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NONDESTRUCTIVE EVALUATION METHODS FOR CHARACTERIZATION OF CORROSION

STATE-OF-THE-ART REVIEW

SwRI Project 17-7958-508

by

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San Antonio, Texas

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NONDESTRUCTIVE TESTING INFORMATION ANALYSIS CENTER

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Corrosion is an industry-wide maintenance problem that has been rapidly expanding with the growth in aging structural components. The question now is whether to replace a structural component or to inspect and repair. Replacement can be performed on low-cost items such as land vehicles; but inspection and repair have been the preferred route for high-cost items such as offshore platforms, aircraft, ships, and missiles. While the inspection and repair approach is justified, the reliability of certain nondestructive evaluation (NDE) inspections is questionable. Methods for detection of hidden corrosion, measurement of material degradation due to corrosion, and quantification of corrosion are not fully developed. The need for improving inspection methods is, however, accelerating with the increasing inventory and age of defense equipment and with the high cost of adding new equipment. This report is a survey of the NDE methods presently being used for detection and evaluation of corrosion. These include visual, magnetic, thermographic, electrochemical, acoustic emission, eddy current, liquid penetrant, and x-ray and neutron radiographic methods.

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ABSTRACT

Corrosion is an industry-wide maintenance problem that has been rapidly expanding with the growth in aging structural components. The question now is whether to replace a structural component or to inspect and repair. Replacement can be performed on low-cost items such as land vehicles; but inspection and repair have been the preferred route for high-cost items such as offshore platforms, aircraft, ships, and missiles. While the inspection and repair approach is justified, the reliability of certain nondestructive evaluation (NDE) inspections is questionable. Methods for detection of hidden corrosion, measurement of material degradation due to corrosion, and quantification of corrosion are not fully developed. The need for improving inspection methods is, however, accelerating with the increasing inventory and age of defense equipment and with the high cost of adding new equipment.

This report is a survey of the NDE methods presently being used for detection and evaluation of corrosion. These include visual, magnetic, thermographic, electrochemical, acoustic emission, eddy current, liquid penetrant, and x-ray and neutron radiographic methods. Their advantages and limitations are part of the discussions. In addition, the report addresses the corrosion problems of the United States Army, Air Force, and Navy. Included with these problems are presently applied NDE methods, where appropriate, and identification of the new methods if conventional methods are not applicable.

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I. INTRODUCTION

Corrosion has been defined as the degradation of a material or its properties because of a reaction with its environment (1). Within the scope of this definition, degradation by corrosion, or corrosion damage, can take many forms. The most common are localized damage such as pitting of a surface, generalized attack where a more or less uniform loss of material occurs over a large surface area, environmental cracking in which the combined effects of corrosion and stress can lead to early failure, and some forms of property degradation such as the preferential loss of an alloying agent. The mechanisms by which corrosion damage occurs are also varied, but can be classified generally as electrochemical, chemical, or physical.

Although no generally accepted norm is available by which the economic impact of corrosion can be measured, one comprehensive survey (2) places the value at billions of dollars per year in the United States alone. Recognition of the severity of the problem by various industries and governmental agencies has led to a significant effort within the past 50 years to prevent and control corrosion. Nondestructive evaluation (NDE) plays an important role in this effort, mostly by providing detection of the early signs of corrosion so that corrective action can be taken before damage becomes severe. As the cost of repair or replacement continues to increase, demands on NDE, particularly for early detection of corrosion, also will increase. Accordingly, the purposes of this review of NDE of corrosion are to survey the needs for NDE techniques, to present the state of the art in meeting those needs, and to highlight methods in the research stage that may prove useful in practical corrosion NDE.

The second section of this review is a survey of corrosion mechanisms, with emphasis on those affecting metals. Also included in this section are a description of the nature of corrosion damage and a summary of its physical factors for use in corrosion detection. The third section is a review of corrosion NDE methods, including those in use and under development. Section IV addresses corrosion detection needs of the U.S. Army, Air Force, and Navy. The final section contains the references, and a glossary of corrosion-related terms is presented in Appendix A.

II. CHARACTERISTICS OF CORROSION

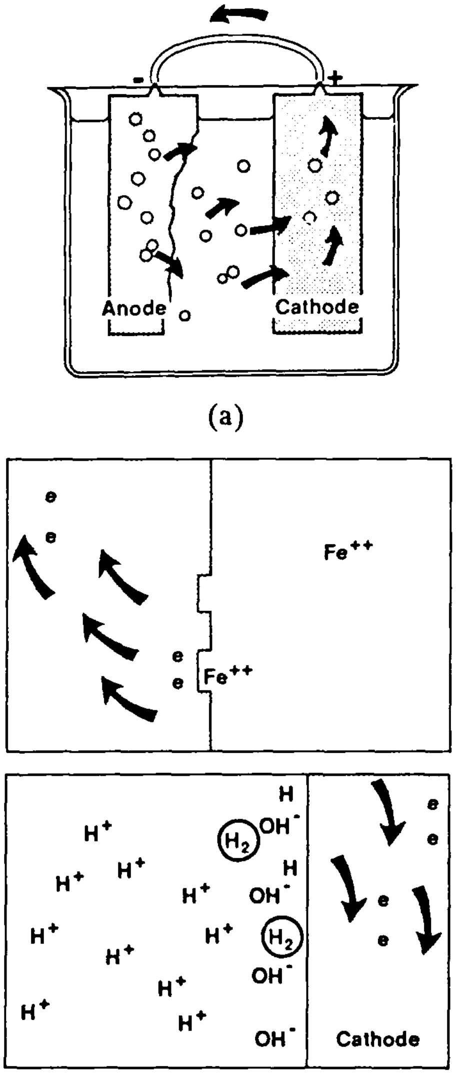
A. Corrosion Mechanisms

1. Overview

Corrosion damage to metals is usually an electrochemical process. This type of corrosion proceeds by means of chemical reactions involving charge transfer among the atomic constituents of the system. Damage occurs at a part of the system called the anode where metal atoms lose electrons as they move from the surface of the metal into an electrolytic solution in contact with the surface. This electron loss mechanism, called oxidation, is characteristic of an anodic region where metal loss occurs. At another part of the system, called the cathode, charge transfer occurs in the opposite direction; i.e., positive ions in the electrolyte recombine with electrons from the metallic cathode to form neutral species. The process of electron capture by positive ions at the cathode is called reduction. Although the reduction mechanism does not result in metal loss, certain forms of damage such as hydrogen embrittlement can occur in cathodic regions.

The essential elements of an electrochemical corrosion process are illustrated in Figure 2-1 (3). In this case the anode is iron, and the cathode is copper; the electrolyte is an aqueous solution capable of sustaining an electric current by means of ionic conduction. At the anode, Fe ions are lost to solution; and each ion leaves two electrons in the metal. Thus the anodic reaction can be written

$$Fe \rightarrow Fe^{++} + 2e^{-} \qquad (1)$$



(a)

(b)

Figure 2-1. An electrochemical cell. (a) Schematic illustration of current flow and (b) anode and cathode reactions. [Ref. (3), reproduced by permission of the National Association of Corrosion Engineers.]

Electrons released by this reaction flow from the anode (at a negative potential with respect to the cathode) and then through an electrical connection shown in the figure as a wire between the two electrodes. At the cathode, electrons combine with positive ions in the solution, usually hydrogen ions, to preserve the overall neutrality of the system. If the cathodic reaction is hydrogen ion reduction, as in this example, neutral hydrogen atoms may combine to form molecular hydrogen, which is often observed as bubble formation on the cathode. Thus the cathodic reaction is

$$2H^+ + 2e^- \rightarrow H_2\ (gas) \qquad (2)$$

The overall reaction can be written as

$$Fe + 2H^+ \rightarrow Fe^{++} + H_2 \qquad (3)$$

This very simple example of a corrosion cell illustrates the essential features of electrochemical corrosion. These are (1) the existence of an electrochemical potential difference between two metal surfaces, (2) the presence of an electrolyte in contact with both surfaces, and (3) an electrical connection to complete the circuit. The electrochemical corrosion cell can, however, take many forms other than that illustrated in the figure; these will be described later when electrochemical corrosion is considered in more detail.

Chemical corrosion differs from the electrochemical process through the absence of separate oxidation and reduction reactions. Consider, for example, the reaction of silver nitrate with sodium chloride to form silver chloride and sodium nitrate:

$$AgNO_3 + NaCl \rightarrow AgCl + NaNO_3 \qquad (4)$$

In this case, positive silver ions combine directly with negative chlorine ions to form the silver chloride precipitate; no separate oxidation reactions occur for silver or reduction reactions for chlorine.

Finally, a third process called physical corrosion produces corrosion without chemical reactions. In physical corrosion degradation is caused by (1) a mechanical process such as impingement of particles carried by a flowing liquid on a surface, (2) cavitation corrosion caused by the sudden formation and collapse of bubbles on a surface, and (3) fretting damage associated with the abrasive interaction of two surfaces rubbing against one another. It often happens that physical corrosion leads to enhanced electrochemical corrosion by removing or damaging surface films or depositions of corrosion products that tend to protect a surface from its corrosive environment.

2. Electrochemical Corrosion Processes

As just noted, one factor associated with electrochemical corrosion is the existence of a potential difference between two surfaces. This difference could be caused by an external source, but is more often a result of a fundamental characteristic of a material in a given electrolytic environment. One result of the oxidation and reduction processes occurring at a metal surface is the alteration of the electrical potential of the metal. Because charge transfer rates differ for different combinations of metal and electrolyte, different equilibrium potentials exist for each metal-electrolyte pair. Thus, potential difference occurs between two dissimilar metals in an electrolytic solution. This natural potential difference provides the driving force in most instances of electrochemical corrosion.

The anodic or cathodic nature of two dissimilar metals in a given electrolyte can be determined by consulting a table called the galvanic series for metals in that electrolyte. As an example, Table 2-1 shows the galvanic series for metals in seawater. The metals are arranged in order of increasing potential; i.e., a given metal is more negative (anodic) than those that appear below it in the table. For example, if zinc and copper are the two electrodes in a seawater solution, then the zinc electrode will be the anode and copper will be the cathode. If, on the other hand, zinc and magnesium were used, then magnesium, being more negative than zinc, would be the anode; and the zinc electrode would be the cathode. Because metal loss occurs at the anode, knowledge of the galvanic series for a particular electrolytic environment can be valuable in deciding where to look for evidence of electrochemical corrosion damage.

If two different metals are brought into contact in an electrolytic solution, the resulting system is the familiar galvanic cell. The metal nearer the top of the galvanic series forms the anode; the other metal is the cathode, and the electrical connection needed to complete the circuit is provided by the contact between the two metals. The rate of corrosion activity is governed by the relative

Table 2-1

GALVANIC SERIES FOR METALS AND ALLOYS IN SEAWATER

Magnesium
Magnesium Alloys
Zinc
Galvanized Steel
Aluminum 1100
Aluminum 2024
Mild Steel
Wrought Iron
Cast Iron
13-Percent Chromium Stainless-Steel Type 410 (Active)
18-8 Stainless-Steel Type 304 (Active)
Lead-Tin Solders
Lead
Tin
Muntz Metal
Manganese Bronze
Naval Brass
Nickel (Active)
76-Ni-16- Cr-7 Fe Alloy (Active)
60 Ni-30 Mo-6 Fe-1 Mn
Yellow Brass
Admiralty Brass
Red Brass
Copper
Silicon Bronze
70:30 Cupro Nickel
G-Bronze
Silver Solder
Nickel (Passive)
76 Ni-16 Cr-7 Fe Alloy (Passive)
13 Percent Chromium Stainless-Steel Type 304 (Passive)
Silver
Graphite
Gold
Platinum

positions of the metals in the table, with greater table position differences corresponding to more activity. As in all electrochemical corrosion processes, damage is observed as metal loss at the anode, accompanied by the formation of corrosion-product deposits on one or both surfaces.

Under certain environmental conditions, some metals exhibit a phenomenon known as passivity. When this happens, a very thin film is formed on the metal surface; and this film acts as a barrier to further corrosion, sometimes reducing the corrosion rate by orders of magnitude. In terms of the galvanic series, the formation of a passivating layer makes the metal more cathodic, thus lowering its position in the activity series. This is indicated in Table 2-1 by the terms "active" and "passive" after certain entries.

If passivity is present on one part of a metal surface and not on another, there will be a potential difference between the active and passive regions, as indicated by a galvanic series like that in Table 2-1; and corrosion of the active (anodic) region will occur. This might happen if the surface layer is removed or damaged in one region, or is prevented from forming by local environmental conditions. Several other situations also cause corrosion cells to form on a single metal surface, with one part of the surface being anodic and another part being cathodic.

Although passivity is usually treated as a separate topic, the formation of a passivating film can be considered as a special case of a more general phenomenon known as polarization. Generally, polarization refers to any effect that tends to alter the corrosion rate. For example, in a weak acid the concentration of hydrogen ions becomes depleted as the reaction proceeds, resulting in a decrease in the hydrogen ion reduction rate at the cathode. This, in turn, leads to a slowing down of corrosion activity. Another possibility is that electron capture at the cathode might be inhibited by some other cathodic reaction, again resulting in a decrease in the corrosion rate. In either case, the process by which the corrosion rate is diminished by cathodic reactions is called cathodic polarization. Similarly, processes limiting the corrosion rate through reactions at the anode are referred to as anodic polarization processes. The overall corrosion rate is therefore controlled by the combined effects of cathodic and anodic polarization.

An agent that tends to reduce polarization and thus enhance corrosion is known as a depolarizer. The most common cathodic depolarizer is oxygen, which can take the place of hydrogen ions in removing electrons from the cathode. The reaction is

$$O_2 + 4e^- + 2H_2O \rightarrow 4OH^- \qquad (5)$$

If cathodic polarization is caused by hydrogen ion depletion and if cathodic polarization is the controlling factor, the corrosion rate will be determined by the availability of oxygen. This explains the common observation that corrosion rates are usually greater in aerated solutions than in solutions containing little oxygen.

Variations in oxygen concentration from one part of a surface to another can lead to the formation of corrosion cells, in much the same way as variations in passivity. In regions when the oxygen concentration is high, electrons are removed more rapidly from the metal than in regions where the concentration is lower. This makes regions of high oxygen concentration more cathodic than regions of low concentration, creating a potential difference between the regions. The end result is a special kind of corrosion cell, called an oxygen concentration cell, in which the region of low oxygen concentration is the anode and the region of higher concentration is the cathode. Oxygen concentration cells are quite common, and tend to occur whenever oxygen is prevented from reaching part of a surface, such as in a crevice or under a surface deposit. As always, metal loss occurs at the anode, which is the hidden or covered part of the surface in an oxygen concentration cell.

Corrosion cells can also be formed if a higher concentration of metal ions in solution exist at one part of an anodic surface with respect to another. In the region with the higher metal ion concentration, it is energetically more difficult to create more metal ions in solution than is the case where the concentration is lower. The high concentration region then becomes cathodic with respect to the low concentration region, leading to what is called a metal ion concentration cell. Such cells might form where velocity gradients in a fluid move past the surface. Metal ions are swept away faster where the velocity is greater, and a corrosion cell is produced in which the region with higher fluid velocity is anodic.

Finally, in this survey of electrochemical corrosion mechanisms, another process can be important when ions of the more noble metals (those near the bottom of the galvanic series) are in solution in contact with a surface of a more active metal (one near the top of the series). An example might be copper ions in solution contacting an aluminum plate. In this case the copper tends to deposit, or plate out, on the aluminum, creating a small island of copper on the surface. Because of the rather large potential difference between the two metals in this case (see Table 2-1), the result is a very active galvanic cell, with the copper deposit being the cathode and the aluminum substrate forming the anode.

