INTRODUCTION

DoD 5000.2-R requires the Program Manager (PM) to "consider and implement corrosion prevention and control activities to minimize the impact of corrosion/material deterioration throughout the system life cycle." Corrosion affects the readiness of most Navy systems and is a major contributor to life cycle cost. Significant savings could be achieved on maintenance and repair costs through design prevention and earlier detection of hidden corrosion. This is even more important with the implementation of the condition-based maintenance and two level maintenance philosophies.

This technical bulletin provides selected information directed at the detection and prevention of corrosion to assist PMs in implementing this requirement. The Navy would like to recognize Dave Rose and Jeff Guthrie of the DoD Advanced Materials and Processes Technology Information Analysis Center for their contributions.

OVERVIEW OF CORROSION MECHANISMS

Corrosion has eight different forms but only one, uniform attack, lends itself to accurate life prediction based upon knowledge of the intended environment. The remaining seven forms are insidious with the actual corrosion damage being localized. The result is that component failure can be unexpected or premature. A discussion on each of the eight forms of corrosion is listed below. Performing an analysis on the potential for a component/structure to corrode involves an assessment on whether any of these corrosion mechanisms could be applicable based upon the material in question and the intended environment.

1. **Uniform Attack:** Corrosion occurring at the same rate over much of the surface area is considered a uniform or general corrosion. General overall corrosion is not too great a concern because it can be predicted and proper materials selection and the use of adherent coatings can preclude this particular corrosion mechanism from occurring. However, uniform corrosion will rapidly attack corrosion sensitive materials should the coating become nicked or scratched.

2. **Crevice Corrosion:** Corrosion that occurs next to or inside a tightly occluded area is referred to as crevice corrosion. This form of corrosion occurs when a liquid corrosive is trapped in a gap between two components, in which at least one is sensitive to this form of corrosion. The gap must be sufficiently narrow (< 1/8 inch) to maintain a stagnation zone. Once this zone is established, the concentration of the corrosive increases as the corrosion reaction takes place. There is a long incubation process, from 6 months to a year, before the reaction commences. However, after initiation the reaction proceeds at a continuously increasing rate. Metals and alloys that rely upon oxide films or passive layers, such as stainless steels, for corrosion resistance are particularly susceptible to crevice corrosion.

3. **Pitting:** Corrosion that has the appearance of pin holes or cavities is referred to as pitting corrosion. This form of corrosion is very destructive since it can cause failure with only a

small percent weight loss of the actual structure. The pits themselves are actually cavities with a diameter that is less than or equal to its depth. The pits can grow to such a depth that they perforate the component in question. Failures resulting from pitting corrosion are almost entirely caused by chloride and chlorine containing ions. Stainless steels are more susceptible to this form of corrosion than any other class of metals or alloys

4. Galvanic Corrosion: Tables displaying the Galvanic Series of selected commercial metals and alloys in seawater are readily available and may be used to judge the relative sensitivity dissimilar metals and alloys have towards galvanic corrosion. In general, materials at the top of the list (e.g., gold, titanium and silver) are corrosion resistant while those at the bottom (e.g., aluminum, zinc and magnesium) are not. Additionally, when two different metals or alloys come in contact with each other, the one that is closest to the top of the table is cathodically protected while the one closest to the bottom becomes anodic and as a result, corrodes. Metals that are listed near each other on the table show far less sensitivity to galvanic corrosion than those that are far apart.

5. Intergranular Corrosion: Three different factors can make an alloy susceptible to this type of corrosion. These factors include impurities at the grain boundaries, enrichment of one of the alloying elements, or depletion of one of these elements in the grain boundary area. Intergranular corrosion occurs when the impurities along the grain boundaries are removed as a result of the corrosive environment. The result is that the individual grains not tightly bonded together fail along the grain boundaries with little applied stress. Intergranular corrosion can occur through the grains.

6. Selective Leaching: This form of corrosion results when one element from a solid alloy is removed through a corrosion process. The most common example is when zinc is removed from brass alloys. Other elements that can experience similar processes include aluminum, iron, cobalt, and chromium. These elements can be removed when the alloys containing them are exposed to aqueous acids.

