures. One method to determine whether 'legacy' materials have corroded in a similar application is to analyze the literature to ascertain whether a particular combination of material and application has been problematic in the past. Another way is to consult senior personnel, those 'old-timers' that may have extensive experience with the design, production, and sustainment of similar legacy applications.



**Figure 1. Generic Process for Selecting Materials to Improve Corrosion Resistance – A Roadmap to Life-Cycle Cost Reduction.**



**Figure 2. Material Property Needs are Derived from System Performance Requirements.**

System requirements define what performance levels are needed from constituent materials. If life-cycle issues are to be addressed as part of a system's overall set of requirements, then corrosion and other time-dependent material properties must be considered.

### Conduct Environmental Assessment

The next step in the process is to immediately discount the forms of corrosion that are unlikely to occur. As an example, erosion corrosion occurs when a corrosion prone material is exposed to a flowing corrosive fluid. If the application being designed will not be exposed to a flowing fluid, then erosion corrosion is irrelevant and can be discounted. To determine the more likely forms that will occur, the analyst should examine the factors responsible for initiating each corrosion mode and then determine which ones are present in the application being designed. Our article, "Corrosion Rules of Thumb: Material Selection Considerations for Various Forms of Corrosion," provides examples of this information.

After a candidate material (or materials) has been selected and the obvious problematic materials have been rejected, the next step is to analyze the environment in which the application will operate. When considering the operational environment many may automatically consider exposure to atmospheric, industrial, or marine conditions as the corrosion inducing factors. While important, such a global or 'macro' view may be too restrictive since conditions imposed by the configuration and operation of the system may result in corrosive microenvironments that need to be considered. For instance, the build-up of scale within storage tanks and piping may result in situations where corrosive ions can accumulate and precipitate hidden corrosion. The same can be said for structural details used in the construction of a system including lap joints, gaskets, and enclosed places that cannot be accessed. These design details and operational conditions are known to concentrate ions, thus creating a corrosive microenvironment within certain regions of an application.

Designers should thoroughly analyze the operating conditions the entire system will be subjected to and determine the potential combinations of design details, temperature, humidity, and chemical exposure that may be present at all points. The designer should also consider the conditions the system may experience throughout its life-cycle including maintenance, storage, and transportation. For example, Army ground vehicles are designed to spend their service lives on dry land, but the few weeks spent lashed to the deck of a ship while being transported over the ocean can easily initiate corrosive actions that can rapidly destroy them. When conducting the corrosion analysis, designers should consider both the micro- and macroenvironments to determine the specific conditions that candidate materials will be exposed to during their service.

A comprehensive analysis of the operating environment can be an extensive undertaking. Therefore, depending upon the time and resources available, the extent of the analysis could

range from general to detailed using a tiered approach. It is most important to first define the general operating conditions (e.g. atmospheric, immersed in liquid, buried, etc.). From there more detail can be added on: industrial atmospheric, tropical seawater, etc. A detailed environmental assessment could include specifics on pH, pollutants present, temperature, and other relevant factors. Design details should not be overlooked since they certainly can initiate the microenvironments responsible for triggering specific corrosion modes.

### Evaluate Materials Based on Potential Corrosion Failure Modes

Once the candidate materials and the environmental conditions have been determined, the analyst must investigate the potential for one or more of the many forms of corrosion to become active. There are several forms of corrosion that should be considered.

- Uniform corrosion
- Galvanic corrosion
- Crevice corrosion
- Pitting corrosion
- Intergranular corrosion
- Selective leaching
- Erosion corrosion
- Stress corrosion cracking (SCC)
- Corrosion fatigue
- Fretting corrosion
- Filiform corrosion

The *MaterialEASE* entitled "A Brief Tutorial on Corrosion Related Material Failure Modes" found in this issue of the *AMPTIAC Quarterly* discusses many of these corrosion forms and provides a summary of the causative factors responsible for activating them. There are also some other forms of corrosion that are less common than those listed above. Additional data relating to the various forms of corrosion can be found by reviewing the literature including reference books, handbooks, and technical reports. Unfortunately, it is seldom the case that all of the data needed to conduct an analysis can be found in one reference.

At this point in the process the designer is left with at least one candidate material and a listing of corrosion modes that must be considered in the analysis. They also now know the application's anticipated environmental conditions. Since the scope of the analysis has been defined, one can assess whether any of the potential forms of corrosion may become active when the candidate material is subjected to the operational environment. If time allows the best way to investigate both of these issues is to perform an analysis of the literature.

**Table 1. Listing of Corrosion Information Sources.**

	Information Sources	Source Description	Internet Address
US Government Data Sources	DOD Advanced Materials and Processes Technology Information Analysis Center (AMPTIAC) <sup>a</sup>	Technical Library & NAMIS Database	<a href="http://amptiac.alionscience.com/InfoResources/docsearch.html">http://amptiac.alionscience.com/InfoResources/docsearch.html</a> <a href="http://namis.alionscience.com/">http://namis.alionscience.com/</a>
	Defense Technical Information Center (DTIC)	Public & Private STINET Database	<a href="http://stinet.dtic.mil/info/s-stinet.html">http://stinet.dtic.mil/info/s-stinet.html</a> (public STINET) <a href="http://www.dtic.mil/dtic/registration/index.html">http://www.dtic.mil/dtic/registration/index.html</a> (Private STINET-limited distribution documents)
	Department of Energy (DOE)	Energy Citations Database	<a href="http://www.osti.gov/energycitations/index.jsp">http://www.osti.gov/energycitations/index.jsp</a>
	National Aeronautics and Space Administration (NASA)	Aeronautic & Space Database Technical Reports Server	<a href="https://www2.sti.nasa.gov/login/wt/">https://www2.sti.nasa.gov/login/wt/</a> <a href="http://ntrs.nasa.gov/">http://ntrs.nasa.gov/</a>
	Federal Aviation Administration (FAA)	Library Search Engine	<a href="http://www.faa.gov/library/">http://www.faa.gov/library/</a>
	National Institute of Standards and Technology (NIST)	NIST Webspace Keyword Search Engine	<a href="http://www.nist.gov/search.htm">http://www.nist.gov/search.htm</a>
Professional Societies & Other Sources	NACE International (The Corrosion Society)	NACE Store Product Search Engine	<a href="http://www.nace.org/nacestore/search.asp">http://www.nace.org/nacestore/search.asp</a>
	ASM International (The Materials Information Society)	ASM Website Search Engine	<a href="http://www.asm-intl.org/">http://www.asm-intl.org/</a>
	SSPC (The Society for Protective Coatings)	SSPC Online Store Search Engines	<a href="http://www.sspc.org/books/bookstore.html">http://www.sspc.org/books/bookstore.html</a>
	SAE International (Society of Automotive Engineers)	SAE Website Search Engine	<a href="http://www.sae.org/jsp/jsp/advancesearch.jsp">http://www.sae.org/jsp/jsp/advancesearch.jsp</a>
	SME (The Society of Manufacturing Engineers)	SME Website Search engine	<a href="http://www.sme.org">http://www.sme.org</a>
	ASTM International (source for standards)	ASTM Standards Search Engine	<a href="http://www.astm.org">http://www.astm.org</a>
	ISO (International Organization for Standardization)	ISO Store	<a href="http://www.iso.org/iso/en/prods-services/ISOstore/store.html">http://www.iso.org/iso/en/prods-services/ISOstore/store.html</a>
	ASCE (American Society of Civil Engineers)	ASCE Online Research Library	<a href="http://www.ascelibrary.org/">http://www.ascelibrary.org/</a>
	ECS (Electrochemical Society)	ECS Website Search Engine	<a href="http://www.electrochem.org/search.htm">http://www.electrochem.org/search.htm</a>
	Swedish Corrosion Institute	Webpage with Report Listing	<a href="http://www.corr-institute.se/english/reports/Rep_list_e.html">http://www.corr-institute.se/english/reports/Rep_list_e.html</a>

<sup>a</sup> AMPTIAC will soon be merged into a new DOD Information Analysis Center (IAC), the Advanced Materials, Manufacturing, and Testing IAC (AMMTIAC). The Internet address will change at that time to reflect the new organization.

The DOD and other Government agencies have invested considerable funds into researching corrosion modes, and mitigating their effects in existing applications. Much of this work has been recorded in technical reports that are available from AMPTIAC and from our sponsor, the Defense Technical Information Center. NASA and DOE also have extensive corrosion resources. These and other sources for corrosion information are summarized in Tables 1 and 2. The reports available from these organizations are excellent sources of relevant data to consult when performing material selection. In many cases they contain “lessons-learned” information that discusses corrosion in applications and operational environments that may be similar to the designer’s current interests. Other sources of information include reference books and handbooks. These sources typically have very good data related to coupon level testing, as well as discussions on problematic materials. Unlike technical reports that address very specific issues that may be relevant to program needs, these resources typically offer more general information.

The information needed to identify and eliminate problematic materials from consideration can be found in the technical literature. Literature investigations are also useful for identifying design details to be avoided and for helping select the appropriate CPAC practices needed to protect the chosen material and ensure that it performs as desired. It’s important to perform these investigations to preclude unac-

ceptable life-cycle costs or catastrophic failure from occurring.

In some situations it might be the case that corrosion susceptibility data concerning a specific material being considered doesn’t exist. In these situations it may be necessary to perform corrosion testing to ascertain the candidate material’s behavior in the intended environment. However, the cost of conducting the tests, as well as the time needed to get them done, must be carefully considered since they could affect the development schedule. There have been many past instances where designers simply assumed that the needed data didn’t exist, so they either neglected the analysis completely or they jumped directly into corrosion testing. This can be a wasteful strategy since the literature is rich with corrosion data.

Following the completion of the literature analysis and/or testing program one should have adequate information to reject any problematic materials, thus yielding a listing of candidate materials that meet performance requirements while simultaneously possessing acceptable corrosion resistance. Please note that a material with ‘acceptable’ resistance may still corrode when exposed to the operational environment (but less severely and at a slower rate). CPAC materials and practices might still be needed to provide the desired overall performance.

#### Select Corrosion Prevention and Control Methods

Perhaps even more daunting than selecting the actual material of construction is choosing the corrosion prevention and con-



**Table 2. Details Concerning Corrosion Information Sources.**

	Information Source	Type of Information	Number of Corrosion Related Reports & Papers	Available Search Engine?	Downloadable PDFs?	Free Service or Fee Based?	Access Restrictions?
US Government Data Sources	AMPTIAC <sup>a</sup>	Papers, Reports, Databases	22,271 <sup>b</sup>	Yes	Yes (Limited)	Partially free. Fee for subscription to controlled-access databases and for ordering hardcopies <sup>c</sup>	Yes, access to limited distribution portion of holdings is controlled
	DTIC	Papers, Reports	38,908 <sup>b</sup>	Yes	Yes	Fee for ordering hardcopies	Yes, access to limited distribution portion of holdings is controlled
	DOE	Papers, Reports	56,763	Yes	Yes	Free Service	No
	NASA	Papers, Reports	34,264	Yes	Yes	Fee for ordering hardcopies	Yes, access to limited distribution portion of holdings is controlled
	FAA	Papers, Reports	>500	Yes	Yes	Free Service	No
	NIST	Papers, Reports	>1000	Yes	Yes	Free Service	No
Professional Societies & Other Sources	NACE	Books, Papers, Reports, Standards, Databases, Videos	74,000	Yes	Yes	Fee for downloading or ordering products	No
	ASM	Books, Papers, Reports, Standards	140	Yes	Yes	Fee for downloading or ordering products	No
	SSPC	Books, Papers, Reports, Standards	>100	Yes	Yes	Fee for downloading or ordering products	No
	SAE	Papers, Reports	2671	Yes	Yes	Fee for downloading or ordering products	No
	SME	Papers, Reports	253	Yes	Yes	Fee for downloading or ordering products	No
	ASTM	Standards	>700	Yes	Yes	Fee for downloading or ordering products	No
	ISO	Standards, Papers, Books	117	Yes	Yes	Fee for downloading or ordering products	No
	ASCE	Papers, Reports	>350	Yes	Yes	Fee for downloading or ordering products	No
	ECS	Papers, Reports	>1000	Yes	Yes	Fee for downloading or ordering products	No
	Swedish Corrosion Institute	Books, Papers, Reports	>150	No	Yes	Fee for downloading or ordering products	No

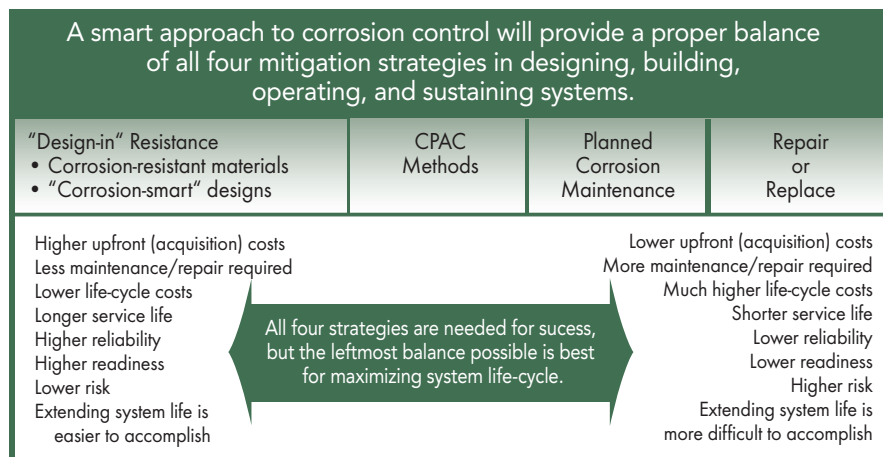
<sup>a</sup> AMPTIAC will soon be merged into a new DOD Information Analysis Center (IAC), the Advanced Materials, Manufacturing, and Testing IAC (AMMTIAC). The Internet address will change at that time to reflect the new organization.