B. Corrosion Damage

1. Overview

Figure 2-2 is a schematic illustration of several forms of corrosion damage (4). The simplest of these is general attack when a more or less uniform loss of material occurs over a surface. In most cases, general attack is caused by very small anodic and cathodic areas on the surface, which switch places as the process continues. The end result is that at one time or another all regions of the surface are anodic, and material loss over a sufficient length of time is approximately uniform.

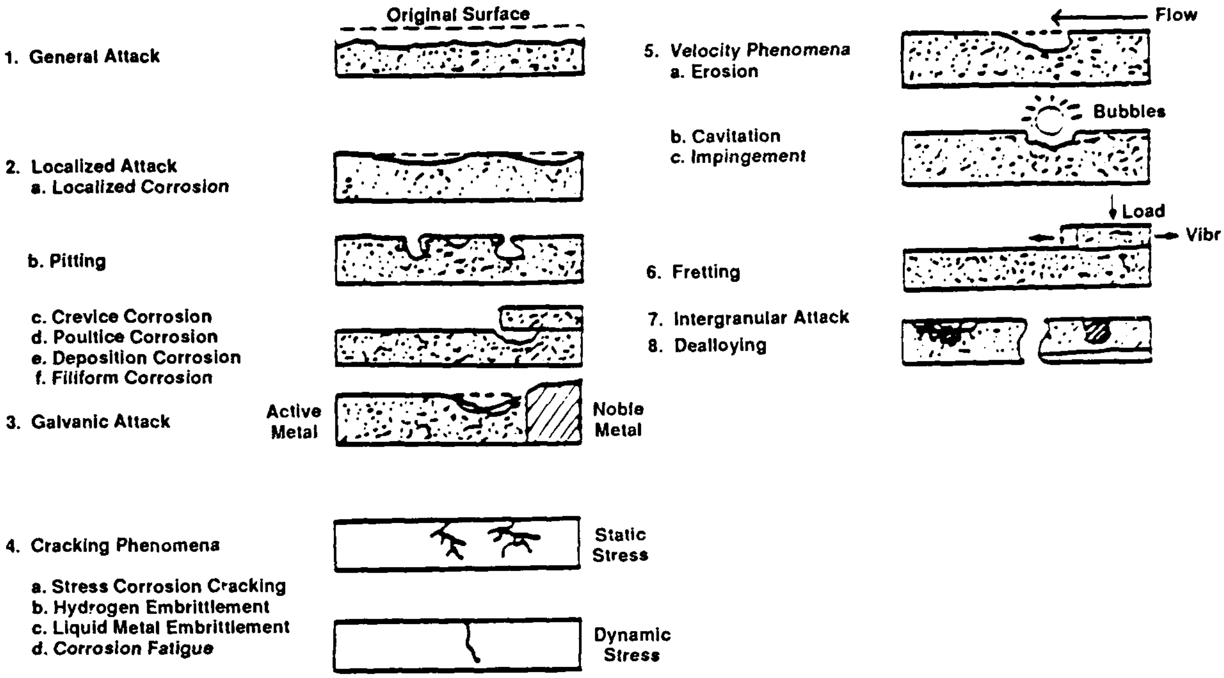


Figure 2-2. Types of corrosion damage. [Ref. (4), reproduced by permission of the National Association of Corrosion Engineers.]

In discussing the NDE of corrosion, it is convenient to divide the remaining forms of corrosion damage into three classes depending on the type of damage observed. The first is localized corrosion, which results in the formation of pits or similar defects. The second is environmental corrosion, which includes the corrosion-enhanced formation of cracks; and the third is degradation of properties in the absence of crack or pit formation.

2. Localized Corrosion

Many forms of localized damage are the result of localized corrosion cells with anode and cathode in close proximity on a surface. Pitting is a particular form resulting from metal loss at a local anode and leading to cavity formation. Shapes of pits vary widely; some are filled with corrosion products while others are not. This form of damage is often observed in metals that are coated or otherwise protected by a surface film, and is probably associated with damaged or weak spots in the coating.

Crevice corrosion is a special form of pitting occurring at crevices or cracks formed between adjacent surfaces. The corrosion mechanism in this case is usually the formation of an oxygen concentration cell, with metal loss in the crack or crevice with a low concentration of oxygen.

Poultice corrosion is similar to crevice corrosion in that an oxygen concentration cell is involved. With poultice corrosion, however, the anodic region of low oxygen concentration is covered by some foreign material on the surface, and metal loss occurs under the covering.

Filiform corrosion is still another form involving oxygen concentration cells, in this case under organic or metallic coatings. Damage is characterized by a network of threads or filaments of corroded material under the surface.

Galvanic attack can also cause pitting of the more active of two dissimilar metals in contact. Depending on the relative areas of the anodic and cathodic surfaces, this form of corrosion can lead to a more dispersed metal loss. Thus, if the anode area is large compared to the cathode area, damage to the anode will tend to be more uniform than if the reverse were true.

In all of the cases just described, the mechanism leading to localized damage is electrochemical in nature. Certain physical forms of corrosion, however, can also produce localized damage. One of these is fretting in which metal is removed by the abrasive action of one surface moving against another. Vibrating machinery produces fretting, and damage is characterized by surface discoloration and deep gouges or pits.

Liquid flowing over a surface also causes velocity-related damage effects. If the flow is turbulent, erosion damage can occur and may accelerate electrochemical corrosion by the removal of protective films. The presence of particles in the liquid usually will accentuate erosive effects. Erosion damage is often uniform, but it can also produce pitted surface areas. Other velocity-related effects are cavitation damage, caused by the formation and collapse of bubbles, and impingement attack, caused by high-velocity flow producing a pattern of localized damage with directional features.

3. Environmental Cracking

Some materials subjected to tensile stress in a specific corrosive environment are susceptible to spontaneous brittle fracture, even though such materials in a noncorrosive environment may be quite ductile. This phenomenon, known as environmental cracking, is different from stress-assisted cracking in which a material, weakened by corrosion damage, cracks under tensile load. Environmental cracking refers to crack formation under the combined effects of stress and corrosion. Examples discussed here are stress-corrosion cracking, hydrogen embrittlement, and liquid metal embrittlement.

Stress-corrosion cracking can occur in a mildly corrosive environment under tensile stress that would not normally be considered excessive. Metal loss is small; and the cracks, which can be either intergranular or transgranular, tend to be multiple branched. The crack-propagation mechanism is not understood in detail, but seems to involve the combined effects of electrochemical corrosion, with an anodic region at the crack tip, and tensile stress, which tends to open the crack to allow further corrosion.

Unlike stress corrosion cracking (an anodic process), hydrogen embrittlement is caused by a cathodic reaction. Normally, when hydrogen ions are reduced at the cathode, they combine to form molecules of hydrogen gas and leave the surface. Under some circumstances, the formation of molecular hydrogen is inhibited, leaving atomic hydrogen free to diffuse into the metal cathode. For uncertain reasons, the presence of atomic hydrogen in a metal matrix causes severe deterioration of ductility, or hydrogen embrittlement.

Embrittlement can also be caused by intergranular penetration of liquid metals. Such reactions are very specific to the embrittling agent; i.e., they occur only for certain combinations of metals and liquid agents. Stainless steels, for example, are very susceptible to embrittlement by molten zinc, aluminum, or cadmium.

4. Property Degradation

In addition to producing defects such as pits or cracks, corrosion can also lead to the deterioration of material properties without the presence of flaws that might be detectable with conventional NDE. Embrittlement by hydrogen or a liquid metal might be considered property degradation, although embrittlement is usually accompanied by cracking and is, therefore, associated with defect formation. Other examples of property degradation are intergranular and transgranular corrosion, corrosion fatigue, and dealloying.

Intergranular corrosion is a highly localized form of damage in which attack occurs along a narrow path that tends to follow grain boundaries. Its cause is from a potential difference developing between the grain boundary and surrounding material, which, in turn, is caused by the trapping and precipitation of impurities at grain boundaries. Because of this dependence on grain-boundary composition, susceptibility to intergranular attack is strongly dependent on metallurgical treatment. In particular, the heat-affected zone near a weld is a region where the temperature produced during the welding process causes impurities to migrate and become trapped at grain boundaries. The heat-affected zone can, therefore, be susceptible to intergranular corrosion.

Transgranular corrosion is similar to intergranular corrosion in that attack is highly localized and follows a narrow path through the material. As the name implies, the paths in this case cut across grains with no apparent dependence on grain-boundary direction. Transgranular corrosion is often associated with corrosion fatigue, although intergranular and sometimes both intergranular and transgranular corrosion are observed.

Corrosion fatigue is a term applied to the degradation of fatigue life in a corrosive environment. It is distinguished from environmental cracking in the sense that corrosion fatigue refers to degradation by any corrosive environment and is not specific to a particular mechanism, while environmental cracking relates to specific metals and environments and specific forms of damage. Corrosion fatigue is distinguished from environmental cracking by the morphology of the fractured surface.

Dealloying, another form of material-degradation, is quite different from those just considered. The term refers to the selective dissolution of an alloy constituent in an anodic reaction. The best-known example is dezincification of brass, in which zinc is preferentially removed, thereby altering the chemical and mechanical properties of the material. Another example is graphitization, which is a selective removal of iron (usually from gray cast iron). In this particular case, the damaged part may appear the same as an undamaged part; but it is porous, extremely brittle, and easily damaged.

C. Corrosion Detection and Measurement

The objectives of corrosion NDE are to detect and measure the extent of corrosion damage and/or corrosion activity. As usual in NDE, emphasis in damage detection is on small flaws, so that repair or replacement of parts and possibly correction of the corrosive environments can be accomplished at minimum cost.

Corrosion NDE is different from other applications because an estimate of corrosion rate may be needed in addition to a measurement of existing damage. To make a cost-effective assessment of the need for corrective action, sometimes identifying flaws of a given type and size in a particular location is not enough. Information on corrosion activity is also needed; i.e., the rate at which damage is occurring. Periodic repetition of an inspection is one means of monitoring flaw growth rate. This approach does, however, require accurate measurement of flaw size. Other alternative measurement approaches more directly related to corrosion rate also are available. But regardless, the need for rate information places additional demands on corrosion NDE over flaw detection alone.

Additional differences exist between corrosion NDE and other applications. Corrosion products, for example, provide an opportunity for NDE that does not exist in a noncorrosive environment. Evaluation of the integrity of corrosion protection systems is another example of a possible NDE application. This section provides a brief review of the physical manifestations of corrosion useful when assessing the need for NDE.

The detection of corrosion pits, cracks, or wall thinning due to general attack of a surface are examples of corrosion NDE problems that differ only in detail from problems encountered in other branches of NDE. For this reason, most of the corrosion NDE examples cited in the next chapter are simply adaptations of conventional NDE methods to corrosion problems--with a few differences. For example, if a corrosion pit is partially filled with a corrosion product with nearly the same physical properties as the host material, then detection and sizing of the flaw are more difficult than would be the case in the absence of corrosion products. The detection of crevice or poultice corrosion might also be more difficult than detection of other types of flaws because the damage is hidden in a crack or crevice or under a patch of material on the surface of the part. Environmental factors might also present special difficulties, such as in situ inspection of underwater structures.

In some situations, corrosion damage can take the form of material-property changes. Embrittlement, for example, is usually accompanied by cracking. Possibly for some cases the measurement of a physical quantity related to ductility would be easier to implement and be perhaps more meaningful than the detection of cracks. Dealloying is another such material-property change that could be amenable to measurement. The existence of intergranular or transgranular corrosion or property changes associated with corrosion fatigue are additional examples.

In principle, electrochemical corrosion always generates corrosion products, although these products are not always detectable. One detectable corrosion product, often by a simple visual inspection, is rust produced in the corrosion of products containing iron. Another is hydrogen gas, which is often found at the cathode in an electrochemical cell. Other products and possibly physical or chemical effects associated with corrosion products could form a basis for corrosion detection.

Electrochemical corrosion also implies the existence of an electric current and an associated magnetic field. These currents and fields are extremely weak, and have only recently been detected in a carefully controlled laboratory environment using a SQUID (Superconducting Quantum Interference Device). On the other hand, electrochemical measurement techniques based on the analysis of DC or AC polarization data can provide estimates of the corrosion current and may find some use in NDE as a means of measuring corrosion rate.

An active electrochemical cell requires the presence of an electrolytic solution and a potential difference between anodic and cathodic regions. When it is possible to make such measurements, electrical potential surveys and data on the resistivity of the solution provide useful information on the possibility for corrosion. Because it is usually impractical to obtain such data on a sufficiently fine spatial grid, applications are limited to the assessment of large-scale corrosion; i.e., conditions amenable to localized cell formation are not measured.

Finally, NDE could be applied to the evaluation of corrosion protection systems such as coatings used to protect metals from corrosive environments. Cathodic protection systems (electrical systems designed to reverse the current flow from a region that is normally anodic) are another example where direct or indirect measurement of current or potential differences could be useful.

III. NONDESTRUCTIVE TEST METHODS FOR CORROSION ASSESSMENT DETECTION

Inspection for corrosion to date has generally been performed by either directly applying the conventional NDE methods or applying after slight modifications. In general, NDE for corrosion has been directed toward finding the appropriate conventional method that can perform such an inspection. This fact was also supported by a survey on corrosion monitoring methods performed in the U.K. (5,6). Thus, very few specific NDE methods exist for corrosion. This section includes a spectrum of the methods applied for a range of corrosion problems. Included are both the application of conventional methods and discussion of novel methods for corrosion NDE.

A. Acoustic Emissions

Acoustic emission (AE) refers to the generation of elastic waves in a material caused by its deformation under stress. Flaws can be detected using AE methods because flaw growth caused by stresses produces acoustic emissions. Material stress can come from mechanical and thermal loading, as well as from a variety of other means.

AE from materials is generally one of two types. The first is low-level and almost continuous. This AE, similar to background noise, can be from plastic deformations, microstructural changes, or a chemical reaction related to corrosion. Low-level AE can also be produced by flaking or removal of corrosion products from a surface. High-level signals in the form of bursts are generally associated with sudden release of energy. This can be due to such factors as growth of discrete flaws like cracks, the burst of bubbles, and cavitation.

The most common tests for AE are on-line monitoring and proof. On-line monitoring is a passive method where AE is recorded for a long time. In this case, the structure is under a constant load, such as pipes transporting gases at constant pressure or a certain chemical reaction. A flaw is flagged if a change occurs in AE from the background noise level. The proof test is different from on-line monitoring, as it employs application of an additional load to produce AE. This external load forces the flaws to grow and produce AE. The proof test is short term compared to on-line monitoring, which can go on for days or even years. Both tests are relevant for detection of corrosion.

AE from corrosion can occur from various processes. Pollock (7) summarized these processes as candidates for detection by AE (see Table 3-1). As seen from the table, three of the listed corrosion processes do not produce detectable emission. Electric currents do not because moving electrons do not stress the lattice. Migration of atoms during film growth will stress the lattice and might be expected to produce continuous AE; but in slow-growing films, the acoustic energy would be very low, and the effect has not been reported to date. Dissolution of metal and active-path corrosion [in stress-corrosion cracking (SCC)] are equally silent; the forces involved in the passage of individual atoms into solution are negligible at ordinary rates of dissolution.

Cracking of the corrosion-product film will produce detectable emission. The energy source is the elastic stress field that develops during film growth or temperature change and releases during sudden cracking, spalling, or exfoliation. Thick, brittle, tenacious films, in general, produce higher amplitude emissions than thin, soft, or weak films; emission may not be detectable for the latter type.