7. Erosion Corrosion: This form of corrosion results when there is movement of one medium adjacent to another that removes the protective material such as surface oxide coating. The moving mediums can be a liquid or slurry such as fluid flow through a pipe. The second form of erosion corrosion is fretting corrosion that occurs by movement of the contact region between two solid materials. This form of corrosion can be induced by vibration or by thermally induced expansion and contraction of materials with different coefficients of expansion.

8. Stress Corrosion: Stress corrosion requires the material in question to be under a tensile stress and also to be exposed to an environment that will initiate cracks within the stressed part. The stress can be as low as 10% of the yield stress for certain alloys and up to 70% for others. Loads applied by mounting bolts, in-service conditions, or even manufacturing processes such as welding can induce stress corrosion.

CORROSION DETECTION TECHNOLOGY

Corrosion detection is a subset of the larger fields of Non-Destructive Evaluation (NDE) and Non-Destructive Inspection (NDI). Many of the technologies of NDE/NDI lend themselves to the detection, characterization and quantification of corrosion damage. No single means of corrosion detection is either ideal or suitable for all forms of corrosion. Table 1 summarizes the major advantages and disadvantages of the primary corrosion detection and characterization technologies, as well as the corrosion mechanism it is used to detect.

Table 1. Summary of Corrosion Detection NDE/NDI Technologies.

Technology	Advantages	Disadvantages	Primarily Detects
Visual	• Relatively inexpensive • Large area coverage • Portability	• Highly subjective • Measurements not precise • Limited to surface inspection • Labor intensive	Surface, exfoliation, pitting and intergranular corrosion
Enhanced Visual	• Large area coverage • Very fast • Very sensitive to lap joint corrosion • Multi-layer	• Quantification difficult • Subjective – requires experience • Requires surface preparation	Same as visual except enhanced through magnification or accessibility
Eddy Current	• Relatively inexpensive • Good resolution • Multiple layer capability • Portability	• Low throughput • Interpretation of output • Operator training • Human factors (tedium)	Surface and subsurface flaws such as cracks, exfoliation corrosion around fasteners and corrosion thinning
Ultrasonic	• Good resolution • Can detect material loss and thickness	• Single-sided • Requires couplant • Cannot assess multiple layers • Low throughput	Corrosion loss and delaminations, voids in laminated structures
Radiography	• Best resolution (~1%) • Image interpretation	• Expensive • Radiation safety • Bulky equipment	Surface and subsurface corrosion flaws
Thermography	• Large area scan • Relatively high throughput	• Complex equipment • Layered structures are a problem	Surface corrosion

	• "Macro view" of structures	• Precision of measurements	
Robotics and Automation	• Potential productivity improvements	• Quality assurance • Reliability	Various

There are a number of corrosion technologies in various stages of maturity. These technologies are being pursued in university research labs, industry R&D programs and government laboratories. Table 2 summarizes some of the trends and directions of the various technologies.

Table 2. Corrosion Detection Technology R&D Trends.

Technology	Trends
Enhanced Visual	• Quantification of corrosion automation of image interpretation • Film highlighters for temporary surface modification • Scanner-based systems
Eddy Current	• More sophisticated signal and data processing (pulsed eddy current, C-scan imaging) • More sophisticated sensors (multi-frequency)
Ultrasonic	• More efficient scanning methods (dripless bubbler, gantrys, etc.) • Dry couplants (including laser stimulation) • Air coupled ultrasonics
Radiography	• Single-sided methods (backscatter) • Three-dimensional image processing (computed tomography)
Thermography	• Time domain analysis (thermal wave imaging) • Multi-spectral (dual-band infrared) • Three-dimensional image processing (computed tomography)
Robotics and Automation	• Attached computer-controlled positioning mechanisms Gantrys (multi-axis) • Crawlers (including vertical and inverted surfaces)
Data fusion	• Image processing (color coding, three dimensional, etc.) • Image correlation (C-scan, etc.) • Multi-mode NDI
Sensor fusion	• Currently only attempted within a single technology (e.g., eddy current, infrared) • No observation of research into combining two different sensors into a single probe for simultaneous measurements

If an NDI method could accurately determine the level of corrosion, including the probability that there is no corrosion present, then the huge costs associated with teardowns could be avoided. This would support the concept of condition based maintenance by providing an accurate assessment of the condition of the system in question.