<sup>b</sup> There is some overlap between the document holdings of the AMPTIAC and DTIC libraries.

<sup>c</sup> AMPTIAC currently has a scanning and database development project underway that will result in over 14,679 corrosion-related electronic documents being available for download from the AMPTIAC/NAMIS websites. Unlimited distribution documents will be free to download.

trol technologies that may be needed to protect it. Some materials require no CPAC methods since they possess surface characteristics that make them resistant to corrosion. Stainless steels are a good example of this. However, most metals (and some other materials) need some form of additional protection from the corrosivity of their operating environment. This article makes no attempt to discuss when, where, and how to employ CPAC methods in any particular design situation, as that has already been the subject of many books (which are more comprehensive than anything we could hope to compile within

these pages). Having stated that, there are several strategies that can be employed to protect a metallic material from corrosion if and when necessary. A global view of these strategies is presented in Figure 3 and the sidebar on CPAC methods, shown on pages 12 and 13. One such strategy is to construct a barrier to prevent the corrosive environment from contacting the surface. Effective barriers include coatings, surface treatments, and corrosion preventive compounds (CPCs) such as greases. Another strategy is to modify the environment itself. Now obviously this won't work when a structure is exposed to the



**Figure 3. Material Property Needs are Derived from System Performance Requirements.**

elements themselves, but corrosion can also happen inside a structure or system, especially if it is totally enclosed. A good example is a heating plant where steam is circulated from the boiler to heat exchangers. The operational environment within this type of enclosed system contains water, which certainly will be laden with minerals and other contaminants that can initiate corrosion reactions. In these situations a chemical substance known as a corrosion inhibitor can be mixed with the fluid to reduce the corrosivity of the environment.

Another approach for reducing corrosion is to employ mechanisms that can modify the electrochemical processes that consume materials. Cathodic protection, either through the use of sacrificial anodes or electronic impressed current devices, can convert a material that normally will corrode quite readily into a material that resists corrosion. This approach works very well for protecting fixed assets, such as steel structures, pipelines, and buried tanks. A final measure for reducing corrosion involves maintenance practices. Routine cleaning can significantly reduce the instances of corrosion, but so too can the reapplication of coatings and corrosion preventive compounds. Removing the corrosive substances and other debris while also ensuring the integrity of the protective barrier is one of the most effective ways to reduce the severity of corrosion.

A complexity with selecting corrosion prevention and control methods is the seemingly infinite number of available choices, especially coatings. It should be noted that a coating is rarely a single material but more typically is a system of materials that includes primer and topcoat layers. Specific functional requirements, such as low observability or camouflage, may dictate even more layers within the system. The important thing to note is that the coating layers must be compatible with each other and also with the metal structure or component being protected.

When selecting coatings an important consideration is that more durable ones typically come at a higher cost but offer the promise of a longer life with reduced maintenance. However, in many cases choosing the most expensive technique, even if it promises the best performance, may be unaffordable. If the component or system being designed can be easily repainted, then a less expensive and poorer performing coating may suffice. On the other hand, if the component or

system is difficult to repaint, either through difficulty of access or by operational needs that preclude taking the item from service, then a better performing coating system is needed. A final consideration is that some classes of materials might receive additional protection from a surface treatment or metallic coating that's applied prior to the primer/topcoat layers. For example, aluminum structures are often treated with an Alodine™[†] conversion coating prior to being primed and top-coated. Similarly, steel alloys are sometimes galvanized. The use of surface treatments or metallic coatings along with the subsequent application of primer and topcoat layers provides the corrosion resistance needed to protect the system or component while in service.

#### Assess Other Factors

Presuming that multiple materials were considered, the time has now come to downselect the material that will ultimately be used. Perhaps the most important thing to understand is that one can seldom select a perfect material, but rather the goal should be to find the least objectionable one. At this point a thorough analysis of the initial candidates has been completed, and most likely, several of the more problematic candidates have already been rejected. Selecting the best of the remaining candidates is based not only upon inherent corrosion resistance and performance, but on a number of other factors including product availability, maintainability, and cost.

**Product Availability and Maintainability Analyses:** Prior to selecting the material and CPAC method that will be employed, one must first determine whether they are available as commercial commodities. Selecting the best CPAC method will be of little value, if it's too difficult to obtain in the quantities required for the production run. Maintainability is an equally important issue that relates more to the CPAC methods that will be employed. Some of the aspects to consider include ease of application of coatings and CPCs, maintenance intervals for reapplication, and ease of access to interior spaces for inspection and reapplication. Some areas of a structure or system may be difficult and prohibitively costly to access, so all maintainability aspects must be closely determined.

**Cost Analysis:** Before conducting the cost analysis one must first determine the life expectancy of the system or component being designed. The strategies employed while conducting the cost analysis differ depending upon whether the system or component will have a short or long life and whether it is a critical or non-critical item. Corrosion may be tolerated to a greater extent in short-lived and non-critical applications. In these situations the cheapest remaining material candidate and CPAC method might be appropriate. Conversely, if the application being designed is critical and failure cannot be tolerated, or if it is a component that is expected to remain in-service for a considerable length of time, then far more thought and effort must be given to selecting both the material and the CPAC method.

When designing critical structures/systems or those that are expected to be operated for extensive periods of time, it's important to consider total ownership costs instead of focusing solely on acquisition costs. Selecting the lowest priced candidate material and CPAC method may initially provide cost savings but as many programs in the past have learned, an inadequate consideration of CPAC approaches during design can ultimately lead to excessive maintenance costs and reduced readiness rates. These two issues are important considerations when deciding to employ a system beyond its planned life span. Life extension of Defense assets has taken greater prominence lately, and it's far easier to maintain an aging system for which corrosion prevention and control were up-front considerations during design.

#### Down-select Final Material and CPAC Method

Ensuring the lowest total ownership costs means that the designer must select both the optimum candidate material as well as the optimum CPAC method if one is necessary. In this context 'optimum' doesn't mean the best overall solution since this may come at an unaffordably high cost. Determining the optimum solution involves balancing acquisition cost along with the predicted life and maintenance requirements of the selected material and CPAC method. For instance, if a metallic structure were painted to protect it from corrosion, then the quality of the coating certainly would influence its durability and expected life. In cases where painted structures are employed, it may very well be advantageous to select a high-quality coating that promises long life, since the time needed to reapply the coating later during maintenance is a factor that contributes to life-cycle costs.

The base metal being protected must be selected with adequate consideration given to both its cost and corrosion resistance. It is important to understand that CPAC measures, such as coatings or other CPCs, will seldom completely protect a structure or component throughout its life. During the time when the chosen CPAC method has lost its effectiveness, the ability of the material to withstand corrosive environments predictably becomes very important, and will help determine when CPAC methods should be reapplied.

When comparing candidates the best technical solution will be the material most resistant to the corrosion modes that can initiate catastrophic failure. The remaining forms of corrosion might very well be controlled through judicious use of CPAC methods, especially if they are high quality and long lasting. But remember, some methods may lose effectiveness over time

so the slight cost increase that may be seen from selecting one metal over another with lesser corrosion resistance might be cheaper in the long run. Deciding which material possesses the best combination of performance and cost can be a difficult proposition to make, but the return on investment is well worth the time in doing so.

#### CONCLUSIONS

For critical applications the best approach for ensuring corrosion resistant designs is to employ the use of trained corrosion specialists or materials engineers to help select the most appropriate materials and corrosion prevention and control practices. However, we realize that for many organizations and designs this may not be feasible. What we present here is an approach that designers can use to improve their consideration of corrosion prevention and control during material selection. The approach may seem a bit complicated, but one thing is certain, using it or a similar process will help reduce corrosion and related life-cycle costs.

The US Government, specifically the Departments of Defense and Energy, as well as NASA and other Federal agencies, have funded literally tens of thousands of corrosion-related research projects over the past many decades. Much of the information resulting from this research is available to help reduce performance risk on new acquisition programs. The difficulty with using this information is obtaining it in a timely fashion. Much of it currently resides in paper collections or microfilm, thus restricting the ease at which it can be obtained. Because of the variety of interests of those who conducted this research, it's likely that information exists that is directly relevant to any given application, intended environment, and candidate material. In the absence of using such data, designers should still endeavor to utilize the more general information contained in reference books and handbooks. Doing one's 'homework' to the maximum extent possible will pay dividends later with reduced life-cycle costs and increased readiness rates.

DOD policy now requires program managers to provide evidence that they have planned for corrosion mitigation when they present their procurement strategies before acquisition review panels, such as the Defense Acquisition Board. For those contractors supporting a DOD-related or other Government acquisition program, it makes sense to use the best design practices and information to ensure the customer is delivered a durable system or structure that possesses the lowest life-cycle costs and highest readiness rates possible, maximizing their return on investment, and providing the US taxpayer with the best value for their tax dollar.

This issue of the *AMPTIAC Quarterly* possesses a good deal of the kind of information needed to make more informed material selection decisions that will reduce future corrosion costs. AMPTIAC is currently developing a handbook entitled *Corrosion Prevention and Control: A Program Management Guide for Selecting Materials*. This new book is nearing completion and will be available in the Spring of 2006. It greatly expands upon the information we present here and will be very useful for both program office staff, as well as prime and subcontractor engineers that are involved in material selection decisions.



## Corrosion Prevention and Control Methods

There are a number of possible approaches to improve the ability of a material, component, or system to withstand the effects of corrosion (see Figure 1). Corrosion prevention and control (CPAC) methods, however, can be divided up into six main groups including coatings, surface treatments, corrosion preventive compounds, inhibitors, cathodic and anodic protection, and strategic methods.

**Coatings:** Coatings may be the easiest, most effective, and least expensive CPAC method available. Durable metallic, inorganic, and organic coatings are frequently used for providing short- or long-term corrosion protection of metals from various types of corrosive media. There are two main types of coatings: barrier coatings and sacrificial coatings. A barrier coating acts as a shield, which isolates the metal being protected from the surrounding corrosive environment. Barrier coatings are typically unreactive, resistant to corrosion, and also protect against wear. Sacrificial coatings preferentially corrode, which is an effective mechanism for protecting the cathodic substrate (see discussion on cathodic protection below).

**Surface Treatments:** These treatments modify a material's surface to improve its corrosion resistance. Conversion coating and anodizing techniques employ chemical reactions to create a stable, corrosion resistant oxide film on the metal's surface. Shot peening is a mechanical process that induces compressive residual stresses on the surface, thus improving resistance to stress corrosion cracking and corrosion fatigue. Laser treatments can modify the surface characteristics of a material including its hardness and morphology. As a result, certain forms of corrosion may be mitigated or prevented. Laser shock peening is a process somewhat analogous to shot peening in that it too can induce compressive residual stresses within a metal's surface region to increase its resistance to stress corrosion cracking and corrosion fatigue.

**Corrosion Preventive Compounds (CPCs):** CPCs offer temporary protection against corrosion and as such, are materials that need to be reapplied during scheduled maintenance. They come in four basic types[1]:

- Water displacing soft films
- Water displacing hard films
- Non-water displacing soft films
- Non-water displacing hard films

Water displacing CPCs penetrate small cracks and crevices, force out any water that may be present, and leave behind a protective film. These films can be oil, grease, solvent, or resin based. They can be hydrophobic (i.e. they repel water) or they can contain corrosion inhibitors (see below).

**Inhibitors:** Inhibitors are chemicals that either react with the surface of a material to decrease its corrosion rate, or modify the operational environment to reduce its corrosivity. Inhibitors may be dissolved in an aqueous solution or dispersed in a protective film. For instance, they can be injected into a completely aqueous recirculating system (e.g. automobile radiators) to reduce the corrosion rate in that system. They may also be used as additives in coating products, such as surface treatments, primers, sealants, hard coatings, and CPCs. Furthermore, some inhibitors can be added to water that is used to wash a component, system, or vehicle. Inhibitors are usually grouped into five different categories: passivating, cathodic, film forming, precipitation, and vapor phase.

**Cathodic and Anodic Protection:** *Cathodic protection* (CP) is a widely used electrochemical method for protecting a structure or important components of a system from corrosion. There are two main classes of cathodic protection: active and passive. Active cathodic protection, also called impressed-current cathodic protection (ICCP), uses an external power supply to provide an electrical current to the surface of a metal. The excess electrons at the surface feed the corrosive medium, thereby protecting the metal from being stripped of its electrons, which would otherwise result in corrosion of the metal. Passive CP systems are simpler than ICCP systems and involve the galvanic coupling of the metal being protected to a sacrificial anode, which protects the adjoining surface by freely giving up electrons and in the process preferentially corroding.