The evolution of gas is a recognized source of low-amplitude emission during corrosion in liquid media. The energy associated with a bubble is converted into kinetic energy when the bubble bursts. Studies done by Scott (8), have shown, however, that AE is associated with the actual formation of the bubble and not from bursting in certain cases. Hydrogen-induced microcracking produces a large number of level emissions caused by finely distributed microcracking, while mere

Table 3-1

PRINCIPAL PROCESSES OF CORROSION AND THEIR AE DETECTABILITY
[Ref. (7), reproduced by permission of the American Society for Testing and Materials]

PROCESS	DETECTABLE BY AE?
Passage of Electric Current	No
Dissolution of Metal	No
Film Formation	No
Film Cracking	Depends on Thickness
Evolution of Gas	Yes-Low Amplitude
Hydrogen Migration/Microcracking	Yes-Low Amplitude
SCC-Active Path	No (Except Plastic Zone)
SCC-Discontinuous Cracking	Yes-High Amplitude
Hydrogen Cracking	Yes-High Amplitude

SCC = Stress Corrosion Cracking

movement of hydrogen atoms is not expected to produce detectable AE.

Stress-corrosion cracking and corrosion fatigue will all produce high-level AE. The energy of AE during crack growth is drawn from the stress field around the crack, which relaxes momentarily as the crack jumps forward. The stress field is created by the external forces in combination with internal pressure if hydrogen is involved. Yuyama (9) has schematically shown the various corrosion processes that produce AE (see Figure 3-1).

AE signals are generated mainly by crack initiation and growth induced by SCC or hydrogen embrittlement. However, the evolution of hydrogen (H_2) gas via cathodic reaction in acid solutions and the breakdown of thick-surface oxide film formed under certain circumstances are also important sources of significant AE. In addition, the fracture or decohesion of phases such as precipitates, second-phase particles, and nonmetallic inclusions and the twinning in the plastic zone of a crack are expected to produce detectable AE. On the other hand, dissolution of metals can hardly be detected by AE technique.

1. Detection of Surface Corrosion

Detection of surface corrosion by AE has been performed for a variety of applications. These methods detect corrosion by detecting AE generated from the breaking of corrosive films or products, chemical reaction, or bursting of bubbles.

Detection of corrosion in aircraft honeycomb structures has been performed at McClellan Air Force Base (10). The test was conducted by heating a local area of the structure and listening for the AE produced by evolution of hydrogen gas or steam. AE from the corroded areas was only detectable for wet areas and not from dry ones.

Birring (11) has performed an AE test on corroded parts obtained from an aircraft. AE activity monitored during application of heat showed that corroded parts produced 15 times the amount of AE counts compared to the noncorroded parts (see Figure 3-2). The AE method was unsuccessful on parts with no deposits of corrosion products. The test concluded that the AE was produced by the breakage of the corrosion film

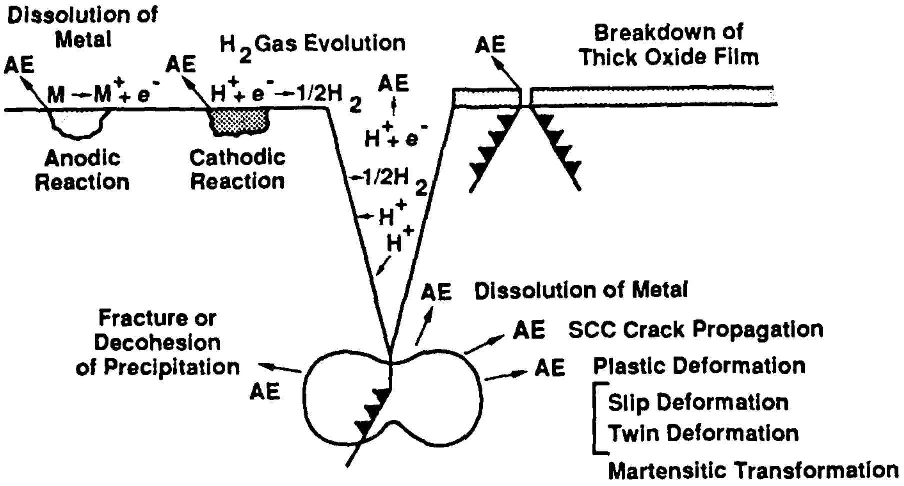


Figure 3-1. Schematic of AE sources during corrosion, stress corrosion cracking, and corrosion fatigue processes [Ref. (9), reproduced by permission of the American Society for Testing and Materials]

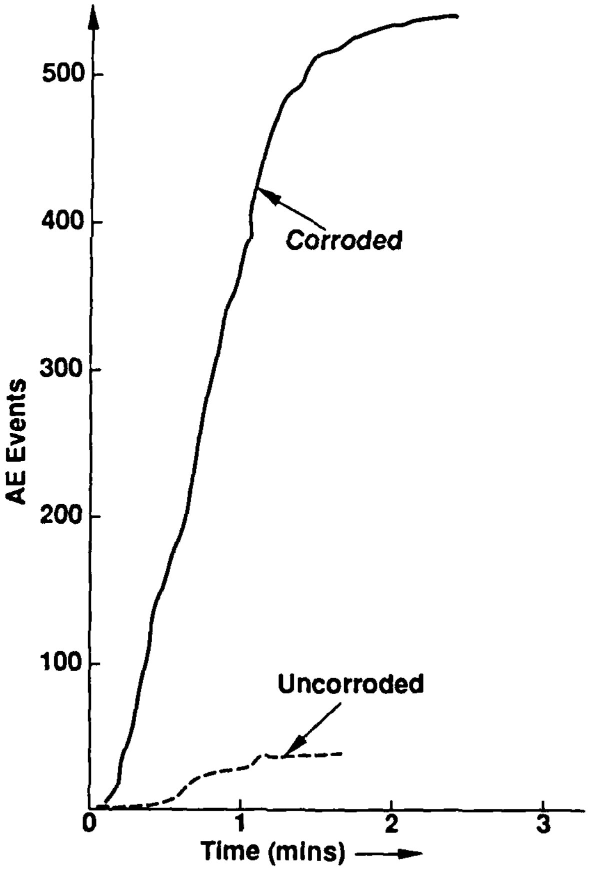


Figure 3-2. Acoustic emission counts recorded while heating corroded and uncorroded specimens. The acoustic emission counts on the corroded specimen were more than 14 times greater than those on the uncorroded specimens (11).

and that AE testing would detect the breakage of corrosion film during thermal expansion.

Scott (8) has conducted studies to monitor AE from a chemical reaction. His work showed that aluminum partly emerged in a solution of sodium hydroxide produced AE. The formation of bubbles on the metallic surface were identified as one of the major sources. He states, however, that not all chemical reactions can be detected by using AE, although AE is produced by most of the reactions involving aircraft alloys and likely corrodants with the notable exception of rust formation.

Fenn and Condello (12) showed that AE can be used to distinguish among various types of films formed by corrosion. Differences in AE energy output and the spectral content were discovered during the fracture of different types of film. They suggest that, by identifying different species of oxides, films would determine the different corrosion mechanisms.

Rettig and Felsen (13) monitored AE produced from a reaction of aluminum wire within salt water. They concluded that failure prediction can be made empirically from the AE counts, rate, cumulative counts, and pulse amplitude. In another study, Mansfeld and Stocker (14) demonstrated that AE count rate accurately reflected the corrosion behavior of aluminum alloys.

Yuyama and coworkers (15) found a relationship between a polarization curve and the AE count in stainless steels. Their results showed that AE is detected only when the reductive breakdown of passive film occurs and hydrogen gas evolves on the specimen surface. No AE was detected when the oxidation breakdown occurred and the metal dissolved into solution.

2. Pitting Corrosion

Detection of pitting corrosion by AE has been very limited until recently. Parry (16) performed laboratory tests to detect AE from corroded pipes and later verified his findings with results from ultrasonics and visual observations. Difficulties were experienced in detection, locations, and grading of the most severe corrosion pits where a pipeline has general heavy corrosion over long lengths of its surface. Such general corrosion produces emissions over the entire length of the line, thus increasing the background level of the data.

AE from pitting is believed to be created from secondary effects of corrosion; i.e., scale and oxide cracking under stress imposed at a level exceeding that at which the oxides and scales were formed. Parry (16) found that emissions were produced as the stress levels in the pipe exceeded the normal operating stress by 10 to 20 percent and that very few emissions were produced above this range.

3. Cracking

The literature currently available contains much information about the application of AE for detection of SCC and corrosion fatigue. Yuyama (9) has studied the initiation and growth of SCC. A double-cantilever beam (DCB) with an artificial crevice was immersed in 3-percent NaCl, and the AE activity was monitored. The tests showed that the AE energy was relatively low until after 10 hours; then it suddenly increased by a large amount. AE energy was found in the middle of the measured zone; namely, the crack tip. It was thus concluded that the high-amplitude AE in Figure 3-3 caused the sudden increase of the AE energy at 10 hours and that the SCC initiated at that time.

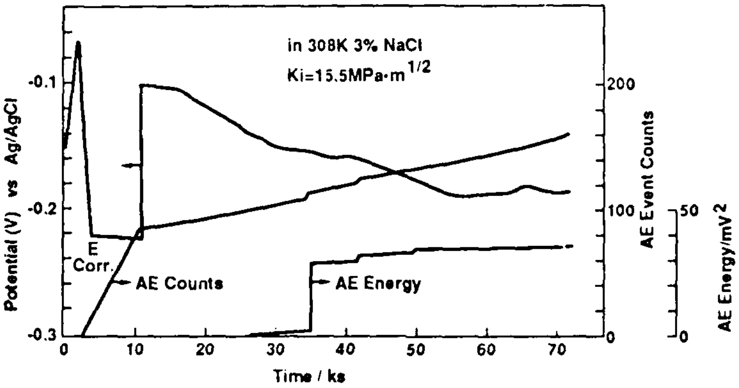


Figure 3-3. AE cumulative event count and energy during the SCC test [Ref. (9), reproduced by permission of the American Society for Testing and Materials]

Cox (17) reported that emissions from a zincalloy-2 specimen of DCB type can be divided into (1) a continuous emission due to plastic deformation at the crack tip and (2) a high-amplitude, burst-type signal because of the propagation of the crack. In most cases, as also observed by Yuyama, an initiation period occurs with low AE activity.

Okada et al. (18) carried out SCC tests for Type 304 stainless steel in 5N H_2SO_4 + 5M NaCl at 25 degrees C and for ferritic and high-strength martensitic stainless steels in boiling magnesium chloride ($MgCl_2$) aqueous solution at 143 degrees C. They measured AE and changes of the electrical resistance or displacement of cantilever beam specimens. The results showed that the significant AE could not be detected during the SCC propagation of Type 304 and ferritic stainless steels; in which case, active-path corrosion (APC) was dominant as the SCC process. The high AE activity, in contrast, was observed during the SCC of high-strength martensitic stainless steel; and, in this case, hydrogen embrittlement was determined to have caused the SCC.

Fiest (19) has applied AE to find detection of intergranular cracking in gas-turbine blades. Such cracks can be significant when present in the area of the fir-tree grooves and the blade root. AE was produced from the microcracks by applying thermal-shock loading. The root area of the blade was heated with an induction coil and quenched. Acoustic emission signals then received were used to detect cracking with a depth range of 10 to 100 microns.

Mehdizadeh (20) has monitored the progress of corrosion fatigue (CF) damage of quenched and tempered carbon/manganese (C/Mn) steel in 3-percent NaCl solution by AE generated during corrosion fatigue test and periodic proof loadings. The result showed that periodic proof testing combined with AE monitoring could be a sensitive method for assessing the progress of corrosion damage. This method can establish the initiation of incipient fatigue cracks after as little as 5 percent of the total fatigue life. A qualitative method based on the saturation of AE during period proof loading was used to determine the remaining fatigue life, and this scheme predicted the remaining fatigue life up to 70 percent of the actual values.

Yuyama et al. (15,21) have made systematic studies of AE produced during CF of a 304 austenitic stainless steel potentiostatically polarized in 1 N H_2SO_4 + 0.5 M NaCl or 1 N H_2SO_4 solutions, using compact tension specimens. The crack growth rates at -0.8V, E_{corr}, and -0.28V were accelerated significantly compared with those observed in air or +0.01V (noncorrosive environments) when ΔK is less than about 37 MPa $m^{1/2}$ and where the transition of the deformation patterns in the crack-tip plastic zone from a hinge type takes place and through-thickness yielding is accomplished. Both AE cumulative event counts and AE energy represented step-like curves, and their increasing rates were found to become greater with the acceleration of crack-growth rates. Figure 3-4 indicates the relationship between ΔK and AE activity.

4. Material Degradation

Acoustic emission has been very effectively used to detect microstructural degradation in materials, including detection of microcracking caused by hydrogen attack and corrosion of selective phases. Jolly (22) applied AE to detect hydrogen attack in a petrochemical plant. A large number of low-level AE signals were received as the hydrogen penetrated in the metal and produced intergranular damage. Triangulation was used to locate the source of AE. Visual observation carried out during a shutdown verified the hydrogen damage, and the AE activity was absent after the pipe section was repaired.

Culpan and Foley (23) applied AE to study the selective phase corrosion attack in seawater of nickel aluminum bronze (NAB). During the process, which occurs particularly in the heat-affected zones of weld repairs, copper is redeposited at the corroded areas, making the phenomenon extremely difficult to detect by conventional nondestructive testing techniques. It was considered likely that the different fracture modes of sound material and corroded material would result in differing forms of AE during deformation. Acoustic emission monitoring was performed on tensile specimens of as-cast, welded, and corroded NAB. The failed specimens were then examined using optical and scanning electron microscopy. Results showed significant differences in the AE behavior of the three types of material. These were revealed in characteristic event counts, event amplitudes, root-mean-square energy outputs, and normalized

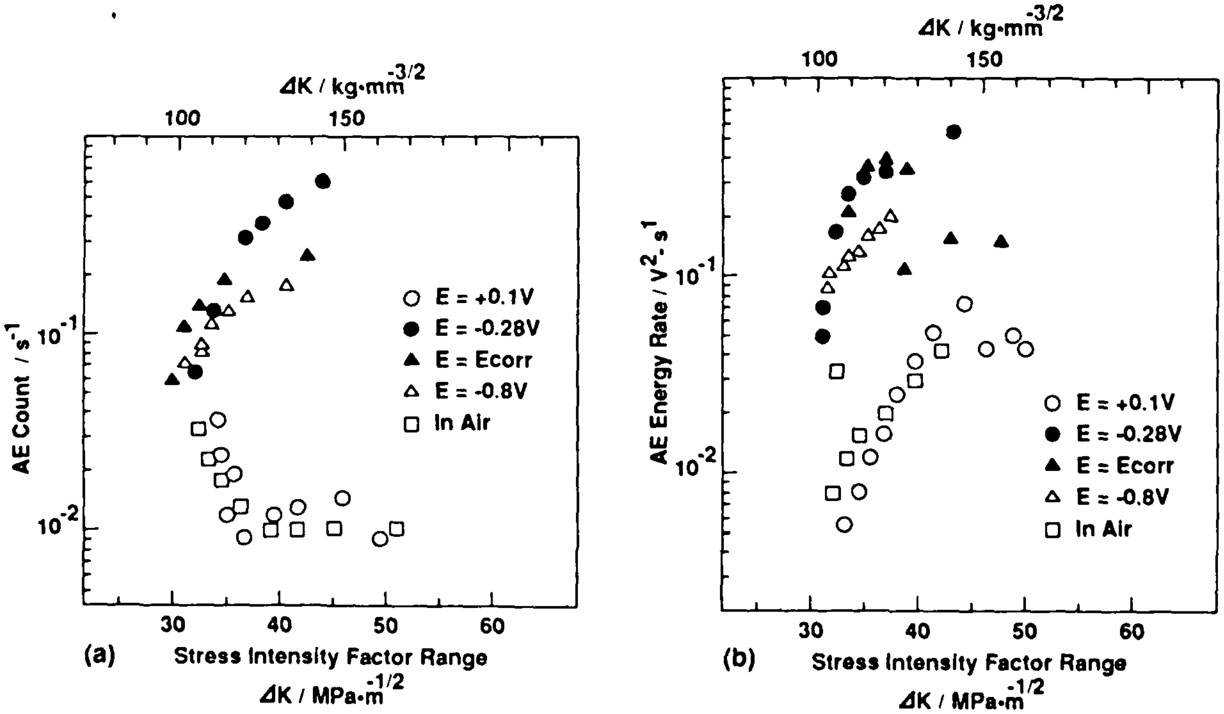


Figure 3-4. Relationship between stress-intensity factor range and AE activity: (a) AE count rate, (b) AE energy rate (solution-treated case) [(Ref. (21), reproduced by permission of the *Journal of Acoustic Emission*]

amplitude analysis of the data. These differences in behavior were correlated with the varying structures of NAB and their behavior under stress.