CORROSION PREVENTION RESOURCES

Prevention of corrosion is the most effective method for maintaining system readiness and performance, as well as reducing total ownership costs. There is a significant amount of information available to the program offices and fleet support activities regarding corrosion prevention and detection. Rather than republish much of this technical information, the following provides sources of information from DoD and industry that can provide assistance with preventing and controlling corrosion in Navy systems.

Advanced Materials and Processes Technology Information Analysis Center (AMPTIAC) - chartered by the Department of Defense to serve as a government and industry focal point for data and information relating to advanced materials and processes and there use in controlling and preventing corrosion. AMPTIAC is sponsored by the Defense Technical Information Center (DTIC).

AMPTIAC's technical scope includes all scientific and technical information pertaining to:

- Ceramics and ceramic matrix composites
- Metals, alloys, and metal matrix composites
- Electronic/optical and photonic materials
- Environmental Protection and Special Function materials
- Organic structural materials & organic matrix composites

AMPTIAC can be accessed at: http://amptiac.iitri.org/

The Coatings Guide ™ - contains several tools to help users identify low-volatile organic compound/hazardous air pollutant coatings that may serve as drop-in replacements for existing coating operations. To date, the Coatings Guide ™ information base has focused on alternative coatings for plastic and metal substrates. The addition of new information on alternative coatings for architectural substrates should be available in the fall of 2001.

Access the Coatings Guide ™ at: http://cage.rti.org/

Corrosionsource.com - provides high quality technical information related to corrosion. Its focus is to educate, enrich and interact, and bring together the worldwide corrosion community. With over 30000 pages of free technical content, Corrosionsource.com is designed to support the technical needs of the worldwide materials and corrosion community. This comprehensive resource provides access to critical corrosion and materials information, data, tools, software and much more. Access this tool at: http://www.corrosionsource.com/

NASA's Scientific and Technical Information (STI) website - helps you find NASA aerospace STI, as well as locate domestic and international STI pertinent to NASA's missions and Strategic Enterprises. Included are a multitude of papers and articles concerning corrosion prevention and control. NASA may be accessed at: http://www.sti.nasa.gov/

Naval Surface Warfare Center (NSWC), Carderock Division - evolved from the merger of the David Taylor Research Center (DTRC) in Carderock and Annapolis, and the Naval Ship Systems Engineering Station (NAVSSES) in Philadelphia. The Carderock Division has been chartered by Congress to develop maritime technology for the Navy and the maritime industry. Additional information is available at: http://www.dt.navy.mil/

North American Technology and Industrial Base Organization (NATIBO) - chartered in March 1987 by the Defense Departments of the U.S. and Canada to promote a cost effective, healthy technology and industrial base that is responsive to the national and economic security needs of the United States and Canada. A Corrosion Detection Technologies Sector Study was completed in March 1998 and identified and assessed the maturity and applicability of corrosion detection technologies to solve the problem of detecting corrosion that is found in both the defense and commercial industry. The study explored the military and commercial applications of these technologies and the transfer of the technologies among government organizations and between government and private industry. The corrosion detection technologies investigated and analyzed were visual, enhanced visual, radiography, ultrasonics, eddy current and thermography. Access this organization at: http://www.dtic.mil/natibo/

NAVMAT P 4855-2; Design Guidelines for Prevention and Control of Avionic Corrosion - presents design and manufacturing information primarily directed to improvement through prevention of corrosion. It supplements the many Government and industry documents currently in existence. In particular, it provides supplemental design and manufacturing information on corrosion prevention techniques. Access this document at: http://web1.deskbook.osd.mil/htmlfiles/DBY_don.asp

International Corrosion Council (ICC) - founded in 1961 to advance corrosion science and engineering represents over 70 countries of the world. Every three years ICC organizes the International Corrosion Congress. Access this organization at: http://www.15icc2002.com/

National Association of Corrosion Engineers (NACE) - established in 1943, with more than fifty years of experience in developing corrosion prevention and control standards, NACE International has become the largest organization in the world committed to the study of corrosion. NACE International provides education and communicates information to protect people, assets, and the environment from the effects of corrosion. Access this organization at: http://nace.org/nace/index.asp

Society of Automotive Engineers (SAE) – provides technical information and expertise used in designing, building, maintaining, and operating self-propelled vehicles for use on land, sea, air and space. Access this organization at: http://www.sae.org/about/index.htm