*Anodic protection* is a more recently developed but less frequently used method of corrosion control. Using an applied electrical current, this method actively creates a passive film on the surface of the material being protected. For some applications, the current can be sustained during the material's service life, in order to maintain the passive film. Passive films are very non-reactive and consequently materials that possess them are resistant to corrosion. The method is typically employed to protect materials that are exposed to strongly alkaline or acidic environments. Anodic protection can only be used on metals capable of forming a passive film such as stainless steels.

**Strategic Methods:** Design, maintenance, and material selection can be strategically used to minimize the extent to which a material, component or system corrodes during its lifetime. Simple elements incorporated into a design can lessen the risk of corrosion. For example, allowing for drainage of water that otherwise might become trapped can effectively reduce corrosion problems. Similarly, employing seals to preclude water from entering a component or system will improve its corrosion resistance. Another effective way to minimize corrosion is to use gaskets to electrically insulate two dissimilar metals, thus eliminating the possibility of galvanic corrosion. Employing a maintenance schedule where a vehicle or structure is periodically cleaned will help reduce corrosion. Salt and debris buildup on vehicles or structures, for example, can accelerate corrosion. Therefore, routinely washing them to remove the contaminants is a sound practice. In addition, regularly touching up protective coatings or reapplying CPCs will help reduce instances of corrosion. Perhaps the most important way to minimize corrosion from occurring in the first place is to make appropriate material selection decisions by carefully considering the application, environment, and potential corrosion problems that might occur. Selecting the appropriate materials and associated corrosion prevention and control practices can reduce maintenance costs and system downtime over the life-cycle of a system.

## REFERENCE

[1] Corrosion Prevention Compounds, Corrosion Doctors' Website, [http://www.corrosion\\_doctors.org/Inhibitors/CPCs.htm](http://www.corrosion_doctors.org/Inhibitors/CPCs.htm)

Design	Material Selection	Processing/Manufacturing	Preventive Maintenance	Monitoring/ Inspection	
<ul style="list-style-type: none"><li>◆ Geometry</li><li>◆ Material interfaces</li><li>◆ Relative sizes</li><li>◆ Joints<ul style="list-style-type: none"><li>• Fastened</li><li>• Welded</li><li>• Brazed</li></ul></li><li>◆ Applied stresses</li><li>◆ Fluid Flow</li><li>◆ Cathodic/Anodic Protection</li></ul>	<ul style="list-style-type: none"><li>◆ Base material<ul style="list-style-type: none"><li>• Metals</li><li>• Organics</li><li>• Ceramics</li><li>• Composites</li></ul></li><li>◆ Heat treatments</li><li>◆ Corrosion Prevention and Control Materials</li></ul>	<ul style="list-style-type: none"><li>◆ Surface treatments<ul style="list-style-type: none"><li>• Cleaning</li><li>• Conversion coatings</li><li>• Anodization</li><li>• Shot peening</li><li>• Laser shock peening</li></ul></li><li>◆ Cold working<ul style="list-style-type: none"><li>• Fasteners</li></ul></li><li>◆ Polishing</li></ul>	<ul style="list-style-type: none"><li>◆ Coatings<ul style="list-style-type: none"><li>• claddings</li></ul></li><li>◆ Quality control<ul style="list-style-type: none"><li>• Impurities</li><li>• Defects</li><li>• Surface condition</li><li>• Joints</li></ul></li></ul>	<ul style="list-style-type: none"><li>◆ Storage conditions</li><li>◆ Cleaning<ul style="list-style-type: none"><li>• Agents</li><li>• Abrasives</li><li>• Inhibitors</li><li>• Biocides</li></ul></li><li>◆ Coating removal</li><li>◆ Recoating</li><li>◆ Corrosion preventive compounds</li></ul>	<ul style="list-style-type: none"><li>◆ Electrochemical sensors</li><li>◆ Visual inspection</li><li>◆ Weight loss coupons</li><li>◆ Bacteria counts/ cultures</li><li>◆ NDI<ul style="list-style-type: none"><li>• Thickness</li><li>• Cracks</li></ul></li></ul>
Corrosion Prevention and Control Materials					
Coatings/Primers	Inhibitors	Sealants/Gaskets	Cathodic & Anodic Protection	Corrosion Preventive Compounds	
<ul style="list-style-type: none"><li>◆ Conversion coatings<ul style="list-style-type: none"><li>• Chromate</li><li>• Phosphate</li></ul></li><li>◆ Anodization</li><li>◆ Platings/claddings<ul style="list-style-type: none"><li>• Nickel</li><li>• Copper</li><li>• Chromium</li><li>• Gold</li><li>• Platinum</li><li>• Aluminum</li></ul></li><li>◆ Sacrificial coatings<ul style="list-style-type: none"><li>• Zinc</li><li>• Cadmium</li><li>• Aluminum</li></ul></li></ul>	<ul style="list-style-type: none"><li>◆ Paints<ul style="list-style-type: none"><li>• Oil varnishes</li><li>• Alkyd resins</li><li>• Epoxide resins</li><li>• Poyurethanes</li></ul></li><li>◆ Enamels</li><li>◆ Powder coatings<ul style="list-style-type: none"><li>• Thermoplastics</li></ul></li><li>◆ High temperature coatings<ul style="list-style-type: none"><li>• MCrAlY</li></ul></li></ul>	<ul style="list-style-type: none"><li>◆ Passive (anodic)<ul style="list-style-type: none"><li>• Chromates</li><li>• Phosphates</li><li>• Molybdates</li></ul></li><li>◆ Cathodic<ul style="list-style-type: none"><li>• Poisons</li><li>• Precipitates</li><li>• Oxygen scavengers</li></ul></li><li>◆ Hydrophobic film formers<ul style="list-style-type: none"><li>• Benzoates</li><li>• Amines</li></ul></li><li>◆ Precipitation<ul style="list-style-type: none"><li>• Phosphates</li><li>• Silicates</li></ul></li><li>◆ Vapor Phase<ul style="list-style-type: none"><li>• Amines</li><li>• Morpholine</li><li>• Hydrazine</li></ul></li></ul>	<ul style="list-style-type: none"><li>◆ Rubber gaskets</li><li>◆ Polymeric gaskets<ul style="list-style-type: none"><li>• Teflon</li></ul></li><li>◆ Metal washers<ul style="list-style-type: none"><li>• Lead</li></ul></li><li>◆ Caulk<ul style="list-style-type: none"><li>• Silicone</li></ul></li></ul>	<ul style="list-style-type: none"><li>◆ Impressed current anodes<ul style="list-style-type: none"><li>• Precious metals</li><li>• Ferrous metals</li><li>• Carbonaceous materials</li></ul></li><li>◆ Sacrificial anodes<ul style="list-style-type: none"><li>• Zinc</li><li>• Magnesium</li><li>• Aluminum</li></ul></li><li>◆ Anodic Protection</li></ul>	<ul style="list-style-type: none"><li>◆ Hard films<ul style="list-style-type: none"><li>• Plasticized resins</li></ul></li><li>◆ Soft films<ul style="list-style-type: none"><li>• Lanolin</li><li>• Petrolatum</li></ul></li><li>◆ Water displacing grades</li><li>◆ Strippable grades</li><li>◆ Oil-based films</li></ul>

**Figure 1: Corrosion Prevention and Control Considerations.**

## NOTES

\* Two different acronyms for corrosion prevention and control can be found in literature: CPAC and CPC. CPAC is used throughout this issue, however, to avoid confusing it with corrosion preventive compounds which also uses the acronym CPC. Interestingly, corrosion

preventive compounds are also referred to as corrosion *prevention* compounds and corrosion *preventative* compounds throughout literature.

† Alodine is a registered trademark of Amchem Products, Inc.

# AMPTIAC PRODUCTS

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## Textile Preforms for Composite Material Technology

This publication is the first and only one of its kind – A panoramic and thorough examination of fiber/textile perform technology and its critical role in the development and manufacture of high-performance composite materials. This product was prepared in collaboration with Drexel University and authored by Dr. Frank Ko, the Director of Drexel's Fibrous Materials Research Center. Dr. Ko is one of the world's foremost authorities on fibrous preforms and textile technology.



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## Computational Materials Science (CMS) A Critical Review and Technology Assessment



AMPTIAC surveyed DOD, government, and academic efforts studying materials science by computational methods and from this research compiled this report. It provides an in-depth examination of CMS and describes many of the programs, techniques, and methodologies being used and developed. The report was sponsored by Dr. Lewis Slotter, Staff Specialist, Materials and Structures, in the Office of the Deputy Undersecretary of Defense for Science and Technology.

**BONUS MATERIAL:** Dr. Slotter also hosted a workshop (organized by AMPTIAC) in April 2001 for the nation's leaders in CMS to discuss their current programs and predict the future of CMS. The workshop proceedings comprise all original submitted materials for the workshop – presentations, papers, minutes, and roundtable discussion highlights and are included with purchase of the above report.

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## Blast and Penetration Resistant Materials

This State-of-the-Art Report compiles the recent and legacy DOD unclassified data on blast and penetration resistant materials (BPRM) and how they are used in structures and armor. Special attention was paid to novel combinations of materials and new, unique uses for traditional materials. This report was sponsored by Dr. Lewis Slotter, Staff Specialist, Materials and Structures, in the Office of the Deputy Undersecretary of Defense for Science & Technology.



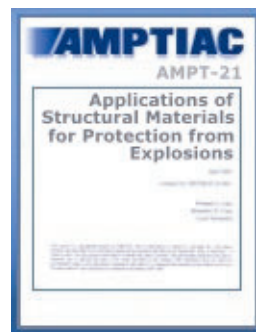
**BONUS MATERIAL:** Dr. Slotter also hosted a workshop in April, 2001 (organized by AMPTIAC) for selected experts in the field of BPRM and its application. The workshop focused on novel approaches to structural protection from both blast effects and penetration phenomena. Some areas covered are: building protection from bomb blast and fragments, vehicle protection, storage of munitions and containment of accidental detonations, and executive protection. The proceedings of this workshop are included with purchase of the above.

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Price: \$115 US, \$150 Non-US

## Applications of Structural Materials for Protection from Explosions

This State-of-the-Art Report provides an examination of existing technologies for protecting structures from explosions. The report does not discuss materials and properties on an absolute scale; rather, it addresses the functionality of structural materials in the protection against blast. Each chapter incorporates information according to its relevance to blast mitigation. For example, the section on military structures describes concrete in arches, and concrete in roof beams for hardened shelters. The discussion on concrete is not limited to materials only; rather, it addresses the issue of structural components that incorporate concrete, and describes the materials that work in concert with the concrete to produce a blast-resistant structure. The report also illustrates various materials used for concrete reinforcement.



Order Code: AMPT-21

Price: \$100 US, \$150 Non-US

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## Material Failure Modes, Part III

### A Brief Tutorial on Corrosion Related Material Failure Modes

*This issue of MaterialEASE is the final installment of a three part series on material failure modes. MaterialEASE 29, published in Volume 9, Number 1 of the AMPTIAC Quarterly, introduced the concept of material failure modes and covered fracture, ductile failure, elastic deformation, creep, and fatigue. MaterialEASE 30, published in Volume 9, Number 2 of the AMPTIAC Quarterly continued the discussion with brief descriptions of impact, spalling, wear, brinelling, thermal shock, and radiation damage. This article completes the series on material failure modes, covering uniform, galvanic, crevice, pitting, intergranular, and erosion corrosion; selective leaching/dealloying; hydrogen damage; stress corrosion cracking; and corrosion fatigue. The three articles taken together make a valuable desk reference for any professional making material selection and design decisions...and that's just what we've done! We have combined these three articles into a desktop reference and placed it on our website for download. Type in the following URL, and download this useful reference guide: <http://amptiac.alionscience.com/deskref>. - Editor*

#### CORROSION

Corrosion is the deterioration of a metal or alloy and its properties due to a chemical or electrochemical reaction with the surrounding environment. The most serious consequence of corrosion is a component or system failure. Failure can occur either by sufficient material property degradation, such that the component or structure is rendered unable to perform its intended function, or by fracture that originates from or is propagated by corrosive effects.

While corrosion manifests itself in many different forms and through various environments and mechanisms, only the most significant forms are discussed in this article. The following sections contain discussions on failures resulting from uniform, galvanic, crevice, pitting, intergranular, and erosion corrosion, selective leaching/dealloying; hydrogen damage; stress corrosion cracking; and corrosion fatigue.

#### Uniform/General Corrosion

Uniform corrosion is a generalized corrosive attack that occurs over a large surface area of a material (Figure 1). The result is a thinning of the material until failure occurs. Uniform corrosion can also lead to changes in surface properties such as increased surface roughness and friction, which may cause component failure especially in the case of moving parts that require lubricity.