B. Eddy Current

Eddy current testing (ET) techniques are useful in the detection and sizing of many types of defects related to corrosion damage. In addition to its well-known applications to crack and pit detection, eddy current can be used to measure thickness changes caused by corrosion, buildup of corrosion products in certain situations, and some changes in material properties such as conductivity degradation caused by intergranular corrosion. The techniques and applications reviewed here include examples of each of these uses of ET.

Corrosion NDE involves a variety of ET techniques ranging from simple applications of well-established inspection procedures to advanced techniques based on the latest developments in eddy current research. While some of the examples cited here focus on the measurement of only one flaw characteristic, such as the depth of a corrosion pit, others demonstrate the ability of a particular technique to detect and characterize more than one aspect of corrosion damage. Some of these multi-purpose techniques are discussed first, followed by reviews of techniques for crack and pit detection, measurements of material thickness, and detection of material-property changes.

1. General Applications of Eddy Current Techniques

If the thickness of a part is on the order of or less than the skin depth, the phase lag of the eddy current probe impedance, relative to the phase of excitation current, can be related to thickness. This well-known technique was used, for example, by Bond (24,25) for the detection of panel thinning and corrosion pit detection in the inspection of aircraft structures. Instrumentation requirements, sensitivity, and the practical aspects of routine inspection for corrosion were also discussed by Bond.

Hagemaier (26-28) used both amplitude and phase information to make quantitative measurements of panel thickness. He inserted an aluminum taper gauge under a probe to provide an impedance plane trajectory as a function of aluminum thickness. Calibration data were obtained from panels of known thickness, and these data formed the basis for thickness determinations with panels of unknown thickness. Even though the calibration data were based on specimens of uniform thickness, the taper-gauge approach has been applied in the characterization of localized thinning caused by corrosion pits. The detection of cracks and foreign material in multilayered structures were also discussed in Hagemaier's publications.

A different application of the phase/thickness relatlionship was discussed by Rowland et al. (29). They describe the remote-field, eddy current effect for the inspection of multilayer, parallel-plate structures. The remote-field technique is normally used for inspection of cylindrical pipes from the inside (30-32). The effect, explained in detail in the referenced articles, is the observed linear variation of phase with pipe-wall thickness when transmitter and receiver coils are separated by about two pipe diameters. Rowland et al. have demonstrated that the same effect is observed in parallel plate structures and can be used to measure plate thickness. They also discussed the uses of unusual eddy current probe configurations for locating corrosion damage and inspecting fastener holes.

In one of the more advanced developments in eddy current technology, Dodd et al. (33-36) used arrays of coils, as many as 16 in one application, to record multifrequency complex impedance data as a function of probe position. These data were used in a least-squares fit algorithm to determine multiple properties such as thickness, conductivity, and flaw size, some of which were related to corrosion damage. In general, application of their procedure to a new test environment requires the following steps: (1) selection of optimum coil dimensions and frequencies to maximize the signal for a property of interest, (2) experimental determination of multifrequency impedance data for known properties, (3) least-squares determination of the coefficients in an expression for a given property written as a polynomial in impedance readings, and (4) application of the array of known coefficients to a least-squares fit of data from an unknown sample to determine the properties of that sample. The method has been successfully applied to the identification of flaws in various structures such as multilayered plates and tubing in the presence of welds and supporting structure.

Flora (37) has used a variation of Dodd's multifrequency, multiparameter technique to detect and image simulated corrosion pits and stress-corrosion cracks through thick sections of material. He used a rather large (3 inches long) electromagnet in place of a transmitter coil to generate eddy currents in the specimen. Signals were measured with a Hall probe or separate pickup coil. The use of a large electromagnet and low operating frequencies resulted in deep penetration of the eddy current field, and enabled detection of flaws at depths greater than would be possible by more conventional ET techniques.

Pulsed ET techniques have also been investigated. Yancey (38), for example, studied the response of simulated cracks and stepped thickness samples to pulsed excitation as a test of a system for the inspection of irradiated fuel rods. Dodd and Deeds (39) also considered the use of pulsed eddy current data in place of multifrequency data in their multiparameter technique. Their idea was to use sampled transient response data as a signature of a given property in much the same way as multifrequency data are now used. There appeared to be some advantage to the pulsed approach in terms of equipment requirements and ability to inspect thin-walled specimens.

Finally, some use has been made of the DC electrical potential drop (DC/PD) method (40) in crack sizing and wall thinning measurements. In the latter case, wall thickness loss, as measured by the DC/PD method, was compared with direct measurements of weight loss to show that the DC/PD method can provide reliable monitoring of thickness loss due to corrosion.

2. Crack Detection

While the principle of eddy current crack detection is the same, the nature of corrosion-related cracks can be quite different from, say, isolated fatigue cracks. Intergranular stress-corrosion cracking (IGSCC), for example, is often characterized by a multitude of multiply branched cracks in the region where damage has occurred. The interaction of an eddy current field with such a region is more complex than the interaction with a single crack of simple geometry. An eddy current scan over a region with IGSCC can produce an impedance plane trajectory that more closely resembles the signal from a region of low conductivity than the signal from a crack. This is more likely if the damaged region is some distance from the probe, as in the detection of IGSCC near the inner wall of a pipe when inspected from the outside. Intergranular corrosion without stress-related cracking can produce a similar signal, and may be indistinguishable from IGSCC by the eddy current method. For this reason, the detection of IGSCC and similar multiply branched cracks is sometimes considered along with the detection of intergranular corrosion as a single class of eddy current detection problems. The detection and characterization of intergranular corrosion and stress-corrosion cracking are reviewed in another section; the detection of more conventional crack-like defects is discussed here.

Some of the techniques described in the preceding section, particularly those of Dodd et al. (33-36), Flora (37), and Hagemaier (26-28), pertain to isolated crack detection as well as to other aspects of corrosion NDE. In fact, almost all discussion of crack detection in the literature is concerned either with simply shaped, isolated cracks (whether corrosion-related or not) or with property changes associated with stress-corrosion cracking. One exception is the work of MacLeod and Brown (41), which was specifically directed at the detection of stress-corrosion cracks in aluminum forgings. Most of their discussion concerned the development of an automated, motor-driven system for wheel hub inspection. Applications to other aspects of aircraft inspection and maintenance were also reviewed.

3. Pit Detection

Both amplitude and phase measurement techniques are used in corrosion pit detection and sizing. With the amplitude method, one assumes that the amplitude of an eddy-current signal is proportional to the depth of a pit. The phase-sensitive technique assumes that remaining wall thickness can be related to the phase of the signal from a pit.

Smith (42) gave a very thorough discussion of the amplitude method and its application to pit sizing in copper and stainless steel tubing. He showed that a good correlation can be established between signal amplitude as a function of pit depth and amplitude as a function of the depth of a drilled hole. He then used drilled holes as simulated pits to study the spatial resolution and sensitivity of his inspection system. To demonstrate the sizing capability of the method, he showed that pit-depth predictions based on drilled-hole calibration data are in good agreement with the depths of actual pits in copper tubing as determined by metallographic examination.

Baron et al. (43) took a different approach to estimate the size of crevice corrosion pits. They started with a theoretical prediction of the signal from a corrosion pit modeled as a rectangular slot. They proposed to use this model as a basis for relating amplitude data as a function of probe position to pit dimensions. Some experimental data for notches were presented, which tended to corroborate the model; but no results were reported on attempts to size actual corrosion pits.

Applications of phase measurements to pit-depth estimation were discussed by Nielsen (44), Bond (24), and Rowland et al. (29). Nielsen used flat-bottomed holes of various depths as calibration standards for pit-depth determination. Although mention was made of confirmation by comparison with data for natural flaws, no data were presented in Nielsen's article; most of his discussion concerned a high-speed probe drive system for heat-exchanger tube inspection. Bond and Rowland et al. were primarily concerned with wall-thickness measurements and only mentioned the possibility of pit sizing.

As was noted before, Dodd et al. (33-36) and Flora (37) used both amplitude and phase information in a multifrequency, least-squares determination of multiple properties. Flora used a three-frequency version of this approach to obtain easily recognizable signals from simulated corrosion pits in a steel plate covered with a nonconducting coating. Results were presented as indicated corrosion depth along a scan line over five simulated pits, and appeared to be in very good agreement with actual flaw depths. He also presented images of flat-bottomed holes and ground areas in a plate as further evidence of the capability of the method.

4. Material Loss

In corrosion monitoring applications, measurement of wall thinning due to loss of material is probably the most common use of eddy-current testing. The linear relationship between phase and wall thickness forms the basis for many such measurements, as in the work of Bond (24) and Rowland et al. (29). In thickness gauging of cylindrical pieces like pipelines, casing, and tubing, the remote-field method (30-32) is often used because it offers certain advantages if the wall thickness is on the order of the skin depth or greater (32).

If the structure to be inspected consists of more than one layer, interpretation of phase-shift data becomes more complicated. In the problem addressed by Hayford and Brown (45), the material of concern was an aircraft structural member to be inspected through an outer layer of aircraft skin. When corrosion occurs on the outside surface of the inner material, corrosion product buildup can cause an increase in the separation of the layers, accompanied by a decrease in the thickness of the inner (second) layer. If, on the other hand, corrosion occurs on the inner surface of the second layer, its thickness decreases; but there is no change in the air gap between the layers. To further complicate matters, the air gap itself may vary from place to place in the absence of corrosion.

Hayford and Brown analyzed the two-frequency eddy-current response of these different situations using a modified form of the computer programs of Dodd et al. (33-36). They concluded that it was possible to distinguish cases of interest by comparing low- and high-frequency phase shifts. Experimental tests were in qualitative agreement with the predictions; but quantitative agreement was lacking, probably because of differences between the experimental geometry and the configurations assumed for the calculations.

All of the above applications were concerned with loss of wall thickness in plates or pipes. Deadmore's (46) study of the volume loss of cylindrical samples exposed to a corrosive environment involved a totally different type of measurement. He placed his samples inside a solenoid and measured the inductance change caused by the change in fill factor as material was lost. In the limited range of specimen diameters of interest, he found the inductance to be a linear function of diameter, which led to a simple relationship between volume loss and inductance change. Comparisons with data from direct measurement of sample diameters showed that corrosion rates deduced from inductance measurements were in good agreement. Deadmore used the same experimental arrangement to study material property changes occurring in the early stages of corrosion; these investigations are discussed in the next subsection.

5. Material Properties

During the early stages of corrosion damage, changes in near-surface properties can occur as a result of intergranular corrosion, formation of corrosion products, or other oxidation and reduction processes. In certain instances, these material-property changes can be observed in an eddy-current test through an accompanying change in the conductivity or permeability in the surface layer exposed to the environment.

For example, in his experiments with cylindrical samples inside a solenoid, Deadmore (46) found that during the initial period of exposure to a corrosive environment, observed inductance variations were indicative of changes in skin depth. In this particular set of experiments, these were attributed to changes in magnetic permeability as the structure of the near-surface region was modified by the corrosion process. When the depth of this form of corrosion damage exceeded the skin depth, such changes were no longer observed; and the rate of change of inductance was determined by material loss.

Karpov et al. (47) also studied material-property changes caused by corrosion that were, in this case, the magnetic permeability of corrosion products of several steels. They found that permeability depended more on the corrosive environment than on the type of steel, and that it did not show much dependence on frequency up to about 100 KHz. In all cases studied by Karpov et al., the relative permeability of corrosion products was less than 5.

Most studies of corrosion-related property changes are concerned with electrical conductivity degradation due to intergranular attack (IGA) or SCC. As noted earlier, sometimes IGA and SCC cannot be distinguished by the eddy-current technique because signals from individual cracks cannot be resolved and both IGA and SCC are observed as a decrease in the effective conductivity of the damaged region. This has led several workers to study localized conductivity variations and their measurement by the eddy-current technique as a means of detecting and measuring IGA or SCC.

In one such investigation, Naumov et al. (48) attempted to correlate the absolute conductivity of an aluminum alloy with the depth of intercrystalline corrosion. They were unable to establish such a correlation because the absolute conductivity seemed to depend on other factors related to variability of the material before corrosion was initiated. On the other hand, they did find a good correlation between depth of corrosion and the change in conductivity caused by corrosion.

The theoretical relationship between depth of IGA and eddy-current response was investigated by Prikhod'ko and Kirillova (49) and Wait and Gardner (50). In both of these calculations, the damaged region was modeled as a layer of material with conductivity and/or permeability that differ from the values in the undamaged material. Prikhod'ko and Kirillova treated the case of a two-layer plate, and analyzed probe impedance as a function of probe dimensions, frequency, liftoff, and the characteristics of the sample. Wait and Gardner examined the case of a hollow cylinder inside a solenoid, and presented numerical results for corrosion damage to both the inside and outside surfaces as a function of frequency. The authors agreed that with proper optimization of the measuring system, the eddy-current technique is capable of determination of the depth of IGA.

Prikhod'ko et al. (51) performed experimental studies of various forms of damage including cavities with and without IGA, and isolated cracks and cavities. They used a high-resolution differential sensor, and were able to resolve individual pulses in the signal as the probe was scanned near the surface of regions with IGA. They suggested that different types of damage can be distinguished by noting the form of the signal produced in a scan of the damaged surface, though in some cases measurements at more than one frequency may be needed. They also presented data on suggested operating frequencies for different depths of IGA.

Photographs and eddy current signals for several examples of IGA and SCC in Inconel tubing were given by Brown (52). He distinguished volumetric IGA where damage is more or less uniform from oriented IGA where intergranular corrosion grows in particular directions, resulting in a crack-like damage that is difficult to distinguish from SCC. Most of Brown's work was directed toward improved detection of volumetric IGA. Through the use of computer models and supporting experiments, he showed that a pancake-type coil, with its axis in the radial direction, is better for IGA detection than a coil with its axis along the tube axis. Brown also noted that attempts to determine the depth of penetration of IGA were not successful when based on either amplitude or phase calibrations with artificial flaws. One might expect that a multifrequency method using both amplitude and phase would fare better in IGA depth determinations. In this regard, Dodd et al. (33) indicated that IGA was included as one of the properties treated in applications to steam-generator tubing, but no details were given.

6. Other Applications

Destructive metallographic determination of the thickness of zirconium oxide corrosion films on irradiated Zircaloy-clad fuel elements is time consuming and expensive because such operations can be performed only in a hot cell. A much simpler measurement involving the use of an eddy-current probe as a proximity sensor was reported by Goddard and Weber (53). They pressed a spring-loaded probe against the nonconducting oxide film and calibrated it to measure the liftoff to the conducting Zircaloy under the film. Measurements agreed with data from metallographic examination to within 4 microns.

In addition to causing damage to a material, corrosion can inhibit the detection of defects caused by other factors such as fatigue. De Graf and De Rijk (54) studied the deleterious effect of corrosion on the probability of detection (POD) of fatigue cracks in aluminum panels using ultrasonic, liquid penetrant, and eddy-current methods. Before corrosion of the panels, the POD was best for penetrant inspection, with eddy current being the second most effective. After corrosion, however, penetrant inspection results were poorer than eddy current, probably because corrosion products inhibited penetration of the liquid. In all cases, the POD was significantly reduced by corrosion, but eddy current detection suffered less than detection by the other methods.

C. Electrochemical Corrosion Monitoring Techniques

All of the NDE techniques in this review can be categorized as corrosion monitoring approaches, since periodic inspection will yield information on the corrosion-attack rate. In this section, however, the term corrosion monitoring is used to refer to measurements relating directly to corrosion rate and only indirectly to flaws produced by corrosion.

For example, some of the techniques described here involve using coupons or probes implanted near the structure of concern or in a similar environment. Data obtained from such test cells are related to the rate of material loss, corrosion current, or some similar quantity pertaining to the corrosion process in the cell rather than to the production of flaws in the structure. Corrosion monitoring data are complementary to corrosion damage data obtained by conventional NDE methods because monitoring data, in the sense use here, covers the rate of structural deterioration, while conventional NDE data pertains to the integrity of the structure at the time of inspection.

The measurement and analysis of corrosion rates are a field in itself. The literature is vast, and the methodology of corrosion science is usually quite different from that of conventional NDE. The following discussion, therefore, is intended only as an overview of corrosion monitoring methods to provide some insight as to the corrosion parameters that can be measured, the difficulties involved, and the potential for further development. Details of the topics outlined here can be found in the references.

1. Electrical Resistance Probe

When the cross-sectional area of an anodic member is decreased as a result of corrosion, its electrical resistance is increased. With objects of a generally cylindrical shape, this increase is quite small and difficult to measure unless large changes occur in the volume. One can, however, choose anodic specimens with large surface area-to-cross section ratios, such as the flat steel shims used by Roberts (55), which lead to much larger resistance changes as corrosion progresses. This approach is the basis of the electrical resistance probe (5,6,55,56), a device designed to measure corrosion activity. Because the device does not directly measure corrosion of the structure of interest, but instead measures corrosion of a specimen forming part of the probe, the probe must be placed in the same environment; and the corroding specimen must be made of the same material as the structure whose corrosion rate is desired. When these conditions are met, the electrical resistance probe offers a reliable and relatively inexpensive means of monitoring corrosion activity.

2. Resistivity and Potential Surveys

In some systems, such as underground piping or steel reinforcement in concrete structures, relatively simple measurements of the resistivity of the embedding medium and/or electrochemical potential maps can be used to assess the susceptibility of the system to corrosion (57). Resistivity of the medium is important because it is a direct measure of the ability of whatever electrolyte may be present to carry the current needed to sustain corrosion (57,58). Potential surveys can identify regions that may be anodic or cathodic by virtue of existing electric fields (5,6,59). In addition, electrochemical potential measurements of various parts of the metal structure itself are often used to locate anodic regions (5,6,57). In the latter case, contact must be made with the part of the structure being inspected; and the potential is measured relative to a standard half-cell, usually a copper-copper sulfate cell.

3. Linear Polarization

Linear polarization (5,6,60,61) refers to a technique that, under favorable circumstances, can yield an indirect measurement of the corrosion current. The technique requires that the current through a cell be measured as a function of the DC voltage applied across the cell. If the voltage-current relationship is linear in the vicinity of the point where the current vanishes, then the corrosion current is given by the Stern-Geary equation

$$i_0 = B_aB_c/[2.303\ R_p(B_a + B_c)]$$

where R_p, the polarization resistance, is the slope of the voltage vs. current curve at zero current, and the parameters B_a and B_c are, respectively, the anodic and cathodic Tafel slopes determined by the polarization characteristics of the two electrodes. In practice, Tafel slopes are often unknown and must be estimated, thus introducing some error in the determination of the corrosion current i_0. Other sources of error are discussed in the literature (60-62).

4. AC Impedance Methods

Like the linear polarization technique, AC impedance techniques (59,60) seek to measure the polarization resistance R_p, which is related to the corrosion current as just noted. The essential difference is that polarization is a DC technique, while the AC method makes use of an alternating applied voltage and the data are analyzed as a function of frequency. The AC technique can provide not only the polarization resistance, but also valuable information on polarization mechanisms at the cathode and anode. Understanding of the mechanisms can be important because the interpretation of AC impedance data is mechanism dependent. The linear polarization technique, on the other hand, simply assumes that the corrosion current is controlled by activation processes in which oxidation and reduction rates are exponentially proportional to the electrode potential. If these rates are not activation-controlled, but are dominated by some other mechanism such as ion concentrations in the electrolyte, then use of the linear polarization method can lead to erroneous results (60,61). Principally, the AC impedance method is preferred by researchers in corrosion science.

The AC impedance data are often interpreted through an analysis of an equivalent circuit model of the corrosion cell. The simplest such model leads to the following expression for the cell impedance (60,61,63):

$$Z = R_s + R_p/(1 + i\omega CR_p)$$

where R_s is the electrolyte resistance, C is the interfacial capacitance, and ω is the angular frequency of the applied voltage. If this simple model holds at all frequencies, then the polarization resistance can be determined by measuring the impedance in the low frequency limit to obtain

$$Z_{low} = R_s + R_p,$$

then measuring Z in the high frequency limit to obtain

$$Z_{high} = R_s,$$

and subtracting to find the polarization resistance

$$R_p = Z_{low} - Z_{high}.$$

Depending on the polarization mechanisms controlling the current, which may be frequency dependent, more complicated models and data interpretation methods may be required (61).

In addition to such fundamental difficulties, experimental problems can occur in obtaining accurate data at low frequencies. Some of these associated with standard laboratory methods are reviewed in the literature (60,61,63). While obstacles to field implementation of the AC impedance technique exist, most believe they are not insurmountable (60).

Several variations of the technique discussed here have been cited in the literature as offering enhanced data-acquisition or interpretation capabilities in certain applications. For the most part, these variations relate to cell or probe design, or the use of auxiliary measuring or data-processing equipment. A few additional techniques do, however, involve either different measurement principles or unusual measurement methods. A brief survey of these other techniques is given here.

Visual methods for monitoring the progress of corrosion are the most widely used in field applications (6,64), though they are probably the least quantitative of available techniques. Modern innovations include the use of small light sources, mirrors, magnifiers, or fiber optics, sometimes in conjunction with photographic or TV recording, in situations where direct visual access is limited (70). Applications of modern optical method such as holography and laser speckle analysis have also been reported (6).

Several reports used hydrogen analyzers (5,6,64,65) to monitor corrosion. The measurement principle is that the reduction of hydrogen at the cathode in many corrosion cells leads to the evolution of hydrogen gas. Thus, if the system has no other sources of hydrogen, then data on the rate of evolution of hydrogen can be interpreted in terms of corrosion rate. While the use of such data to determine absolute corrosion rate may be all but impossible except in the simplest cells, hydrogen content data should suffice in many applications as at least a qualitative indicator of corrosion activity.

In some situations, monitoring the corrosiveness of the environment in a general sense may be easier and more desirable than attempting to monitor corrosion rates in several different systems exposed to the environment. When faced with the many and varied problems associated with corrosion in naval aircraft, Agarwala (66) used a series of simple electrochemical galvanic cells which, when exposed to the environment of concern, provided a measure of the overall corrosiveness of the environment.

Electrochemical potential surveys are routinely used to locate regions where potential gradients indicate the possibility of corrosion in underground systems (57) or large reinforced concrete structures (59). When Strommen and Rodland (67) needed similar data in an underwater environment, they developed a novel electric-field-strength sensor for mapping fields in the presence of submerged pipelines. The probe, carried by a remotely controlled submarine vehicle, provided data that could be interpreted in terms of the adequacy of cathodic protection and the presence of serious coating defects.

An unusual variation of the AC impedance technique was reported by Murphy et al. (68). Instead of using direct measurement of the current to determine the complex impedance as a function of frequency, they used a superconducting quantum interference device (SQUID) to measure the associated magnetic field at points above the ground over a buried gas pipeline. Though the analysis of their data is rather complicated, Murphy et al. were able to demonstrate agreement between their results and impedance measurements made in a more conventional way. In this application, use of an aboveground scan with a SQUID magnetometer has obvious practical advantages over the usual AC impedance method in which electrical contact must be made at several points along the pipe.

Finally, recent work at the University of Manchester (69,70) suggested a novel and very simple technique for monitoring corrosion. Through careful analysis of the spontaneous fluctuations of the potential of a freely corroding electrode, this work showed that the time history of such fluctuations can be related to corrosion current, and thus to the rate of loss of material. This "electrochemical noise" approach is, however, very new and must be considered still under development.

D. Liquid Penetrant

Liquid penetrant testing (PT) method is commonly used for surface inspection to detect cracks or other discontinuities. The penetrant can be either a colored dye or fluorescent that penetrates the defects by capillary action. After a short time, excess penetrant is wiped off the surface, and a developer applied. The developer draws the penetrant out of the cracks and spreads it on the surface indicating a flaw. A crack is indicated by a continuous line, while pits are represented by dots.

Liquid penetrant has generally been applied for the detection of surface-opening cracks. The Turkish Air Force (71) inspects the rims of aircraft for cracks (including SCC) using PT. Another example for detecting SCC in the H-link connected to the landing-gear strut is the application of a fluorescent penetrant.

E. Magnetic Methods

The magnetic leakage field method of flaw detection (72,73) is widely used in inspection of ferromagnetic tubular goods for corrosion-related pitting and other forms of damage. Information on this inspection method and interpretation of the inspection data, however, are usually considered proprietary by organizations involved in pipeline or down-hole, well-logging services, so few detailed discussions about it are available in the open literature.

On the other hand, from informal discussions, unpublished reports, and conference proceedings, some general agreements emerge. For example, the equipment most often used includes an electromagnet for inducing magnetization in the region to be inspected, and one or more sensor coils to measure the rate of change of leakage flux from the magnetized region as the system is propelled along the inside of the pipe. For the inspection of pipes prior to installation, encircling coils are often used to induce magnetization. Variations, such as the use of permanent magnets instead of electromagnets or coils, are occasionally reported (74,75).

Two classes of problems with flux-leakage techniques are unsolved in the inspection of magnetic tubular goods. First, distinguishing signals from corrosion pits from those caused by localized regions of abnormally low magnetization is often difficult. The signals from pits and such magnetic "hard spots" are qualitatively similar, and attempts at quantitative analysis are complicated by uncertainties regarding the magnetic permeability of the pipe and hard spot. One way around this difficulty is to magnetically saturate the material so that the magnetization of the hard spot is approximately the same as that of the host material, thus reducing the magnitude of the anomalous signal. However, this usually requires the application of very strong magnetizing fields, which can be difficult to achieve in practice.

Second is the problem of estimating pit size in terms of through-wall penetration of the flaw. This is usually done by comparing the flaw signal amplitude with data from artificial flaws. A problem with this approach is that corrosion-pit shapes can be very irregular, and flaw shape can affect signal amplitude. Also, uncertainties in the permeability of the host material are directly related to uncertainties in the amplitude and flaw-size relationship. A few have attempted to analyze flux-leakage flaw response in more detail (76-80), but as yet no generally useful sizing relationships have been developed.

The magnetic flux leakage method is finding application in the inspection of ropes and cables made of strands of ferromagnetic material. One approach is to induce magnetization in the piece by means of an encircling coil energized by a DC current. With this technique, the leakage field associated with broken strands is measured using a Hall-effect probe or an auxiliary sensor coil. A complementary technique involves measurement of the AC impedance variations of an encircling coil caused by irregularities in the cross-sectional area of the specimen. Haynes and Underbakke (81) describe practical field tests of instrumentation using both the AC and DC techniques. They conclude that instrumentation capable of a combination of inspection techniques offers the best possibility of detecting both localized flaws and overall loss of cross section caused by generalized corrosion and wear. Detailed information is presented on the practical characteristics of a commercially available device using both the AC and DC techniques.

A totally different form of magnetic testing is described by Pizzi and Walther (82). They address the problem of early detection of high-temperature corrosion of certain superalloys and stainless steel. Their measurement technique is based on the observaion that, during the early stages of corrosion, the elemental composition of a near-surface layer in some such materials may be rich in iron, cobalt, or nickel, giving rise to change in the magnetic susceptibility observed at the surface. The probe, described in more detail elsewhere (83), consists of a small permanent magnet mounted on a rod connected to an extensometer cell. A magnetic susceptibility change produces a change in the force exerted on the magnet by the magnetization induced in the sample, and the change in the force is measured by the displacement of the connecting rod. Pizzi and Walther give several examples of applications to early corrosion detection in turbine blades and high-temperature creep specimens.

F. Radiography and Radiation Gauging

In principle, radiographic NDE methods are capable of detecting and measuring both generalized and localized corrosion damage. With either type, corrosion is measured by analyzing the radiographic image through comparisons with calibration images of specimens of known thickness. If damage is localized, then calibration is not necessary for flaw detection alone because the presence of pitted areas is evidenced as regions where the image intensity differs from that of surrounding regions. If, on the other hand, damage occurs as uniform thinning, then comparison with a calibration image is necessary to determine the extent, if any, of material loss.

In X-ray transmission radiography, image contrast is determined by the attenuation characteristics of the specimen material and variations in the thickness of the irradiated part. Because X-ray attenuation is large in materials with high atomic numbers, such as most engineering metals and alloys, loss of material results in a relatively large increase in the transmitted X-ray flux. The presence of a large corrosion pit is therefore evidenced by a localized region of higher X-ray intensity, which causes the gray-scale level of the image in that region to differ from that of neighboring regions.

Image formation with neutron radiography is somewhat different. Neutron attenuation is determined by the scattering and absorption cross sections of the elemental constituents of the material, and these cross sections vary greatly from one element to another. Of particular importance in corrosion NDE is the fact that hydrogen has a relatively large neutron cross section. Thus, because corrosion products are usually hydroxides, corrosion products often attenuate neutrons more than the base material. The neutron radiographic image is determined by the distribution of corrosion products rather than metal loss, as is the case in an X-ray radiograph.

This fundamental difference between neutron and X-ray radiography is well-illustrated by the work of Rowe et al. (84), who used both methods in the inspection of aluminum-alloy airframe structures for corrosion damage. The neutron experiments were conducted with thermal (slow) neutrons from a nuclear reactor, while X-ray radiography tests made use of conventional X-ray equipment. Realtime imaging systems were employed in both types of tests, and digitized images were subjected to various forms of digital image enhancement (84,85) to improve flaw detectability. Under laboratory conditions, the X-ray method was found capable of detecting metal thickness changes as small as 0.08 mm, and neutron radiography could detect hydroxide layers of the same thickness. However, because the corrosion product thickness in the system studied by Rowe et al. was estimated to be about 3 times the corresponding metal loss, the neutron method is about 3 times more sensitive in terms of metal loss.

Under conditions more closely resembling those of an actual airframe inspection, the presence of an interfering structure was found to result in significant deterioration of flaw images. As might be expected, interfering metal structures had a greater effect on X-ray images, while hydrogenous materials, such as the sealer used in some structures, tended to mask corrosion images obtained by the neutron method. The most serious obstacle, however, to implementation of neutron radiography in airframe inspection is that a portable neutron source of the intensity needed for this application is not presently available. While development of a suitable neutron source is feasible, Rowe et al. concluded that X-ray radiography, which has adequate sensitivity to corrosion damage, is presently the more cost-effective of the two radiographic methods for airframe inspection.

In another application of X-ray radiography, Hill and Galbraith (86) described the conceptual design of a system for inspecting crude-oil flow lines in the Eastern Operating Area at Prudhoe Bay. Their system, which may make use of gamma radiation instead of X-rays, is a computerized, realtime design intended to provide high-speed, 100-percent inspection of up to 500 feet of line per crew day. Analog data from video recordings are digitized, stored, and processed to enhance defect detection and sizing. The data base generated by such inspections can be maintained on a mainframe computer, along with data from other forms of inspection and coupon testing to provide a detailed history of corrosion-related data.