In most cases corrosion is inevitable. Therefore, mitigating its effects or reducing the corrosion rate is essential to ensuring material longevity. Protecting against uniform corrosion can often be accomplished through selection of a material that is best suited for the anticipated environment. The selection of materials for uniform corrosion resistance should simply take into consideration the susceptibility of the metal to the type of environment that will be encountered. Aside from selecting a



**Figure 1. Uniform Corrosion on Iron Piping in a Fire Sprinkler System Caused by Leaks in the Threaded Joints. (Photos Courtesy of Corrosion Testing Laboratories, Inc.)[1].**

# Material

## E A S E

**Table 1. Guidelines for Mitigating Uniform Corrosion.**

- Select material that has inherent resistance to corrosion in anticipated operating environment.
- Use barrier coatings (organic or metallic).
- Apply surface treatment to generate uniform oxide layer on surface of metal.
- Use vapor phase inhibitors to deactivate corrosive environment in closed systems (e.g. heat exchanger, boiler, etc.).
- Install cathodic protection system (i.e. impressed current, sacrificial anodes).
- Design system with proper drainage such that there is no standing water.
- Implement routine maintenance schedule to clean/rinse material surfaces.

material that is resistant to uniform corrosion, protection schemes such as barrier coatings can be implemented. Organic or metallic coatings should be used wherever feasible. There are also coatings where additional elements, such as chromium, are incorporated for corrosion resistance. When coatings are not used, surface treatments that artificially produce the metal oxide layer prior to exposure to the environment will result in a more uniform layer with a controlled thickness. A uniform oxide layer can provide effective corrosion resistance for some materials. Also, vapor phase inhibitors may be used in such applications as boilers to adjust the pH level of the environment, thus reducing the rate of corrosion. Table 1 provides a brief list of guidelines that can help minimize uniform corrosion.

### Galvanic Corrosion

Galvanic corrosion is a form of corrosive attack that occurs when two dissimilar metals (e.g. stainless steel and magnesium) are electrically connected, either through physically touching each other or through an electrically conducting medium, such as an electrolyte. When this occurs, an electrochemical cell can be established, resulting in an increased rate of oxidation of the more anodic material (lower electrical potential). The opposing metal, the cathode, will consequently receive a boost in its resistance to corrosion. Galvanic corrosion (shown in Figure 2) is usually observed to be greatest near the surface where the two dissimilar metals are in contact.

There are a number of driving forces that influence the occurrence of galvanic corrosion and the rate at which it occurs.



**Figure 2. Galvanic Corrosion between a Stainless Steel Screw and Aluminum. A Cathodic Material for Fasteners is Preferred.[2].**

**Table 2. Guidelines for Mitigating Galvanic Corrosion[3].**

- Use one material to fabricate systems or components where practical.
- If mixed metal systems are used, select combinations of metals as close together in the galvanic series as possible, or select metals that are galvanically compatible.
- Avoid the unfavorable area effect of a small anode and large cathode. Small parts or critical components such as fasteners should be the more noble metal.
- Insulate dissimilar metals wherever practical, for example, by using a gasket. It is important to insulate completely if possible.
- Apply coatings with caution. Keep coatings in good repair, particularly the one used on the anodic member.
- Add inhibitors, if possible, to decrease the aggressiveness of the environment.
- Avoid threaded joints for materials far apart in the galvanic series.
- Design for the use of readily replaceable anodic parts or make them thicker for longer life.

Among these influencing factors are the difference in the electrical potentials of the coupled metals, the relative area of each metal, the system geometry, and the environment to which the system is exposed.

In most cases, galvanic corrosion can be easily avoided if proper attention is given to the selection of materials during design of a system. It is often beneficial for performance and operational reasons for a system to utilize more than one type of metal, but this may introduce a potential galvanic corrosion problem. Therefore, sufficient consideration should be given to material selection with regard to the electrical potential differences of the metals. Cathodic protection, electrical insulation, or coatings can also help protect materials from galvanic corrosion. Table 2 provides a brief list of guidelines that can help minimize galvanic corrosion.

### Crevice Corrosion

Crevice corrosion occurs as a result of water or other liquids getting trapped in localized stagnant areas creating an enclosed corrosive environment. This commonly occurs under fasteners, gaskets, washers and in joints or in other components with small gaps. Crevice corrosion can also occur under debris built-up on surfaces, sometimes referred to as “poultice corrosion.” Poultice corrosion can be quite severe, due to a gradually increasing acidity in the crevice area.

Several factors including crevice gap width, depth, and the surface ratios of materials affect the severity or rate of crevice corrosion. Tighter gaps, for example, have been known to increase the rate of crevice corrosion of stainless steels in chloride environments. The larger crevice depth and greater surface area of metals will generally increase the rate of corrosion.

**Table 3. Guidelines for Mitigating Crevice Corrosion.**

- Ensure application is designed to have proper drainage and is absent of areas that can trap moisture and debris.
- Use welded joints instead of mechanical fasteners.
- Select materials that are inherently resistant to corrosion.
- Avoid use of hydrophilic, water absorbing materials.
- Seal gaps and use gap fillers.
- Use and routinely reapply corrosion preventive compounds (e.g. greases and oils).
- Implement a routine maintenance schedule to clean/rinse material surfaces.

Materials typically susceptible to crevice corrosion include aluminum alloys and stainless steels. Titanium alloys normally have good resistance to crevice corrosion. However, they may become susceptible in elevated temperature and acidic environments containing chlorides. Copper alloys can also experience crevice corrosion in seawater environments.

To protect against problems with crevice corrosion, systems should be designed to minimize areas likely to trap moisture, other liquids, or debris. For example, welded joints can be used instead of fastened joints to eliminate a possible crevice. Where crevices are unavoidable, metals with a greater resistance to crevice corrosion in the intended environment should be selected. Avoid the use of hydrophilic materials (strong affinity for water) in fastening systems and gaskets. Crevice areas should be sealed to prevent the ingress of water. Also, a regular cleaning schedule should be implemented to remove any debris build up. Table 3 provides a brief list of guidelines that can help minimize crevice corrosion.

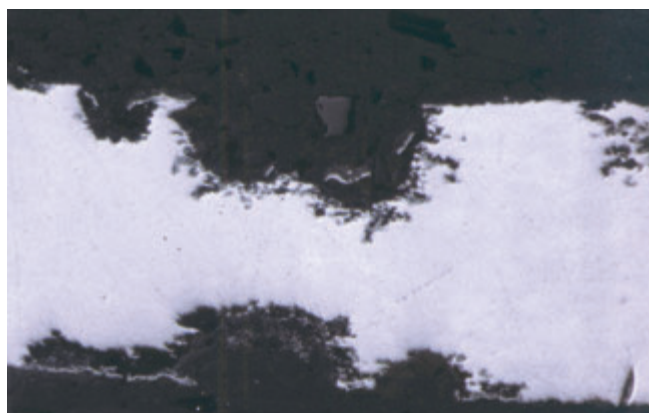
### Pitting Corrosion

Pitting corrosion, also simply known as pitting, is an extremely localized form of corrosion that occurs when a corrosive medium attacks a metal at specific points causing small holes or pits to form (Figure 3). This usually happens when a protective coating or oxide film is perforated, due to mechanical damage or chemical degradation (see Figure 4). Pitting can be one of the most dangerous forms of corrosion because it is difficult to anticipate and prevent, relatively difficult to detect, occurs very rapidly, and penetrates a metal without causing it to lose a significant amount of weight. Failure of a metal due to the effects of pitting corrosion can occur very suddenly. Pitting can have side effects too, for example, cracks may initiate at the edge of a pit due to an increase in the local stress. In addition, pits can coalesce underneath the surface, which can weaken the material considerably.

Among metals and alloys, stainless steels tend to be the most susceptible to pitting corrosion. Polishing the surface of stainless



**Figure 3. Corrosion Pit in Grooved Copper Tube (Photo Courtesy of Corrosion Testing Laboratories, Inc.)[1].**



**Figure 4. Pitting Corrosion of Copper Radiator Fins under Tin Coating (200X Magnification – Photo Courtesy of Corrosion Testing Laboratories, Inc.)[1].**

steels can increase the resistance to pitting as opposed to etching or grinding the surface. Alloying can have a significant impact on the pitting resistance of stainless steels. Conventional steel has a greater resistance to pitting than stainless steels, but is still susceptible, especially when unprotected. Aluminum in an environment containing chlorides and aluminum brass (Cu-20Zn-2Al) in contaminated or polluted water are usually susceptible to pitting. Titanium is strongly resistant to pitting corrosion.

Proper material selection is very effective in preventing the occurrence of pitting corrosion. Another option for protecting against pitting is to mitigate aggressive environments and environmental components (e.g. chloride ions, low pH, etc.). Inhibitors may sometimes stop pitting corrosion completely. Further efforts during design of the system can aid in preventing pitting corrosion, for example, by eliminating stagnant solutions or by the inclusion of cathodic protection. In some cases, protective coatings can provide an effective solution to the problem of pitting corrosion. However, they can also accelerate the corrosion process at locations where the coating has been breached and the base metal is left exposed to the corrosive environment. Table 4 provides a brief list of guidelines that can help minimize pitting corrosion.

**Table 4. Guidelines for Mitigating Pitting Corrosion.**

- Select material that is inherently resistant to pitting corrosion.
- Use inhibitors to neutralize corrosive environment in closed systems.
- Eliminate potential build-up of stagnant moisture through proper design.
- Use cathodic or anodic protection.
- Ensure quality application of protective barrier coatings to surface of metal.
- Use surface treatments, such as anodization and conversion coatings, or metal cladding.
- Polish surface to remove surface defects.
- Add alloying elements to metal (e.g. Mo and Cr) for enhanced pitting resistance.



# Material

## E A S E

### Intergranular Corrosion

Intergranular corrosion attacks the interior of metals along grain boundaries. It is associated with impurities, which tend to deposit at grain boundaries, and/or a difference in crystallo-



**Figure 5. Exfoliation of an Aluminum Alloy in a Marine Environment[2].**

graphic phase precipitated at grain boundaries. Heating of some metals can cause a “sensitization” or an increase in the level of inhomogeneity at grain boundaries. Therefore, some heat treatments and weldments can result in a propensity for intergranular corrosion. Some metals may also become sensitized while in operation if

used at a high enough temperature to cause such changes in internal crystallographic structure.

Intergranular corrosion can occur in many alloys, but stainless steels, as well as some aluminum and nickel-based alloys, are predominantly susceptible. Stainless steels, especially ferritic stainless steels, have been found to become sensitized, particularly after welding. Aluminum alloys also suffer intergranular attack as a result of precipitates at grain boundaries that are more active. Exfoliation corrosion (shown in Figure 5) is considered a type of intergranular corrosion and occurs in materials that have been mechanically worked to produce elongated grains in one direction. Precipitation of intermetallic phases at grain boundaries can make certain high nickel alloys susceptible. Methods to limit intergranular corrosion are listed in Table 5.

**Table 5. Guidelines for Mitigating Intergranular Corrosion.**

- Keep impurity levels to a minimum.
- Properly select heat treatments to reduce precipitation at grain boundaries.
- Specifically for stainless steels, reduce the carbon content, and add stabilizing elements (Ti, Nb, Ta) which preferentially form more stable carbides than chromium carbide.

### Selective Leaching/Dealloying

Dealloying, also called selective leaching, is a less common form of corrosion where one element is targeted and consequently extracted from a metal alloy, leaving behind an altered structure

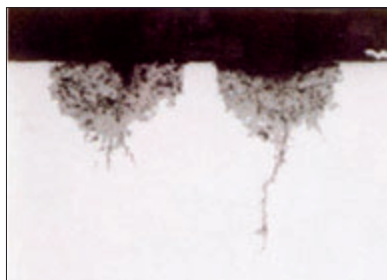


**Figure 7. Dezincification of Commercial Bronze Wax Actuator from a Water Supply System (Photos Courtesy of Corrosion Testing Laboratories, Inc.)[1].**



(Figure 6). The most common form of selective leaching is dezincification (shown in Figure 7), where zinc is extracted from brass or other alloys containing significant zinc content. Left behind are structures that have experienced little or no dimensional change, but whose parent material is weakened, porous and brittle. Dealloying is a dangerous form of corrosion because it can reduce a strong, ductile metal to one that is weak, brittle and subsequently more susceptible to mechanical failure. Since there is little change in the metal's dimensions, dealloying may go undetected, and failure can occur suddenly. Moreover, the porous structure is open to the penetration of liquids and gases deep into the metal, which can result in further degradation. Selective leaching often occurs in acidic environments.

Reducing the aggressive nature of the atmosphere by removing oxygen and avoiding stagnant solutions and debris buildup can prevent dezincification. Cathodic protection can also be used for prevention. However, the best alternative, economically, may be to use a more resistant material such as red brass, which only contains 15% Zn. Adding tin to brass also provides an improvement in the resistance to dezincification. Additionally, inhibiting elements, such as arsenic, antimony, and phosphorous can be added in small amounts to the metal to provide further improve-



**Figure 6. Dezincification of Brass Heat Exchanger Tube (100X Magnification – Photo Courtesy of Corrosion Testing Laboratories, Inc.)[1].**

**Table 6. Guidelines for Mitigating Selective Leaching.**

- Use material that is inherently resistant to selective leaching.
- Some alloying elements for certain metals can improve resistance to selective leaching.
- Avoid stagnant solution/debris buildup.
- Use inhibitors to neutralize corrosive environment.
- Use cathodic protection.
- Avoid using copper with significant zinc content.