The ability of neutron radiography to image corrosion products (Figure 3-5), particularly in aluminum structures, has motivated several researchers to explore applications to aircraft corrosion, with the work of Rowe et al. (83) being the latest example. Currently the USAF is installing three neutron radiographic facilities at the McClellan AFB in Sacramento, California (87). As was noted earlier, the principal difficulty with neutron radiography is the need for a large thermal neutron flux to form an image in a reasonable exposure time. A high-source strength, in turn, requires shielding to protect personnel from the radiation hazard. If a radioactive source such as Cf-252 is used, shielding must be provided at all times, except perhaps during the actual exposure when personnel can be excluded from the exposure site.

An alternative approach is to use a portable neutron generator, which is a particle accelerator producing neutrons through the deuterium-tritium reaction. The advantage offered by a neutron generator over a radioactive source is that the generator can be turned off, so no shielding is needed during transport and setup; the disadvantage is that neutron yield from commercially available devices is about an order of magnitude lower than desirable for radiography of large structures. Regardless, whether one uses Cf-252 or a neutron generator, the source must be surrounded by a moderating material to slow down the fast neutrons produced by the source to the thermal energies required for imaging. Further discussion of the capabilities and limitations of neutron radiography in corrosion detection is found in Berger (88) and references cited therein. Newacheck (89) provides a brief review of other applications.

One of the earliest examples of neutron radiography applied to aircraft corrosion was reported by John (90). He designed a portable system using a Cf-252 source with images recorded on film. The source was housed in its shield except during exposure when it was moved by means of a remotely driven cable to the imaging position in the moderator capsule. Because no shielding was provided other than that used by the moderator during the exposure, personnel had to be removed from an exclusion area of 42.7 meter radius when the source was transferred to the moderator. With this system a fuel-tank area as large as 0.6 m^2 could be inspected in a single exposure of 2-1/4 hours. Several examples of the detection of corrosion and other defects are given in John's paper.

Garret (91) and Antal (92) were also involved in early studies of neutron radiography applied to aircraft inspection. Garrett used thermal neutrons from a rector to study the various factors influencing image quality. He recommended further research on neutron image converters, which are devices emitting light through interactions with thermal neutrons to provide the link between the neutron flux transmitted by a specimen and an optical or electronic image. Antal, on the other hand, focused on the source problem, and recommended further development of a transportable neutron generator.

The development of neutron generator systems designed specifically for radiography are reported by Dance et al. (93) and Kedem et al. (94). Both systems have the capability of source and imager positioning for radiography of sections of aircraft structures. From the brief description given in Ref. (94), this system seems to make use of near realtime video imaging with post-processing capabilities

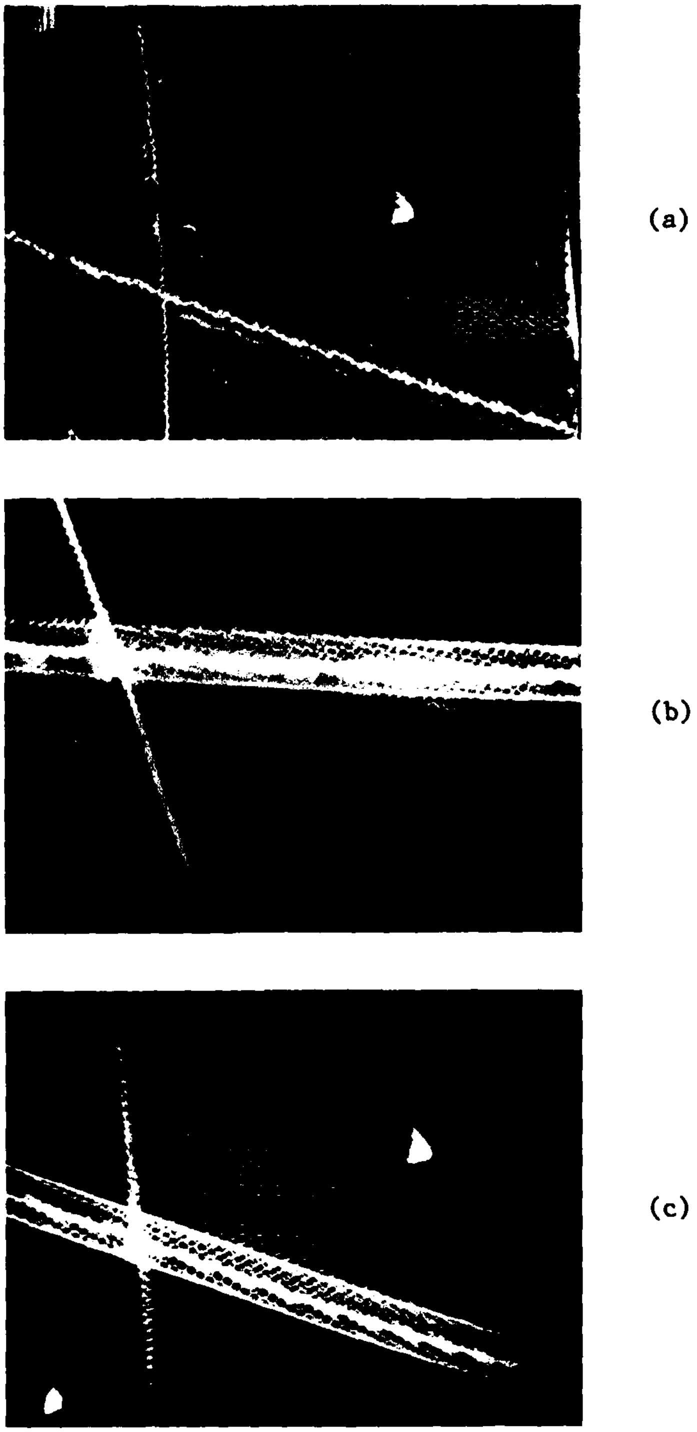


Figure 3-5. Comparison of neutron radiography with X-radiography. Shown in (a) is a photograph of a corroded (dark area) honeycomb structure. The N-ray image in (b) displays a corroded honeycomb structure with the bright N-ray image accurately showing the extent of corrosion. The X-ray image of a corroded honeycomb structure in (c) gives no indication of corrosion. [Ref. (87), reproduced by permission of G. A. Technologies]

for image enhancement. The mobile neutron generator/imager designed by Dance et al. was tested with several combinations of converter screens and films, as well as a low-light television imaging system. Reference (93) contains numerous examples of radiographs of aircraft structures obtained in field testing of the equipment. The system was delivered to the Army and is now installed at the Army Materials Technology Laboratory.

Crosbie et al. (95) addressed a different aspect of neutron source development. In an effort to reduce the cost of a high-intensity Cf-252-based radiographic facility, they designed a stationary system that used a subcritical assembly of enriched U-235 fuel plates in a moderating medium. When a relatively small amount of Cf-252 is introduced into the assembly, neutron multiplications is achieved through interactions with the U-235. The end result is that a much higher neutron flux is available for radiography than would be the case with the same amount of Cf-252 alone.

Instead of conventional through-transmission radiography, backscattered radiation, together with some form of tomographic data processing, can be used to produce images of corrosion damage in structures where access is limited to only one side. Preliminary results from a system using gamma-ray backscatter for the inspection of offshore structures were reported by Bridge et al. (96). They used a collimated Co^{60} source with an array of 16 collimated detectors to build up images of data from volume elements corresponding to the intersection of source and detector collimator solid angles. Their work included a discussion of the probabilities of void detection and false alarm as a function of imaging speed.

Another form of backscatter inspection was reported by Frasca et al. (97). They used backscattered beta radiation for the detection of corrosion products under an epoxy coating on an aluminum substrate. The system makes use of a Sr^{90} - Y^{90} collimated and shielded source with plastic scintillator detectors mounted alongside. Experiments with artificial flaws filled with corrosion products indicated that pit depths of 2 to 20 mils were detectable. Corrosion also could be detected on the back side of an aluminum or magnesium skin with thickness up to 20 mils.

Finally, Peters (98) employed yet another technique to detect the presence of corrodent materials deposited on steam-generator turbine blades. His system used 14-Mev neutrons from a neutron generator, time-of-flight gating instrumentation, and a NaI($T\ell$) scintillator detector and associated gamma-ray spectroscopy equipment. The idea was that 14-Mev neutrons interact with the nuclei of atomic constituents (principally Na, Cl, S, and O) of the corrodent material to produce gamma rays through inelastic scatter. The energies of gamma rays produced in this way are characteristic of the target nuclei and can be used to detect their presence through measurement of the backscattered gamma-ray spectrum. The time-of-flight system was used to eliminate much of the background radiation produced by neutron interactions with other materials by selecting a time interval corresponding to the distance from the source to a turbine blade and back to the detector. The system used by Peters had a source intensity of 10 neutrons/s. and was capable of detection 10^{-3} g/cm^2 Na with an exposure time of 10^4 s.

G. Thermography

Thermography is the study of the temperature pattern of a specimen's surface on application of heat. Thermography can be used to detect flaws because, after inducing a thermal impulse, the flaw affects the transient response of the surface temperature. This technique can also be used to detect loss of thickness by corrosion under paint.

McKnight and Martin (98) found infrared thermography to be a feasible method to evaluate the performance of coatings on steel in the laboratory. The presence of localized corrosion products under an intact film and air- and water-filled blisters was observed as varying gray levels representing temperature variations. The localized corroded area appeared hotter than the surrounding area. Neither corrosion nor blistering was observed on visual inspection. They were able to resolve slightly corroded and blistered areas 1 mm in diameter on smooth substrates. For 50-μm profile sandblasted panels, the resolution was about 1.2 to 1.5 mm. For the coated panels exposed to an elevated humidity and temperature environment, water-filled blisters under a pigmented film and localized corrosion under a clear film could be detected if the diameter of the area were greater than 1 mm. They recommend further research to improve the resolution sufficiently to detect the initial breakdown of the coating/substrate interface on smooth or sandblasted substrates.

Preliminary tests by Birring et al. (11) showed that thermography was able to detect 3-mm deep, 50-mm diameter, flat-bottom holes in 6-mm thick aluminum plate. A flame from a propane torch was used to instantaneously heat the surface opposite the side-drilled hole, and the temperature of the heated surface was then measured by an AGA thermovision camera. The area at the opposite side of the side-drilled hole was found to be hotter than the remaining areas until a steady state was achieved. Experimental results showed that thermography can detect large changes in thickness (≈50 percent) of plates. The method is difficult to apply in detecting small thickness changes due to corrosion.

Birring et al. (11) also used thermography to successfully detect corrosion under paint. For the experiments, a 1500W lamp was used to heat the plate surface for a short time (≈1 second). The surface temperature of the specimen was monitored by a thermovision camera. Photographs clearly showed the hot areas where corrosion was present. Besides the fact that the method successfully located corrosion on several plates, an additional advantage of thermography was its speed, which reduces inspection costs. This method also is easy to apply for aircraft inspections.

Research into the application of thermography to detect corrosion in boiler tubes was funded by the Electric Power Research Institute (EPRI) (100, 101). This work covered three approaches for heating the boiler tubes: rising water, water spray, and steam flash. In the first method, hot water was introduced into the boiler tubing; and the line at which the water came in contact with the dry tubes as it rises was observed. During this procedure, the areas with thinning were expected to get hotter at a faster rate than the surrounding tubing areas. The temperature differential between the two areas can be observed, however, during a short period of time with the infrared camera.

In the water-spray method, the instrument was focused high on the tubes. A water spray was directed into the tubes just below the point of focus, and then the spray and the focus were moved together down the tube surface. The instrument followed the spray so that the focus delayed the spray by 1 second while scanning the tube surface. When using this method, the flaws where wall thinning had occurred showed a hot spot for a short period of time (≈1 second).

The third method, steam-flash, introduced superheated steam into the boiler tubes suddenly; and the temperature of the tube surface was observed with the infrared camera. The thin area showed a hot spot for a short time (≈1 second) until the steady state was reached. This method has some drawbacks for use in a boiler because sudden changes in boiler temperature could produce high stresses, which may be detrimental.

Of the three approaches described, the water-spray method had the maximum potential for field application. The method was able to detect flaws deeper than 50 percent of tube thickness with a minimum diameter of 7.5 mm. Water-spray examination can be done at a speed of 78 square meters per minute.

H. Ultrasonics

Ultrasonics has been used to detect corrosion in a range of applications. In most of the cases, the conventional techniques have been directly applied or applied with minimal modification. These techniques are based on the analysis of high-frequency sound waves reflected/scattered from a discontinuity. The discontinuity could be a crack, pit, or any other anomaly that can be caused by corrosion. The most common analysis of ultrasound includes determining the reflected signal and measuring its amplitude and arrival time. A signal indicates a flaw or discontinuity with signal amplitude relating to flaw size and arrival time establishing flaw location. Advanced ultrasonic techniques include measurement of small changes in velocity (less than 1 percent), analysis of the backscatter from the microstructure, and application of complex wave modes. Enhancement of ultrasonic results is provided by imaging, signal processing, and pattern recognition. Some of the latest advances and future areas include application of electromagnetic acoustic transducers (EMATs) and phased-array technology.

1. Surface Corrosion

Surface corrosion is measured by the ultrasonic pulse-echo method, i.e., an ultrasonic transducer transmits waves towards the specimen; signals are reflected from the front and back surfaces, and the time difference between these two signals is used to measure the remaining thickness (see Figure 3-6). These measurements can be taken with commercially available digital thickness gauges if the specimens have smooth surfaces. The performance of the digital gauges degrades rapidly with an increase in surface roughness (102) (see Figure 3-7) because of ultrasonic scattering (Figure 3-8). With extremely rough surfaces, performance degradation can cause random numbers to be generated by the digital readout. Digital thickness measuring instruments, therefore, are not recommended on rough surfaces. Instead, an analog representation of the signal (see Figure 3-6) can be used to identify the front and back surface reflections for corrosion application.

When only one of the two surfaces is corroded, the transducer is placed on the smooth surface for good contact. When inspecting from the corroded (rough) side, a bubbler with a water column for coupling the ultrasound can be employed. Bubblers have an added advantage of using focused transducers to direct the beam inside the specimen and reduce the scattering noise (102). The focused transducer and bubbler combination can be used to a certain level of roughness; then their performance degrades, and errors in thickness measurement increase. Selection of an ultrasonic technique with increased surface roughness is summarized in Table 3-2.

Detection of hidden surface corrosion can also be performed by ultrasonics. In such a case, scattering caused by corrosion is used as an indicator of corrosion (11). With no corrosion, the ultrasonic reflected signals are well resolved and free of noise.

2. Pitting Corrosion

Inspection of components with pitting corrosion (pits greater than 2-mm diameter) is more difficult than generalized surface corrosion. An immersion transducer with a bubbler, as described earlier, could be used when pitting is only present on the surface opposite the transducer. The ultrasonic beam should be focused within the thickness of the specimen where the bottom of pits is expected. Beam focus reduces scattering from the surface, as the beam is incident in a small area. Another approach for such an application has been reported by Splitt (103). They have used a dual transducer where the ultrasonic beam incident on the bottom of the pit is reflected to the transducer (see Figure 3-9). A scanning system called corroscan for pipes and risers has been developed by Det Noske Veritas (104). It consists of a meter water part operated by a diver, with registration and processing equipment placed over water.

Another system for detection of corrosion in naval boilers is discussed by Peters et al. (105). A very satisfactory semi-automatic conversion probe was developed to evaluate external corrosion in generator tubes above the mud drum of naval boilers. To accomplish this inspection of a steam generator, Furlan et al. (106) developed an internal probe with a helical minimum. Designed to detect cracks, the system can also detect OD corrosion.