**Figure 8. Erosion (Cavitation) Corrosion of a Brass Pump Impeller. Air Bubbles Eroded the Soft Copper Oxide Protective Layer Enabling Corrosion of the Base Metal. (Photo Courtesy of Corrosion Testing Laboratories, Inc.)[1].**

ment. Avoiding the use of a copper metal containing a significant amount of zinc altogether may be necessary in systems exposed to severe dezincification environments. Table 6 provides a brief list of guidelines that can help minimize selective leaching.

### Erosion Corrosion

Erosion corrosion is a form of attack resulting from the interaction of an electrolytic solution in motion relative to a metal surface. It has typically been associated with small solid particles dispersed within a liquid stream. The fluid motion causes wear and abrasion, increasing rates of corrosion over uniform (non-motion) corrosion under the same conditions. Erosion corrosion is evident in pipelines, cooling systems, valves, boiler systems, propellers, impellers, as well as numerous other components. Specialized types of erosion corrosion occur as a result of impingement and cavitation (Figure 8). Impingement refers to a directional change of the solution, whereby a greater force is exhibited on a surface such as the outside curve of an elbow joint. Cavitation is the phenomenon of collapsing vapor bubbles, which can cause surface damage if they repeatedly hit one particular location on a metal.

There are several factors that influence the resistance of a material to erosion corrosion including hardness, surface smoothness, fluid velocity, fluid density, angle of impact, and the general corrosion resistance of the material to the environment. Materials with higher hardness values typically resist erosion corrosion better than those that have a lower value. There are some design techniques that can be used to limit erosion corrosion. These are listed in Table 7.

**Table 7. Guidelines for Mitigating Erosion Corrosion.**

- Avoid turbulent flow.
- Add deflector plates where flow impinges on a wall.
- Add plates to protect welded areas from the fluid stream.
- Increase hardness of surface using surface treatment (e.g. shot peening) or hard coating/plating.

### Hydrogen Damage

There are a number of different ways that hydrogen can damage metallic materials, resulting from the combined factors of hydrogen and residual or tensile stresses. Hydrogen damage can result in cracking, embrittlement, loss of ductility, blistering and flaking, and microperforation.

Hydrogen induced cracking (HIC) refers to the cracking of a

ductile alloy when under constant stress and where hydrogen gas is present. Hydrogen is absorbed into areas of high triaxial stress producing the observed damage. A related phenomenon, hydrogen embrittlement, is the brittle fracture of a ductile alloy during plastic deformation in a hydrogen gas containing environment. In both cases, a loss of tensile ductility occurs with metals exposed to hydrogen which results in a significant decrease in elongation and reduction in area. It is most often observed in low strength alloys, but also occurs in steels, stainless steels, aluminum alloys, nickel alloys, and titanium alloys.

Another form of damage occurs when high pressure hydrogen attacks carbon and low-alloy steels at high temperatures. The hydrogen will diffuse into the metal and react with carbon resulting in the formation of methane. This in turn results in decarburization of the alloy and possible crack formation. Metal plating operations, for example, can cause hydrogen embrittlement. Methods to deter hydrogen damage are listed in Table 8.

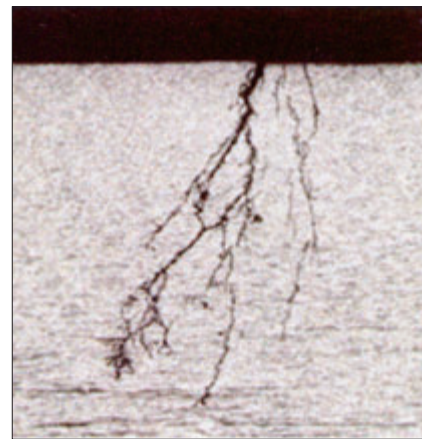
**Table 8. Guidelines for Mitigating Hydrogen Damage.**

- Limit hydrogen introduced into the metal during processing.
- Limit hydrogen in the operating environment.
- Design structures to reduce stresses (below threshold for subcritical crack growth in a given environment).
- Use barrier coatings.
- Use low hydrogen welding rods.

### Stress Corrosion Cracking

Stress corrosion cracking (SCC) is an environmentally induced cracking phenomenon (Figure 9) that sometimes occurs when susceptible metals are subjected to a tensile stress and a corrosive environment simultaneously. This is not to be confused with similar phenomena such as hydrogen embrittlement, in which the metal is embrittled by hydrogen, often resulting in the formation of cracks. Moreover, SCC is not defined as the cause of cracking that occurs when the surface of the metal is corroded resulting in the creation of a nucleating point for a crack. Rather, it is a synergistic effort of a corrosive agent and a modest, static stress. Another form of corrosion similar to SCC, although with a subtle difference, is corrosion fatigue. The key difference is that SCC occurs with a static stress, while corrosion fatigue occurs under a dynamic or cyclic stress.

Stress corrosion cracking is a process that takes place within the material, where the cracks propagate through the internal structure, usually leaving the surface unharmed. Aside from an applied



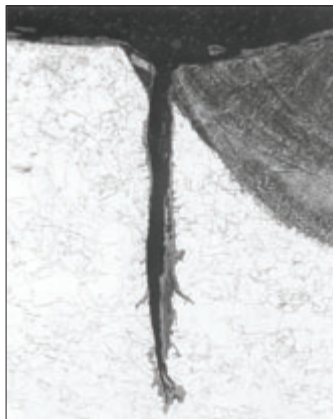
**Figure 9. Stress Corrosion Cracking (50X Magnification) in 304L Stainless Steel Pipeline (Photo Courtesy of Corrosion Testing Laboratories, Inc.)[1].**

**Table 9. Guidelines for Mitigating Stress Corrosion Cracking.**

- Choose a material that is resistant to SCC.
- Employ proper design features for the anticipated forms of corrosion (e.g. avoid crevices or include drainage holes).
- Minimize stresses including thermal stresses.
- Modify environment (neutralize pH, reduce oxygen content).
- Use surface treatments (shot peening, laser shock peening) which increase the surface resistance to SCC.
- Any barrier coatings will deter SCC as long as it remains intact.
- Reduce exposure of end grains (i.e. end grains can act as initiation sites for cracking because of preferential corrosion and/or a local stress concentration).

mechanical stress, a residual, thermal, or welding stress along with the appropriate corrosive agent may also be sufficient to promote SCC. Pitting corrosion, especially in notch-sensitive metals, has been found to be one cause for the initiation of SCC. SCC is a dangerous form of corrosion because it can be difficult to detect, and it can occur at stress levels which fall within the range that the metal is designed to handle.

Stress corrosion cracking is dependent on environmental factors including temperature, solution, and stress, as well as the metallic structure and composition.[4] However, certain types of alloys are more susceptible to SCC in particular environments, while other alloys are more resistant to that same environment. Increasing the temperature of a system often works to accelerate the rate of SCC. The presence of chlorides or oxygen in the environment can also significantly influence the occurrence and rate of SCC. There are several methods that may be used to minimize the risk of SCC. Some of these methods are listed in Table 9.



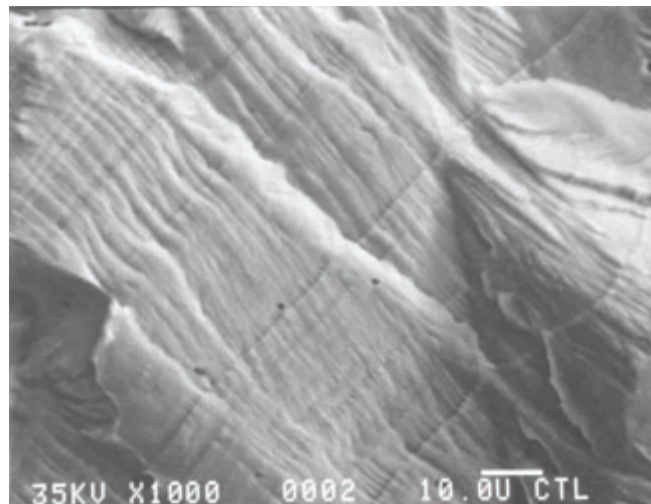
**Figure 10. Corrosion Fatigue Crack (60X Magnification) Adjacent to a Weld in 316 Stainless Steel (Photo Courtesy of Corrosion Testing Laboratories, Inc.)[1].**

It is often considered to be a subset of stress corrosion cracking, but the fracture mechanics and methods of prevention deviate enough from those of SCC that it warrants a separate discussion. Furthermore, SCC occurs under static stress while corrosion fatigue occurs under a cyclic stress (part of which is tensile stress).

Corrosion fatigue is a potential cause for the failure of many types of metals and alloys in various types of environments.

### Corrosion Fatigue

Corrosion fatigue is the environmentally-assisted mechanical degradation of a material due to the combined effects of corrosion and fatigue (a direct result of cyclic stress loading). This corrosion mode is shown in Figure 10. It is often



**Figure 11. Fatigue Striations Observed with Scanning Electron Microscope (1000X Magnification – Photo Courtesy of Corrosion Testing Laboratories, Inc.)[1].**

Materials that experience corrosion fatigue essentially exhibit a decrease in fatigue strength due to the effects of electrochemical degradation (corrosive environment). The stress required for both crack initiation and propagation is lower in corrosive environments. The crack growth rate can be much higher in a corrosive environment than it is in a non-corrosive environment. Therefore, the fatigue life of a material is shortened if it is simultaneously exposed to a corrosive environment and fatigue conditions. Like the general case of fatigue, corrosion fatigue cracking is often characterized by “beach marks” or striation patterns (shown in Figure 11), which are perpendicular to the crack propagation direction.

There are a number of factors that affect the onset of corrosion fatigue and the growth rate of cracks caused by this form of corrosion. For example, corrosion damage, such as pitting, causes stress raisers in the vicinity of the pit, much like notch

**Table 10. Guidelines for Mitigating Corrosion Fatigue.**

- Polish surface to make material more resistant to crack initiation.
- Limit operating temperatures.
- Reapply coatings or corrosion preventive compounds in damaged areas.
- Employ designs which minimize stresses to the components.
- Choose heat treatments that reduce residual stresses.
- Use surface treatments that enhance corrosion fatigue resistance, such as shot peening or laser peening.
- Use inhibitors and barrier coatings to block corrosive species from the metal.
- Reduce hydrogen contamination during fabrication, heat treatment or manufacturing.
- Select materials that are not sensitive to corrosion fatigue.



effects. This can lead to crack initiation at a stress below that for a material in a non-corrosive environment. The crack will then propagate at a faster rate, as corrosive elements enter the crack. Temperature, metal composition, strength and fracture toughness are other examples of environmental and material factors that affect the occurrence and rate of corrosion fatigue.

Similar to preventing stress corrosion cracking, material selection is very important in corrosion fatigue prevention. Fracture toughness and strength are both important material properties when considering how to protect against corrosion fatigue. Other methods to deter corrosion fatigue are listed in Table 10.

## CONCLUSION

Corrosion is a widespread and costly problem. While some of the damage it causes is simply cosmetic, several corrosion modes can cause catastrophic failure before they are even identified as a problem. Therefore, for critical components and systems, it is very important to understand the various forms of corrosion failure that were discussed in this article. Material selection during system or component design is the first step in preventing a catastrophic corrosion problem.

The three-part series of articles on material failure modes presented in this and the previous two issues of the *AMPTIAC Quarterly* has covered the most common and significant failure mechanisms. However, there is another entire field related to system failure, and that is electronic failure. For many systems, electronic failure is significant and should be considered during the design phase of a system or component.

## ACKNOWLEDGEMENT

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## REFERENCES

- [1] Corrosion Testing Laboratories, Inc. (<http://www.corrosionlab.com/>)
- [2] *Corrosion Technology Testbed*, NASA Kennedy Space Center, <http://corrosion.ksc.nasa.gov/>
- [3] E.B. Bieberich and R.O. Hardies, *TRIDENT Corrosion Control Handbook*, David W. Taylor Naval Ship Research and Development Center, Naval Sea Systems Command, DTRC/SME-87-99, February 1988; DTIC Doc.: AD-B120 952
- [4] M.G. Fontana, *Corrosion Engineering*, 3rd Edition, McGraw-Hill, 1986

This three-part series on  
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# Corrosion Rules of Thumb

## Material Selection Considerations for Various Forms of Corrosion

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In order to prevent corrosion related failure modes from occurring they should be considered during the design and material selection stages of system development. Accounting for many of the issues that are correlated with corrosion, including test, design, and metallurgical factors facilitates the development of an inherently corrosion resistant design. This article addresses the major considerations for the common forms of corrosion that factor into design and material selection, and presents some general 'rules of thumb' used in selecting materials for corrosion resistance.

The 'rules of thumb' are contained in the following sections that address each of the main forms of corrosion. The sections identify the major failure modes, followed by discussions of the test, design, and metallurgical considerations. With respect to test and design considerations, the primary properties used for quantitative measurement, if there are any, are identified. For many forms of corrosion, there are no quantitative measurement techniques, and thus materials are only rated based upon their relative susceptibilities. Additional design features that are conducive to the creation of corrosive microenvironments are highlighted. The primary metallurgical factors for each form of corrosion are also identified. Some of the major material classes are discussed as to their relative susceptibility and resistance to the form of corrosion under consideration. Together, this information provides a basis for the down-selection of candidate materials.

The information discussed above has been organized into six categories for each form of corrosion including measurement, design considerations, misapplication of data, metallurgical features, susceptible alloys, and resistant alloys. Each of these categories is explained in some detail below.

**Design Considerations:** Includes material properties subject to degradation and the potential for the corrosion form to lead to catastrophic failure.

**Measurement:** Refers to the methods used to determine the extent to which a form of corrosion has affected a material.

**Misapplication of Data:** Describes principles that are often misunderstood or misused leading to an adverse effect in terms of corrosion.

**Metallurgical Features:** Refers to material characteristics that influence the susceptibility of the material to corrosion or the rate at which corrosion will occur.

**Susceptible Alloys:** Alloys that are known to be susceptible to the form of corrosion under consideration. The list presented is

not comprehensive, but the idea is to convey the types of alloys that may experience the most severe problems with that particular form of corrosion.

**Resistant Alloys:** Alloys that are known to be resistant to the form of corrosion under consideration. The list presented is not comprehensive, but the idea is to convey the types of alloys that may be the most resistant to that particular form of corrosion.

Although some specific environments are mentioned, they have been largely left out of this article, because most of the environmental factors are applicable to all of the forms of corrosion. Such factors include composition, impurities, temperature, pH, degree of aeration, velocity and turbulence of the environment. The operating environment, including any applied stresses, must be accurately identified and defined during the selection process. If the environment is not properly identified, misapplication of data and/or information can result. Other background information about the various forms of corrosion is contained in the *MaterialEASE* in this issue. The *MaterialEASE* also contains guidelines for mitigating the forms of corrosion, which have thus been excluded here.

### UNIFORM CORROSION

Failure due to uniform corrosion is a result of the general thinning of material, reducing its load capacity until the material fails. This kind of failure is extremely rare however, since uniform corrosion is well defined and can be easily mitigated through the use of coatings or by providing an adequate metal thickness for a specified design life. Furthermore, it is highly likely that a different failure mode will precede uniform corrosion failure.

#### Test and Design Considerations (Uniform)

- |                        |                                                                                                                                                           |
|------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|
| Design Considerations  | <ul style="list-style-type: none"><li>• Mass loss</li><li>• Reduction in load bearing capacity</li></ul>                                                  |
|                        | <ul style="list-style-type: none"><li>• Measurement</li><li>• Thickness loss</li><li>• Weight loss</li></ul>                                              |
| Misapplication of Data | <ul style="list-style-type: none"><li>• Corrosion rates are averaged values</li><li>• Uniform corrosion rates can't be used for localized forms</li></ul> |

Extensive uniform corrosion testing has been performed on both coated and uncoated metals. In the case of uncoated oxide-film forming metals, the uniform corrosion rate will decrease once the oxide layer has been established. Eventually



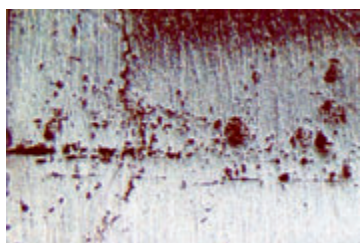
the corrosion rate will reach equilibrium provided the environment remains constant. There is ample uniform corrosion rate data available in the literature in the form of thickness or weight loss over time when exposed to a particular environment. Typically, weight loss data are converted to thickness reduction in mils per year. In this respect, the thickness loss is an averaged value over the entire surface, where some areas will have more thickness loss and some less. That is, the corrosion rate is reported in terms of a mean value with no deviation. Uniform corrosion rates can be effective for calculating the thickness loss of bulk structures, although attention must also be given to the localized forms of corrosion since they may affect the metal more severely than uniform corrosion. It is extremely important to note that uniform corrosion rates should never be used to estimate the extent of localized corrosion forms.

Metallurgical Considerations (Uniform)	
Metallurgical Features	<ul style="list-style-type: none"> <li>• Metal composition</li> <li>• Oxide films</li> </ul>
Susceptible Alloys	<ul style="list-style-type: none"> <li>• Magnesium alloys</li> <li>• Low alloy irons and steels</li> </ul>
Resistant Alloys	<ul style="list-style-type: none"> <li>• Stainless steels</li> <li>• Copper alloys</li> <li>• Nickel alloys</li> <li>• Titanium alloys</li> </ul>

Uniform corrosion is a process that involves the metal interacting with a particular environment on a macroscopic scale. Magnesium alloys and low alloy irons and steels are by far the most susceptible metals to uniform corrosion. They are almost always coated for protection against uniform corrosion. One exception is weathering steels, which have small amounts of chromium, nickel, and copper in their composition. Uncoated weathering steels have been successfully used for large structural components, such as bridge beams and trusses. In the case of aluminum, most alloying elements reduce its corrosion resistance. An exception is chromium where small amounts (0.1 – 3.0 wt.%) are beneficial to aluminum-magnesium alloys. The remaining metal classes are considered to be fairly resistant to uniform corrosion.

## PITTING CORROSION

Pitting corrosion (Figure 1) can lead to the catastrophic failure of a component, especially in applications that require gas- or liquid-tight seals, as narrow pits can go undetected and eventually perforate the material. Furthermore, pits are often identified as the nucleating point of a crack or the initiator of a crack. Corrosion pits can also reduce the integrity of the surface of a material, which can lead to a susceptibility or increase in surface wear.



**Figure 1. Pitting Corrosion of Stainless Steel Tubing.[1]**

Test and Design Considerations (Pitting)	
Design Considerations	<ul style="list-style-type: none"> <li>• Crack initiator</li> <li>• Can cause perforation</li> <li>• Can lead to wear problems</li> </ul>
Measurement	<ul style="list-style-type: none"> <li>• Depth</li> <li>• Diameter</li> <li>• Density of pits</li> <li>• Shape</li> </ul>
Misapplication of Data	<ul style="list-style-type: none"> <li>• No way of isolating pitting from other forms of corrosion</li> <li>• May be difficult to distinguish from uniform corrosion</li> <li>• Difficult to predict penetration rate</li> </ul>

The depth and diameter of a pit are the primary measures for analyzing the extent of pitting corrosion on a material. A statistical distribution of pits or the density of pits on the surface of a material can also be used to metric the extent of pitting corrosion on a material.

Since pitting often leads to other forms of corrosion, such as uniform corrosion, stress corrosion cracking and corrosion fatigue, it is sometimes difficult to isolate it from other forms. For example, in some situations pitting may be confused with uniform corrosion and vice-versa. This is because pits having a wide diameter and shallow depth may be considered uniform corrosion. Furthermore, a high density of pits on a material surface may cause them to overlap, resulting in an appearance similar to uniform corrosion. It is very difficult to predict the penetration rate of corrosion pits through the thickness of a metal, even with test data. This is because pits do not have standard dimensions even under similar environmental conditions.

Metallurgical Considerations (Pitting)	
Metallurgical Features	<ul style="list-style-type: none"> <li>• Alloying content</li> <li>• Alloying contaminants</li> <li>• Scale formation</li> </ul>
Susceptible Alloys	<ul style="list-style-type: none"> <li>• Austenitic stainless steel</li> <li>• Aluminum brass</li> <li>• Si, C, Ti, Nb in steel</li> <li>• All passivated metals</li> </ul>
Resistant Alloys	<ul style="list-style-type: none"> <li>• Titanium alloys</li> <li>• High Ni steels</li> <li>• Mo and Cr alloying elements</li> <li>• Steel with high nitrogen content</li> </ul>

Pitting may be caused or enhanced by several metallurgical features, including alloying content, defects or contaminants. Alloys that are known to exhibit a particular susceptibility to pitting corrosion are listed in the table above. Some alloying elements increase the susceptibility of steel to pitting including silicon, carbon, titanium and niobium. All passivated metals (e.g. stainless steels and nickel-based alloys) are to some extent susceptible to pitting corrosion. Alloys that are known to exhibit a particular resistance to pitting corrosion are also listed in the table above. Molybdenum and chromium alloying elements are known to increase an alloy's resistance to pitting.

## CREVICE CORROSION

Crevice corrosion has been known to lead to failure in fastening systems, electrical contacts, piping systems and storage tanks. This form of corrosion is of particular concern in aircraft lap joints, as the build up of corrosion products can cause separation of the two metals, known as pillowing.

### Test and Design Considerations (Crevice)

Design Considerations	<ul style="list-style-type: none"> <li>• Strength loss</li> <li>• Perforation</li> <li>• Fastening systems can create crevices</li> <li>• Loss of electrical continuity</li> <li>• Geometries and interfaces conducive to electrolyte entrapment</li> </ul>
Measurement	<ul style="list-style-type: none"> <li>• Qualitative measure</li> </ul>
Misapplication of Data	<ul style="list-style-type: none"> <li>• Difficult to distinguish from other forms of corrosion</li> <li>• Established data not easily transferable to other systems due to high dependence on environmental conditions</li> </ul>

Crevice corrosion is only measured qualitatively by metals' relative susceptibility to environmental conditions. The crevice gap width and depth, and the surface ratios of materials can all affect the extent of crevice corrosion. The larger crevice depth and greater surface area of metals will generally increase the rate of crevice corrosion. The degree of attack, however, is highly dependent upon the environment's exact constituents and concentration, as well as the humidity and temperature. This makes quantitative laboratory measurements, such as the area and depth of attack, in most cases not characteristic of field experiences. Therefore, crevice corrosion testing is a tool that can be used to expose the relative susceptibilities of materials under certain environmental conditions.

### Metallurgical Considerations (Crevice)

Metallurgical Features	<ul style="list-style-type: none"> <li>• Passivated metals are susceptible</li> </ul>
Susceptible Alloys	<ul style="list-style-type: none"> <li>• Low alloy steels</li> <li>• Stainless steels</li> <li>• Aluminum alloys</li> </ul>
Resistant Alloys	<ul style="list-style-type: none"> <li>• Copper alloys</li> <li>• Titanium alloys</li> </ul>

In general, passive metals have a greater susceptibility to crevice corrosion. In particular, these include aluminum alloys and stainless steels. Most alloying elements for aluminum alloys reduce crevice corrosion resistance. Silicon, for example, when used in amounts > 0.1%, can markedly reduce the crevice corrosion resistance of aluminum alloys in seawater.[2] In the case of stainless steels, the addition of molybdenum and/or manganese will increase resistance. Copper and nickel alloys have good resistance to crevice corrosion, although some cases of attack have been experienced under stagnant seawater environments. Titanium alloys normally have good resistance to crevice corrosion, however, they may become susceptible at elevated temperature acidic environments containing chlorides. Adding palladium to titanium alloys increases their resistance to crevice attack under such conditions. Copper alloys have good resistance to crevice corrosion, although there have been some peculiar instances of corrosion occurring on the outside of the crevice in seawater environments.

## FILIFORM CORROSION

Filiform corrosion can lead to blistering underneath organic coatings on a metal substrate, and consequently cause the coating to fail. This failure occurs as delamination from the base metal and chipping, leaving the base metal unprotected from the surrounding environment. As a result, filiform corrosion can also lead to other forms of corrosion.

### Test and Design Considerations (Filiform)

Design Considerations	<ul style="list-style-type: none"> <li>• Coating failure</li> <li>• Cause of other forms of corrosion</li> </ul>
Measurement	<ul style="list-style-type: none"> <li>• Length and width of filaments</li> </ul>
Misapplication of Data	<ul style="list-style-type: none"> <li>• Difficult to tie filiform to property loss</li> </ul>

Filiform corrosion often manifests itself in filament-shaped columns of corrosion stretching across the surface of the material. Thus, the extent of filiform corrosion can be measured by the length and width of filaments. However, tests for filiform corrosion are mainly to identify if the material system (base metal + organic coating) is susceptible to filiform corrosion or not. It is difficult to tie filiform to property loss or material degradation beyond surface damage, mainly because it leads to other forms of corrosion, which can cause more serious damage.