Conventional ultrasonic methods cannot be applied when pitting inhibits

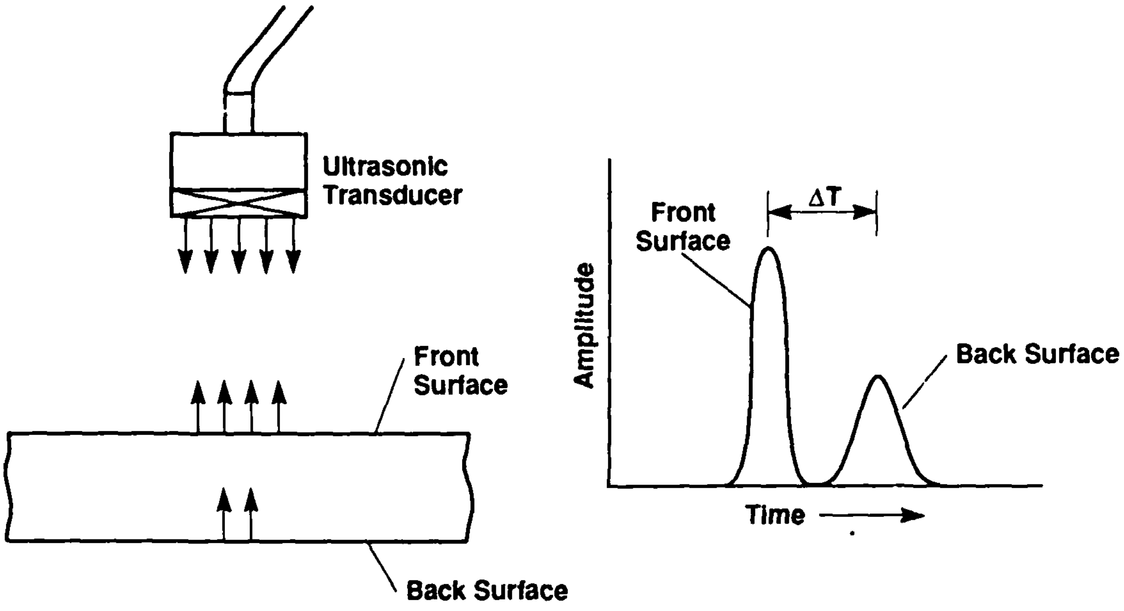


Figure 3-6. Thickness measurement method. The time difference between the ultrasonic signals reflected from the front and back surfaces is used to calculate thickness.

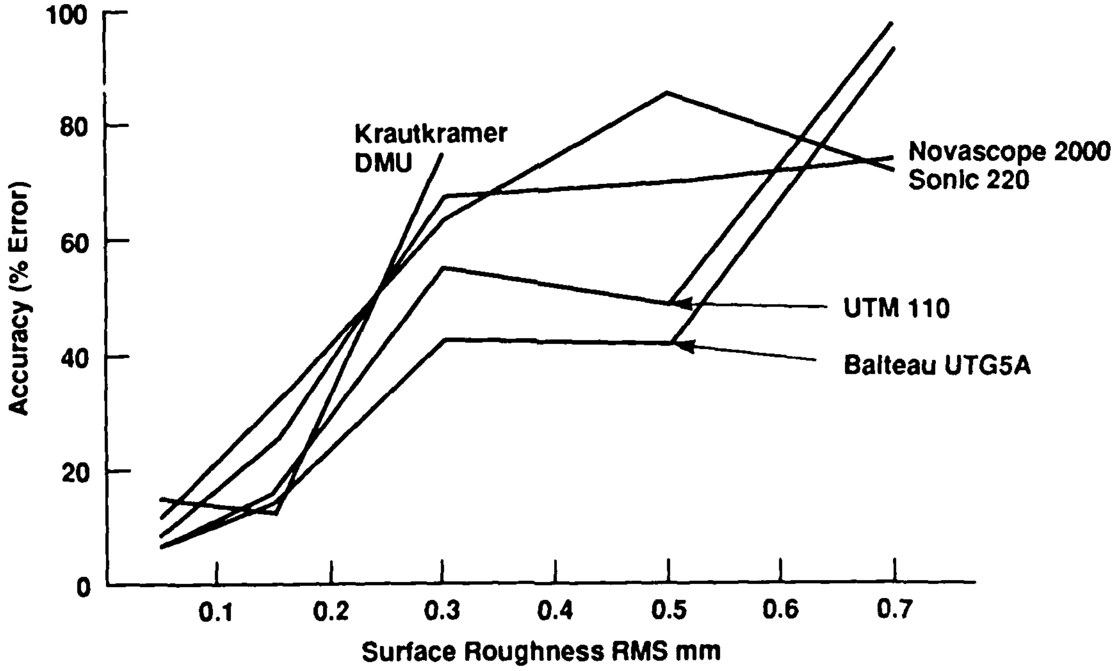
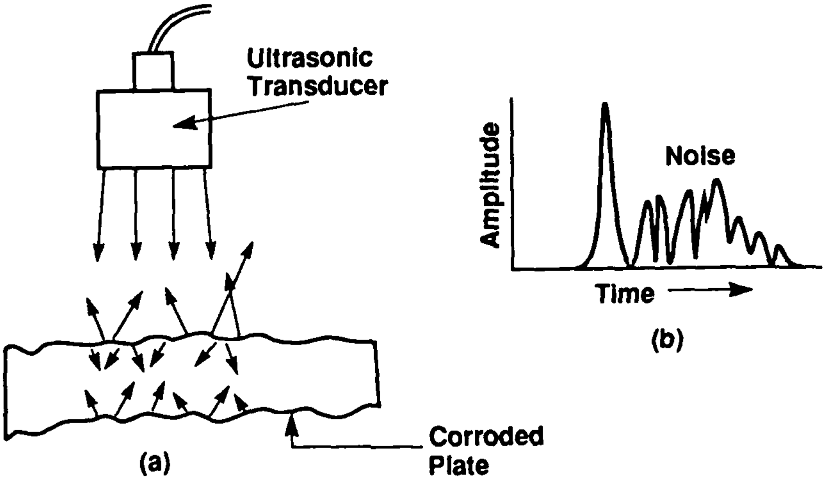


Figure 3-7. Measurement error for commercially available thickness gauges. Thickness measurement error increases with an increase in surface roughness (102).



(a) (b)

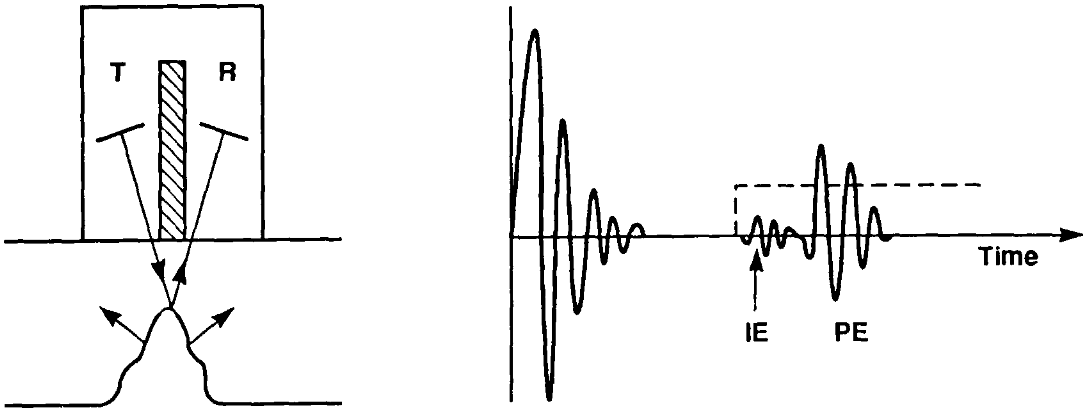
Figure 3-8. Thickness measurement of corroded plate using conventional ultrasonic method. (a) Scattering is caused by corroded surface. (b) Back-surface signal cannot be resolved in scattering-generated noise (102).

Table 3-2

APPLICATION OF ULTRASONIC TECHNIQUES TO MEASURE REMAINING THICKNESS ON SAMPLES AFFECTED BY SURFACE CORROSION

Surface Condition		
Inspection Side (in contact with the transducer)	Opposite Side	Ultrasonic Techniques
Smooth	Smooth	Digital Thickness Gauge
Smooth	Rough	Contact/Bubbler
Smooth	Extremely Rough	Bubbler with Focused Transducer
Rough	Smooth	Bubbler
Rough	Rough	Bubbler
Extremely Rough	Smooth	None of the Above

Note: Rough: pit depths less than 2 mm
Extremely rough: pit depth greater than 2 mm



T = Transmitter
R = Receiver

IE = Incident echo from the front surface
PE = Pit echo

Figure 3-9. Sound reflection from a pitting hole. The time difference between IE and PE gives the remaining thickness [Ref. (103), reproduced by permission of the Scientific Research Institute of Introscopy].

resolution of the front- and back-surface signal. In such cases, a technique developed by Birring can be used (107). In this technique, an ultrasonic focused transducer is aligned over the pit (see Figure 3-10). The surface of the pit acts as a lens collimating the beam in the material. Well resolved front- and back-surface signals are obtained to measure the remaining thickness.

Ultrasonics can also be used to measure pit depths. In such a case, a transducer that focuses the beam over the front surface is employed. The arrival time of the front-surface reflection is used to map the profile of the component.

3. Cracking

Conventional crack-detection techniques are used to detect cracking in the form of IGSCC, SCC, or corrosion fatigue. These techniques generally use refracted shear or longitudinal waves transmitted at an angle of 30 to 60 degrees. The reflected signal from the crack indicates its presence. Although conventional ultrasonic techniques are widely used, their performance is unsatisfactory. Conventional methods are known to have low probabilities of detection, especially for IGSCC in stainless steels. The problem with crack detection is the low amplitude signal from the disoriented cracks and the high noise levels from the stainless-steel grains that lower the signal-to-noise (SNR) ratio.

To address this need for reliable detection, EPRI initiated several programs on NDE technique development and conducted round robin tests (108), which have had a limited success so far. Some of the conclusions from the literature regarding detection of IGSCC in stainless steels are:

(1) Desired frequency range for detection is 1.5 to 2.3 MHz (108,109).

(2) The irregular shape of IGSCC produces a broader angular scattering pattern than fatigue cracks (110).

(3) Dual-element transducers produce a higher SNR than does a single element (109).

(4) Spatial averaging improves SNR (109).

(5) Longitudinal waves work better than shear waves for flaw detection in welds (109).

Another method to detect cracks is to use Lamb waves. Alers (111), Salzburger and Holler (112), and Datta et al. (113) have used electromagnetic acoustic transducers (EMAT) to detect cracks using Lamb waves. The major advantage from EMAT is that inspection can be done in a noncontact mode, allowing high-speed and high-temperature applications. Its low efficiency, however, reduces the probability of detection.

Exfoliation is another form of cracking produced by corrosion. Hagemaier (26) has reported a simple ultrasonic pulse-echo technique to detect corrosion around the fasteners in aircraft structures (see Figure 3-11). An ultrasonic transducer is placed at the periphery of the fastener holes, and the backwall signal is monitored. Exfoliation in the holes obstructs the sound waves and results in a loss of backsurface signal. This technique can be further improved by using focused transducer beams directed more toward the exfoliation damage.

4. Material Degradation

Ultrasonics is one of the most powerful methods for detecting material degradation. Material microstructure can change ultrasonic velocity, attenuation, or backscatter. Cavities and microcracks in the material reduces the ultrasonic velocity and increases attenuation (111,112, 114-117). Impedance mismatch at the grain boundaries in the material increases ultrasonic backscatter. Further information on the microstructure can be obtained by analyzing the ultrasonic parameters with variations in the frequency.

Theoretical work in this area has been done to show the quantitative effects of microstructure on ultrasonic velocity and attenuation. Temple (118) showed a reduction in wave velocities with microcracks. He predicted the reduction to be more for longitudinal waves than for shear waves. Goebbels (115) and Birring (119) have also reported the velocity to be dependent on the frequency. Prikhod'ko (116) has calculated the velocity and attenuation changes in stainless steels with a distributed intergranular attack. Prikhod'ko also provides experimental data to validate his theoretical results.

One of the areas where ultrasonics has been successfully used is in the detection of hydrogen attack. This is a phenomenon whereby hydrogen penetrates the metal, reacts with carbides, and produces methane-filled bubbles in microcracks. The problem has been known to exist in petrochemical and fossil plants. Hydrogen attack can be detected from a reduction in the ultrasonic wave velocities (120,121,122). In fact, the reduction in the longitudinal-wave velocity (v_ℓ) is more than that for shear waves (v_s). This results in a reduction of the ratio v_ℓ/v_s, or t_s/t_ℓ, where t is the transit time. The fact that the ratio can be a useful parameter allows an inspection to be performed without knowing the thickness of the component (121).

The backscatter technique also has a major potential for nondestructive materials characterization of materials. Goebbels (115) pioneered the application of this technique for taking grain-size measurements. The technique has been successfully applied to detect microcracks, inclusions, and segregates. Birring (120) applied the technique to detect hydrogen attack and measured a 21-dB increase caused by hydrogen attack in a 1.8-cm thick pipe sample (see Figure 3-12).

While the backscatter technique shows a major potential, there are some drawbacks. When inspecting materials, backscatter will be produced by microcracks and inclusions; and it may be difficult to differentiate between the two. Nakashiro (123) has conducted spectral analysis of the backscattered signals to resolve such issues.

Ultrasonic materials characterization is a fairly new development in nondestructive testing. This area is expected to become much more significant in solving problems

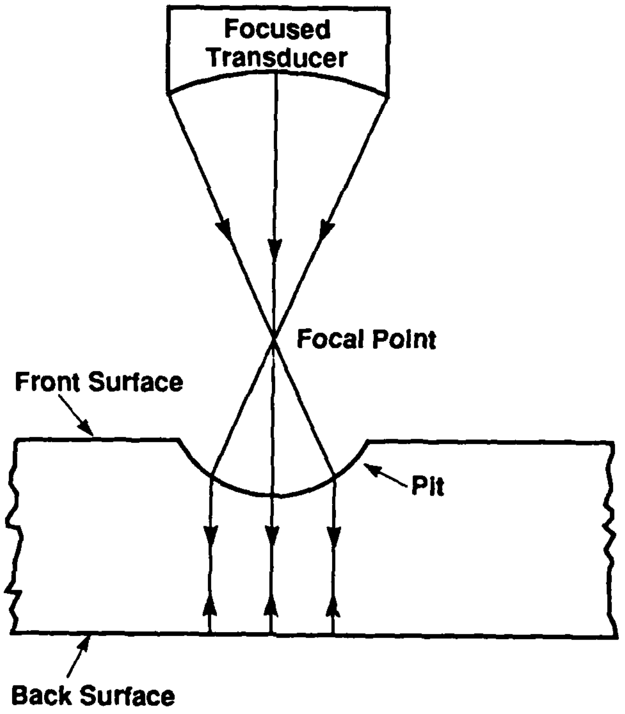
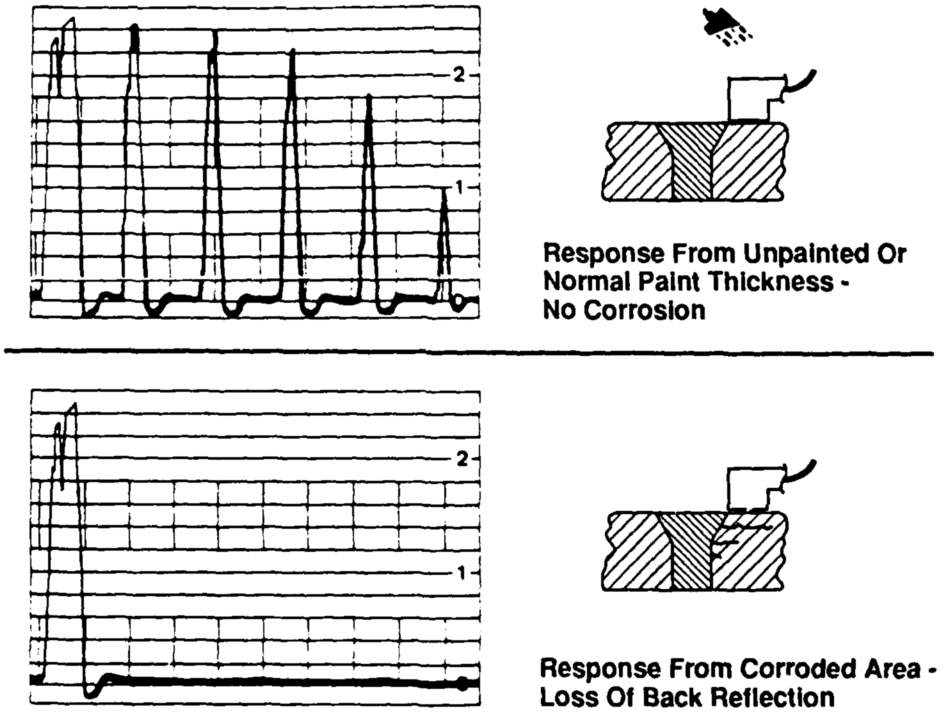


Figure 3-10. Focused transducer concept. The curvature of the pit collimates the diverging beam in the steel plate, resulting in a strong back-surface reflection (107).