### Metallurgical Considerations (Filiform)

Metallurgical Features	<ul style="list-style-type: none"> <li>• Coating thickness</li> </ul>
Susceptible Alloys	<ul style="list-style-type: none"> <li>• Alloys with permeable, brittle, hydrophilic, organic coatings</li> </ul>
Resistant Alloys	<ul style="list-style-type: none"> <li>• Alloys with thick, less permeable coatings</li> <li>• Alloys with non-organic coatings</li> </ul>

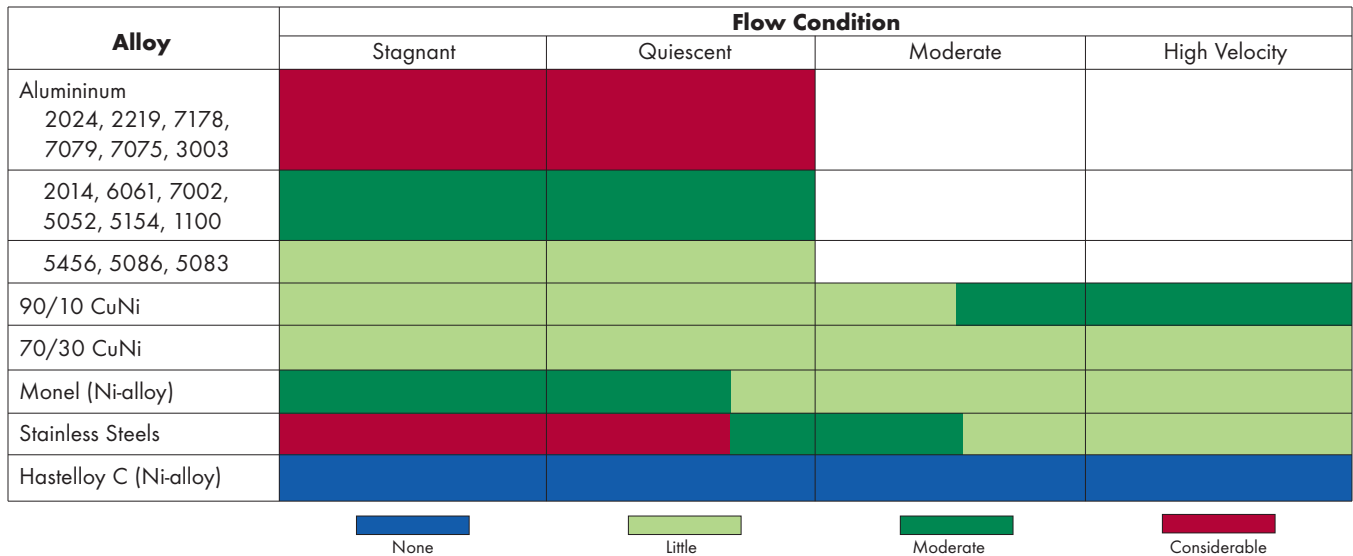
Coating thickness plays an important role in filiform corrosion, and thickness is a good indication of whether material systems will be susceptible or resistant to this form of corrosion. Any metal that is prone to corrosion in general and has a permeable, brittle, or hydrophilic organic coating is susceptible to filiform corrosion. Metals with thicker, less permeable coatings are generally resistant to filiform corrosion.

## EROSION CORROSION

Erosion corrosion results in a thinning of material that can cause failure under load, as well as perforation and surface wear leading to reduced efficiency of components such as propellers, impellers, and bearings. Impingement and cavitation attack are two types of erosion damage and can be accelerated under corrosive conditions.

### Test and Design Considerations (Erosion)

Design Considerations	<ul style="list-style-type: none"> <li>• Strength loss</li> <li>• Perforation</li> <li>• Wear</li> <li>• Thickness</li> <li>• Impingement</li> <li>• Cavitation</li> </ul>
Measurement	<ul style="list-style-type: none"> <li>• Qualitative measure</li> <li>• Thickness loss</li> </ul>
Misapplication of Data	<ul style="list-style-type: none"> <li>• Laboratory tests do not correlate well with field experience</li> <li>• Confused with mechanical erosion</li> </ul>



**Figure 2. Susceptibility of Metals to Corrosion in a Flowing Water Environment.[3]**

All the factors that influence the resistance of a material to erosion corrosion and their exact relationship are difficult to define. Some factors include surface smoothness, fluid velocity, fluid density, angle of impact, and the general corrosion resistance of the material to the environment. Erosion corrosion can be measured in thickness loss, although laboratory test data does not always correlate well to field experience. As a result, materials are often qualitatively rated as to their relative susceptibility to erosion corrosion. Non-corrosive, or mechanical erosion is a common phenomenon, but is governed by a different mechanism than erosion corrosion. Thus, it is important not to confuse erosion corrosion with ordinary mechanical erosion.

Metallurgical Considerations (Erosion)	
Metallurgical Features	• Hardness
Susceptible Alloys	• Low alloy steels • Aluminum alloys
Resistant Alloys	• Stainless steels • Nickel alloys • Titanium alloys

In general, harder materials are more resistant to erosion corrosion, but there are some exceptions. The metal's susceptibility to the environment is also a factor, which in some cases can counter the effect of material hardness. Low alloy steels, cast irons, and aluminum alloys are the most susceptible to erosive attack by impingement. Copper alloys resist impingement attack, but are susceptible to cavitation damage. Nickel/aluminum and nickel/copper alloys can be used for applications where cavitation is likely to occur, although they will suffer material loss under severe conditions. Nickel/chromium alloys, austenitic and precipitation-hardening stainless steels, and titanium alloys provide the highest degree of resistance to cavitation attack. Stainless steels and some nickel alloys are more susceptible to corrosion under stagnant water conditions, usually by pitting and crevice attack. Thus, the amount of downtime a system will experience should also be considered when selecting materials resistant to erosion corrosion. Figure 2 shows the relative corrosion susceptibility of some alloys in a flowing water environment.

### GALVANIC CORROSION

As with many other forms of corrosion, galvanic corrosion can cause a reduction in a material's strength, and thus can lead to catastrophic failure under load. Galvanic corrosion can also result in perforation failure by compromising the integrity of sealed joints. Electronic components, such as electrical contacts and connectors, are often susceptible to galvanic corrosion.

Test and Design Considerations (Galvanic)	
Design Considerations	<ul style="list-style-type: none"> <li>• Loss of strength</li> <li>• Perforation in applications that are required to be sealed (e.g. valves)</li> <li>• Electronic components</li> <li>• Fasteners must be cathodic</li> </ul>
Measurement	• Galvanic series (difference in corrosion potentials between metals)
Misapplication of Data	• The order of metals on the galvanic series chart changes depending on electrolyte (seawater versus salt water – NaCl)

Since galvanic corrosion can accelerate the rate of corrosion of a metal, it can lead to the failure of a component much sooner than expected. Evaluation of galvanic corrosion does not take into account the amount of corrosion damage (e.g. weight loss), but rather considers the potential for galvanic corrosion to occur. Essentially, the corrosion potential, or electronegativity, of a metal can then be measured in an electrolyte. The electronegativity of a second metal can be measured in the same electrolyte. When comparing the electronegativity of the two materials, the potential for galvanic corrosion can be determined.

The tabulated galvanic series commonly displayed in the literature represents the relative electronegativity of various metals and alloys in a single specified electrolyte (usually salt water). It should be noted that their order on the table could vary according to the electrolyte used for the test, which is an important consideration when designing a system to operate in an environment other than salt water. Therefore, the electrolyte dependence of the galvanic series must be considered, otherwise the misuse of data will result.



Metallurgical Considerations (Galvanic)	
Metallurgical Features	<ul style="list-style-type: none"> <li>• Electropotential difference between metals is driving force for galvanic corrosion</li> </ul>
Susceptible Alloys	<ul style="list-style-type: none"> <li>• Aluminum</li> <li>• Magnesium</li> <li>• Zinc</li> <li>• Cadmium</li> <li>• Dissimilar metals</li> </ul>
Resistant Alloys	<ul style="list-style-type: none"> <li>• Similar metals on galvanic series</li> <li>• Metals that can form impermeable scale</li> </ul>

The electropotential difference between metals in a bimetallic system is the driving force for galvanic corrosion reactions. Therefore, there will be a stronger driving force for metals with a greater difference in electropotential, and conversely a weaker driving force for metals with a smaller difference in electropotential. There are several metals and alloys that are typically anodic to all other metals in most environments. These include zinc, magnesium, cadmium and aluminum. For this reason these alloys are very prone to galvanic corrosion when electrically coupled with another metal. In general, metals and alloys that are far apart on the galvanic series chart are likely to create a galvanic cell, and the more anodic member will corrode more rapidly than it would if it were not electrically coupled with a cathodic metal.

In a bimetallic system, metals and alloys that are close together on the galvanic series chart will be more resistant to galvanic corrosion. Furthermore, metals and alloys that are typically cathodic to other metals in most environments will be resistant to galvanic corrosion. Caution must be taken when selecting a noble metal, since the introduction of a highly cathodic material can cause corrosion problems for adjacent metals in the same system that have traditionally been resistant to corrosion. Galvanic corrosion can be used to protect a system or component from corrosion. Sacrificial coatings such as zinc or cadmium are very effective means of protecting a metal. These materials will preferentially corrode, thus protecting the more cathodic metal to which they have been applied.

### SELECTIVE LEACHING / DEALLOYING

Dealloying (Figure 3) can lead to a dramatic drop in strength for a material, due to the selective removal of an integral alloying element. This process can leave behind a weakened and brittle material that is far more susceptible to fracture than its original form. As a result, in some applications dealloying can lead a component to catastrophic failure.

Test and Design Considerations (Dealloying)	
Design Considerations	<ul style="list-style-type: none"> <li>• Drop in strength</li> <li>• Loss of ductility</li> <li>• Catastrophic failure</li> </ul>
Measurement	<ul style="list-style-type: none"> <li>• Weight loss</li> <li>• Presence of dealloyed element in corrosive media</li> </ul>
Misapplication of Data	<ul style="list-style-type: none"> <li>• Weight loss may be misleading since metals can redeposit from solution</li> <li>• Difficult to separate other corrosion modes from weight loss test data</li> </ul>



**Figure 3. Dezincification of Brass Containing a High Zinc Content.[4]**

Selective leaching can be measured by weight loss, and by analyzing the presence of alloying elements dissolved in a corrosive media. Sometimes dealloyed elements can be deposited back on the surface of the metal after it has been leached from the metal. This results in the material showing only a very slight drop in weight. Furthermore, selective leaching may be difficult to differentiate from other corrosion modes when analyzing weight loss test data.

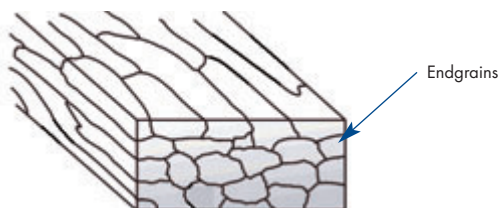
Metallurgical Considerations (Dealloying)	
Metallurgical Features	<ul style="list-style-type: none"> <li>• Alloy composition</li> <li>• Heat treatment</li> <li>• Welding processes</li> </ul>
Susceptible Alloys	<ul style="list-style-type: none"> <li>• Cast iron</li> <li>• Aluminum and silicon bronzes</li> <li>• High nickel alloys</li> <li>• Copper alloys, especially with high Zn content</li> <li>• Solders</li> <li>• Au and Ag in sulfide, nitric acid</li> <li>• High carbon steel</li> </ul>
Resistant Alloys	<ul style="list-style-type: none"> <li>• Red brass (&lt;15% Zn)</li> <li>• P, Sb, As increase brass resistance</li> <li>• 2-3% Ni in cast iron in soil</li> <li>• Austenitic stainless steel in brackish water</li> </ul>

Metallurgical features possibly affect selective leaching the most, especially because this form of corrosion is strongly dependent on alloy composition. Heat treatment and welding processes can affect selective leaching of a component, but to a much lesser extent.

Dezincification, denickelification, desulfurization, dealuminumification, desiliconification, destannification (removal of tin), and decarburization are all types of dealloying that can decompose materials containing the elements indicated by the name. Alloys that are typically resistant to selective leaching, as well as those that are particularly susceptible, are listed in the table above.

### INTERGRANULAR AND EXFOLIATION CORROSION

Intergranular and exfoliation corrosion can be detrimental in that there may be no apparent weight loss of material even though there can be a significant reduction in strength. Intergranular corrosion can also effectively produce weakened areas along grain boundaries that are susceptible to crack formation. Cracks may then propagate until complete fracture occurs under an applied stress. Intergranular corrosion in mechanically worked (primarily rolled or extruded alloys) is termed exfoliation corrosion which resembles 'flaking' of the material. Exfoliation corrosion primarily occurs where a corrosive environment can easily attack the endgrains (shown in Figure 4) of susceptible materials. Exfoliation can also result in a general strength loss of the material until failure under load occurs.



**Figure 4. Mechanically Worked Material Producing Elongated Grain Structures.**

#### Test and Design Considerations (Intergranular)

Design Considerations	<ul style="list-style-type: none"> <li>• Strength loss</li> <li>• Crack initiation</li> <li>• Adjacent to fasteners (exfoliation)</li> </ul>
Measurement	<ul style="list-style-type: none"> <li>• Qualitative measure</li> <li>• Weight loss</li> </ul>
Misapplication of Data	<ul style="list-style-type: none"> <li>• Highly dependent upon heat treatment</li> </ul>

Like many forms of corrosion, intergranular and exfoliation corrosion are measured qualitatively. Tests are highly dependent upon alloy composition, heat treatment and test technique. In these tests, materials are typically exposed to an acidic media, which readily attacks grain boundary precipitates, if present. Weight loss measurements are used in some cases to identify susceptible materials. However, this depends on the removal of grains from the material as a result of the corrosion process. Microscopic examination may also be used to identify this corrosion mode.

#### Metallurgical Considerations (Intergranular)

Metallurgical Features	<ul style="list-style-type: none"> <li>• Alloy/heat treatments that produce grain boundary precipitates which are anodic to the base metal</li> <li>• Rolled and extruded alloys (exfoliation)</li> </ul>
Susceptible Alloys	<ul style="list-style-type: none"> <li>• Welded stainless steels</li> <li>• Some aluminum alloys</li> <li>• Some nickel alloys</li> </ul>
Resistant Alloys	<ul style="list-style-type: none"> <li>• Quenched aluminum alloys</li> <li>• Nickel alloys containing Cr and Mo</li> </ul>

Intergranular and exfoliation corrosion occur as a result of the precipitation of intermetallic compounds in grain boundaries, which are more anodic than the base material. The most predominant susceptibilities have been observed in stainless steels and some aluminum and nickel-based alloys. Some stainless steels, especially ferritic stainless steels, have been found to become sensitized to this form of corrosion, particularly after welding. Welding can cause the precipitation of chromium carbides at grain boundaries in the heat affected zone often leading to intergranular corrosion. Aluminum alloys are traditionally vulnerable to intergranular and exfoliation attack, especially the 2024, 5083, 7030, and 7075 alloys with certain heat treatments. Quenched aluminum alloys are more resistant to intergranular corrosion because the fast cooling rate prevents the formation of grain boundary precipitates. Highly alloyed nickel can be susceptible to intergranular corrosion by the precipitation of intermetallic phases at grain boundaries, while nickel alloys containing chromium and molybdenum are typically resistant.

## STRESS CORROSION CRACKING

The primary concern with stress corrosion cracking (SCC) is that it can lead to the catastrophic failure of a component. When stress corrosion cracks form in a component under an applied load, the material will lose strength until it fails which can occur instantaneously.

#### Test and Design Considerations (SCC)

Design Considerations	<ul style="list-style-type: none"> <li>• Drop in strength</li> <li>• Catastrophic failure</li> </ul>
Measurement	<ul style="list-style-type: none"> <li>• Crack propagation rate, <math>da/dt</math> (<math>a</math> – crack length; <math>t</math> – time)</li> <li>• Critical stress intensity factor, <math>K_{ISCC}</math></li> </ul>
Misapplication of Data	<ul style="list-style-type: none"> <li>• Pure metals can be susceptible to SCC</li> <li>• <math>K_{ISCC}</math> can be directionally dependent</li> <li>• <math>K_{ISCC}</math> is environmentally dependent</li> </ul>

The magnitude of SCC can be measured experimentally based on a rate of crack propagation. This measure identifies how quickly a material may fail under an applied load in corrosive conditions. The susceptibility of a material to SCC may also be estimated based on a critical stress value that will propagate a crack under corrosive conditions. This factor is called the stress corrosion cracking stress intensity factor,  $K_{ISCC}$ .

A common misconception regarding this form of corrosion is that pure metals are always resistant to stress corrosion cracking, when in fact, they can be susceptible. Stress corrosion cracking differs from many of the other forms of corrosion in that there exists numerical data, in the form of  $K_{ISCC}$ , that quantifies the phenomenon. This data, however, can be directionally dependent, and the designer or engineer needs to be careful in applying it to the proper direction of the material under consideration. Furthermore,  $K_{ISCC}$  is environmentally dependent, and as a result the environment in which the test data was produced should be taken into consideration.

#### Metallurgical Considerations (SCC)

Metallurgical Features	<ul style="list-style-type: none"> <li>• Impurities decrease resistance</li> <li>• For carbon steel, susceptibility increases with increasing C content up to 0.12 wt%</li> <li>• Steels have high susceptibility when composition includes Ni up to 9%</li> <li>• When Ni content is &lt;1% and &gt;40%, steels have low susceptibility</li> <li>• Mo, V, and Nb alloying elements improve resistance in titanium alloys</li> <li>• Mechanical working of aluminum alloys increases directional susceptibility</li> <li>• Heat Treatment</li> </ul>
Susceptible Alloys	<ul style="list-style-type: none"> <li>• Carbon steel</li> <li>• HSLA steel (&gt;1200 MPa strength)</li> <li>• Austenitic stainless steel</li> <li>• 2000 and 7000 series aluminum alloys</li> <li>• Titanium alloys</li> <li>• Magnesium alloys</li> <li>• Copper alloys</li> <li>• Zirconium alloys</li> <li>• Alloys with highly protective oxides</li> </ul>
Resistant Alloys	<ul style="list-style-type: none"> <li>• Aluminum-magnesium alloys with &lt;4% Mg</li> </ul>

There are many metallurgical factors that affect the nucleation and/or propagation of a stress corrosion crack or a material's susceptibility/resistance to SCC in general. For instance, impurities in a metal will often decrease its resistance to stress corrosion cracking. Alloying elements can also affect the susceptibility or resistance to SCC. The presence of up to 0.12% carbon in carbon steel increases its susceptibility to SCC. Nickel content in steels has a significant effect on their resistance to SCC. For example, steel with Ni content up to 9% is highly susceptible to SCC, and when the Ni content is less than 1% or greater than 40%, steel has a low susceptibility to SCC. Molybdenum, vanadium and niobium all improve the resistance of titanium to SCC. Post-fabrication heat treating, mechanical working, and joining also have an effect on a material's susceptibility to SCC. Mechanical working (e.g. extrusion) of aluminum alloys, for example, increase the directional susceptibility to SCC.

Alloys that are known to have problems with stress corrosion cracking in salt water include those shown in the table. Aluminum-magnesium alloys with <4% Mg are typically resistant to SCC.

## CORROSION FATIGUE

Corrosion can cause a reduction in the fatigue strength of a material. As a result, a component designed to withstand a normal fatigue load can experience catastrophic failure if the same load is applied under corrosive conditions.

### Test and Design Considerations (Corrosion Fatigue)

Design Considerations	<ul style="list-style-type: none"> <li>Reduced fatigue strength</li> <li>Catastrophic failure</li> </ul>
Measurement	<ul style="list-style-type: none"> <li>S/N curves</li> <li>Crack growth rate, da/dt</li> </ul>
Misapplication of Data	<ul style="list-style-type: none"> <li>Interacts with other forms of corrosion such as pitting</li> <li>Difficult to distinguish corrosion fatigue from SCC and hydrogen damage</li> </ul>

Since corrosion fatigue occurs under the conditions of cyclic stress, data applicable to this form of corrosion are S/N curves (S – applied stress; N – cycles to failure) for a material in a particular corrosive medium. In addition, determining the cycles to failure is a way to measure the durability of a material in a corrosive medium. The crack growth rate can also be used to measure the progression of corrosion fatigue cracking.

Corrosion fatigue may be initiated by or interact with other forms of corrosion, such as pitting, which can supply crack initiation points. As a result, using data simply for corrosion fatigue may lead to underestimating the extent of corrosion damage to a material. In addition, this form of corrosion is sometimes difficult to distinguish from stress corrosion cracking and hydrogen damage. This again may lead to a difficulty in identifying the problem or finding the appropriate solution to prevent or mitigate further damage.

### Metallurgical Considerations (Corrosion Fatigue)

Metallurgical Features	<ul style="list-style-type: none"> <li>Heat treatment</li> <li>Composition</li> <li>Increasing tensile strength improves normal fatigue properties but is detrimental to corrosion fatigue properties</li> <li>Ferrous alloys do not have an endurance limit in a corrosive environment</li> </ul>
Susceptible Alloys	<ul style="list-style-type: none"> <li>Same as SCC</li> <li>Coating processes that produce residual tensile stresses or hydrogen reduce corrosion fatigue resistance</li> </ul>
Resistant Alloys	<ul style="list-style-type: none"> <li>No metal is immune to corrosion fatigue</li> <li>Similar to SCC</li> </ul>

Similar to stress corrosion cracking, there are many metallurgical factors that contribute to the nucleation and/or propagation of a corrosion fatigue crack, or a material's susceptibility/resistance to corrosion fatigue, in general. For example, heat treatment and composition are major factors that can influence a material's susceptibility to corrosion fatigue. Tensile strength may also be an indication of susceptibility to corrosion fatigue. Increasing tensile strength improves normal fatigue properties, but is detrimental to corrosion fatigue properties. The endurance limit is the lower bound on the stress required to propagate fatigue cracks in ferrous alloys. However, ferrous alloys do not have an endurance limit in a corrosive environment.

Stress corrosion cracking is similar to corrosion fatigue in that many of the same alloys that are susceptible to SCC are also susceptible to corrosion fatigue. Coating processes that produce tensile stresses or hydrogen often reduce the corrosion fatigue resistance of the base material. While there is practically no metal which is immune to corrosion fatigue, those that are somewhat resistant to stress corrosion cracking are usually also resistant to corrosion fatigue.

## FRETTING CORROSION

Fretting corrosion can result in fatigue strength loss (fretting fatigue), surface wear, and electrical contact failures. Electrical contacts have been known to experience fretting corrosion as a result of thermal cycling and the difference in thermal expansion coefficients of the contacting metals.

### Test and Design Considerations (Fretting)

Design Considerations	<ul style="list-style-type: none"> <li>Strength loss</li> <li>Wear</li> <li>Loss of electrical continuity (in electronics)</li> </ul>
Measurement	<ul style="list-style-type: none"> <li>Qualitative measure</li> </ul>
Misapplication of Data	<ul style="list-style-type: none"> <li>Use of corrosion fatigue data</li> </ul>

Fretting corrosion is another form that is measured in qualitative terms, and much of the data/information has been accumulated from field experience. Fretting can decrease the fatigue strength in materials (fretting fatigue), although the number of contributing factors including the environ-



ment, contacting metal, applied load, and the degree of motion all make fatigue strength measurements due to fretting unreliable. Although fretting fatigue may be considered a type of corrosion fatigue, corrosion fatigue data should never be used in relation to fretting corrosion.

Metallurgical Considerations (Fretting)	
Metallurgical Features	• Hard/soft metal combinations
Susceptible Alloys	• Steel against steel
	• Nickel against steel
	• Aluminum against steel
	• Antimony plate against steel
	• Tin against steel
	• Aluminum against aluminum
	• Zinc-plated steel on aluminum
Resistant Alloys	• Iron-plated steel against aluminum
	• Lead against steel
	• Silver plate against steel
	• Silver plate against aluminum plate
	• Steel with a conversion coating against steel

The hardness of the contacting metals is a major factor in the susceptibility of a material system to fretting corrosion. For example, a hard metal/soft metal combination provides the best fretting corrosion resistance. General susceptible and resistant alloy combinations are listed in the table above.[5] Thermal expansion coefficients should also be considered when selecting materials, especially for electrical contacts.

## SUMMARY

The proper selection of materials should include consideration of corrosion in the design phase of new systems. Knowledge of the forms of corrosion and the data used to characterize the various forms are essential for effective design and material selection. This article covered some of the key factors that contribute to a material's susceptibility or resistance to the major forms of corrosion. It is clear that if corrosion costs are to be reduced in the future, either a corrosion or materials engineer needs to be included in the design/material selection processes, or the designers and personnel responsible for material selection must have a better understanding of the various forms of corrosion and how they effect system performance and life-cycle costs.

## REFERENCES

- [1] Corrosion Technology Testbed, NASA Kennedy Space Center, <http://corrosion.ksc.nasa.gov/>
- [2] *Handbook of Corrosion Data*, 2nd Edition, Eds. B.D. Craig and D.S. Anderson, ASM International, 1995
- [3] W.K. Boyd and F.W. Fink, *Corrosion of Metals in Marine Environments*, MCIC-78-37, March 1978; DTIC Doc.: AD-A054583
- [4] Corrosion on Flood Control Gates, US Army Corps of Engineers, [http://www.sam.usace.army.mil/en/cp/CORROSION\\_EXTRA.ppt](http://www.sam.usace.army.mil/en/cp/CORROSION_EXTRA.ppt)
- [5] *Corrosion in the Aircraft Industry*, ASM Handbook, Vol. 13: Corrosion, 9th Edition, ASM International, 1987, pp. 1019-1057

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### This Year's Tri-Service Corrosion Conference a Big Draw

Nearly 400 technical and management professionals from government and industry gathered November 14-18 in Orlando, Florida for the 2005 Tri-Service Corrosion Conference. Held on a biennial basis, the Tri-Service Conference is the preeminent gathering of personnel who address corrosion issues within the defense community. The conference's technical program has traditionally been run by corrosion specialists from the three services on a rotating basis. Technical direction for this year's conference was provided by Drs. John Beatty and Ralph Adler, both from the US Army Research Laboratory. The conference was chaired by Mr. Daniel J. Dunmire; from the DOD's Office of Corrosion Policy and Oversight, and head of its working group - the Corrosion Prevention and Control Integrated Product Team (CPC IPT). This year's theme was *Transcending and Integrating Corrosion Prevention and Control for the Department of Defense*. In addition to the near-record number of attendees, fifty-seven exhibitors set up displays at the conference, representing corrosion products and services of companies, government agencies, and technical societies. Several pictures from the conference are shown below. The next Tri-Service Conference will be held December 4-8, 2007 in Denver, Colorado, where the theme will be *Integrating Corrosion Prevention and Control in Policy, Planning, and Programming*. Technical program direction will be provided by the Air Force.



Representatives of the CPC IPT in front of their booth: pictured left to right – Dr. Lewis Slotter (Defense Research & Engineering), Mr. Daniel J. Dunmire (Office of Corrosion Policy and Oversight), and Col. Larry Lee (USAF, ret.).



Conference Attendees Conversing in the Exhibit Hall.





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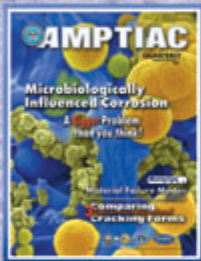
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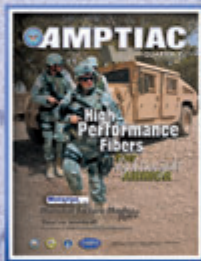
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