Response From Unpainted Or Normal Paint Thickness - No Corrosion

Response From Corroded Area - Loss Of Back Reflection

Figure 3-11. Contact ultrasonic CRT responses at 10 MHZ [Ref. (26), reproduced by permission of *Materials Evaluation*]

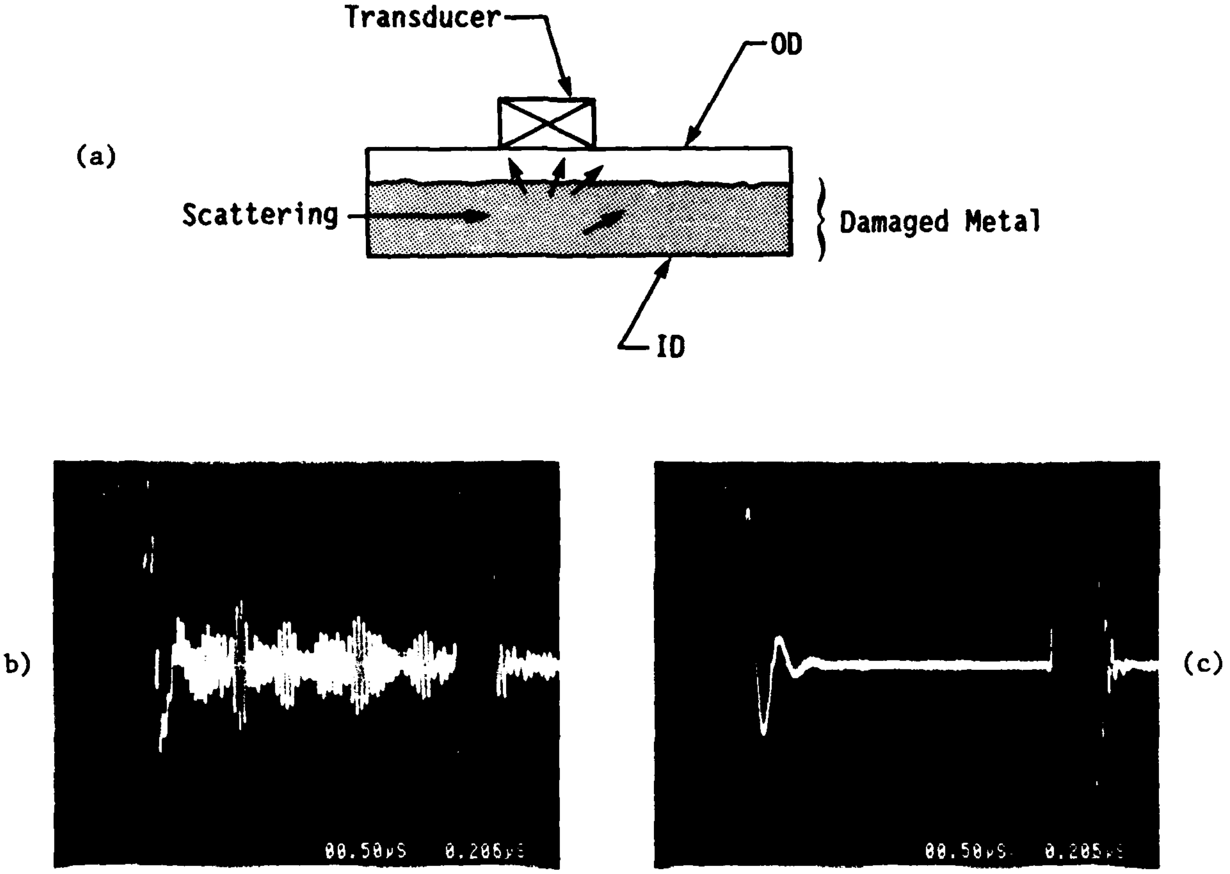


Figure 3-12. Backscattering measurements. (a) Configuration to take back-scattering measurements. (b) Backscattering from sample A-2 attacked by hydrogen. (c) Backscattering for sample A-5 with no damage (120).

related to characterization of microstructure, including degradation of materials caused by corrosion.

I. Visual Inspection

Visual inspection is performed whenever the corroded surfaces are visible by sight or by using borescopes. Many photographic examples of various forms of corrosion damage are found in Ref. 4. Visual inspection is simple, fast, easy to apply, and usually low in cost. Using this method, the inspection is performed on external surfaces of aircraft and also on internal areas which can easily be made accessible by the removal of access panels or equipment. The accessibility of the inspected area can sometimes be extended by making use of mirrors and borescopes. An evaluation of the commercially available borescopes for visual inspection has been done by Light (124). His study identified twelve types of borescopes that are commercially available. Recently, fiber optics has been introduced to inspect through small openings (125). Records of visual tests can be made in photographic cameras and video cameras.

1. Surface Corrosion Inspections

For some inspections, paint can be removed in areas where its adhesion appears to be poor and corrosion seems to be located underneath. The same procedure applies to protective layers and sealants. The inspection aims at identifying the characteristic signs of corrosion such as change in color, bulges, cracks, and corrosion products. The evaluation is based on the outward appearance of damage and the type and composition of corrosion products.

2. Cracks

Large cracks can be detected by careful visual inspection. Hagemaier (126) has given examples of detecting SCC in aluminum landing-gear forgings, aluminum frame forgings, and steel main landing gear.

3. Pits

Visual inspection has been used to detect pitting corrosion in high-strength steel, main-landing-gear truck beams. Corrosion can occur in the four lubrication holes if the lubrication (grease) is not replaced at periodic intervals as specified by the aircraft maintenance manual. The pitting, if undetected, can result in stress corrosion.

Inservice inspection of these pits requires removal of the lubrication fitting and grease from each hole. The internal surface of each hole is checked using a 0-degree (forward-looking), 2.8-mm diameter endoscope, which is a high-quality medical borescope. If corrosion products or pitting are revealed, the hole is checked a second time with a 70- or 90-degree (side-view) endoscope. When pits are detected, the beam is removed from the aircraft; and the pits are removed by oversizing the affected holes.

Borescopes are extensively used to detect pitting corrosion in boiler tubes. Some experience is required with borescopes to get the depth information of pits because borescopes have a single viewing window, which inhibits a 3-D projection.

IV. CORROSION DETECTION NEEDS

Corrosion occurs in a variety of components and structures. The National Bureau of Standards (NBS) report published in 1978 (2) provides an exhaustive list of industrial components affected by corrosion. The report also computes the total losses due to corrosion for each of the industrial sectors and estimates the corrosion costs that could be avoided. While it is not possible to cover each of the areas in detail, this section discusses in a limited way the corrosion needs relevant to the Federal Government and specifically to the Department of Defense (DoD).

The authors of the NBS report obtained data from the three services of DoD, National Aeronautics and Space Administration (NASA), Coast Guard, Government Services Administration (GSA) Legislative Branch, and NBS. Maintenance and repair costs for these agencies came from various sources. In a few cases, corrosion costs were found; generally, however, careful estimates of the fraction of losses due to corrosion were required. The total capital items considered here were estimated to represent $650 billion (97.6 percent of those owned by the Federal Government). They included real capital (buildings and structures, for example) and "personal" capital (aircraft, ships, and ordnance, for example). Corrosion cost information was determined in this study for 83.4 percent of the total capital owned by the Government. Costs for the remainder were then estimated.

Information on aircraft was obtained from the Air Force, Navy, and Coast Guard. The total Federal capital in aircraft was estimated to be $195 billion. The annual corrosion maintenance cost of these was estimated to be $990 million. Lifetime in service was judged to be unaffected by corrosion, but was instead determined by obsolescence. However, a redundant excess of aircraft of 5 to 8 percent results from the influence of corrosion on aircraft downtime.

Detailed maintenance records were available for ships in both the Navy and Coast Guard fleets; however, corrosion-specific actions were not identified. Certain assumptions regarding the proportion of corrosion-related work at the fleet, tender, and shipyard repair levels were made. In summary, the Coast Guard annual corrosion cost at $7.5 million and the Navy cost at $392 million produced a total cost of about $400 million for ships, which is 0.7 percent of the estimated Federal capital in ships of $56 billion.

Real property (buildings, structures) comprises 36 percent of the total Federal capital. The inventory is quite variable, with ten types of buildings and sixteen types of structures. Because it was not possible to examine the corrosion costs in all cases, data from DoD, which owns about 70 percent of the Federal buildings and structures, were used to deduce total losses. The annual DoD corrosion maintenance costs were calculated to be $280 million. Data were also gathered from the Coast Guard, NASA, GSA, and NBS; and total Federal real property corrosion maintenance costs were determined to be $375 million annually.

Combining the expenses for aircraft, ships, and real property leads to an annual maintenance corrosion cost estimate of $1.775 billion on 84 percent of all Federally owned capital. Based on that, a total cost of corrosion maintenance in the Federal sector is estimated to be about $2 billion annually.

To determine the full effect of corrosion in the Federal sector, costs caused by the need for redundant capital and by shortening of equipment lifetimes due to corrosion must also be included. For example, in the case of Federally owned aircraft, there is no estimated change in lifetime, but there is an estimated 6-percent capital redundancy. This causes a yearly capital redundancy cost due to corrosion of $2.4 billion, compared to a yearly maintenance cost of $986 million. In other cases such as automobiles, there is little redundant equipment; but the lifetime is shortened. When the considerations are applied to all the capital equipment of the maintenance expenses, these corrosion costs together amount to about 2 percent of the Federal budget. Of the $8 billion total cost of corrosion to the Federal Government, about 20 percent is estimated to be avoidable.

In the next few subsections, some of the corrosion NDE needs for specific branches of DoD are identified. While an effort was made to identify individual needs, some do overlap. For example, all three branches use helicopters that have the same corrosion problems. Corrosion of reinforcement in buildings is another common problem, and so is the weather. The geographical area has a strong influence on the corrosive nature of the environment. Figure 4-1 shows the corrosion environments in the United States (127). In general, corrosion is more severe in the Northeast, Southeast, and along the West Coast of the United States. The severity of corrosion is less in the Central United States.

Corrosion problems related to DoD occur in a wide range of components, including aircraft, ships, land vehicles, buildings, and munitions. Importance to corrosion problems usually is given when it directly affects the safety, fleet readiness, and depreciation of value. Because of these factors, aircraft have always been given prime importance with reference to corrosion. This was demonstrated when the USAF organized a workshop in "Nondestructive Evaluation of Aircraft Corrosion" in 1983 (28,128-132). Presentations during the conference were made by personnel from the Air Force, Army, and Navy to recommend research and development programs dealing with the detection of corrosion in aircraft.

In 1985, a NATO member conference on the "Management of Corrosion" (72,127,133) was organized by the Advisory Group for Aerospace Research and Development (AGARD). This conference explored the relationship between environmental corrosivity and corrosion problems in military systems. Four management strategies were discussed during the conference: protective coating selection, design of vehicles, determination of manufacturing and maintenance specifications for aircraft, and special problems of marine environments.

Realizing corrosion as a major discipline of interest, the three services started a literature database entitled Corrosion Information and Analysis Center (CORIAC). The CORIAC files can be accessed through the Metals and Ceramics Information Center (MCIC) database. Currently, the CORIAC files center has approximately 1000 records of information.

The following three subsections discusses the problems related to Army, Air Force, and Navy, respectively. Because of the overlap in the problems among the three services, it is recommended that all three subsections be read.

A. Army Corrosion Problems

Corrosion problems for the Army occur in helicopters, aircraft, land vehicles, facilities, and monitors. The problems related to the aircraft are common to the Air Force and Navy and are covered in the subsection on Air Force problems.

Baker (130) from the Army Aviation R&D Command has given several examples of corrosion in helicopters. He addressed areas where a good NDE method could be used for field or department inspections. The major aircraft components affected were main-rotor mast extension, blade, and retention nut; pitch-change link; functional and nonfunctional main landing gears; and aircraft control tubes. He identified the need for an NDE method for thickness measurement of corrosion-protection coatings whose thickness can reduce with service. Another area in need of an NDE method is the control tubes. Water enters the control tubes, causing internal corrosion. The extent of such corrosion can not be determined, and an NDE method is needed here. Unnecessary replacement of tubing is common on older aircraft where the amount of corrosion is unknown.

Shaffer and Lynch (133) have identified corrosion problems experienced in recent years that resulted in avionic failures. The avionic equipment that suffers the most from environmental effects are those mounted external to the airframe such as electronic

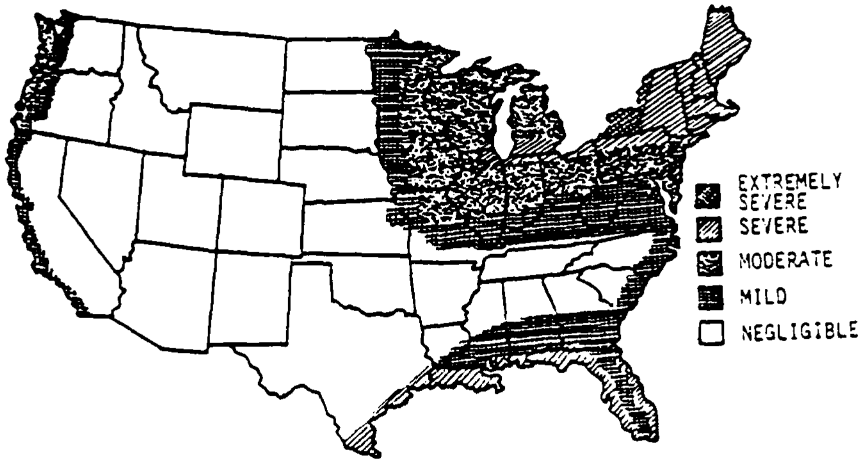


Figure 4-1. "Marine" corrosion environments in the United States [Ref. (127), reproduced by permission of AGARD]

countermeasure pods, photographic pods, antennas, and lights. Because of their exposure to moisture from rainstorms or low-level flights over water, they are targets for corrosion. Two prime examples of susceptibility to this condition are the clamshell doors on helicopters and radomes on fixed-wing aircraft. These doors and radomes leak extensively when the gaskets become worn or damaged.

After moisture or fluids enter an airframe or avionic compartment, it may follow a natural conduit directly into a sophisticated piece of avionic equipment. Hydraulic and fuel lines, control surface linkages, oxygen lines, waveguides, structural stringers, and electrical wire/cable runs act as natural conduits to moisture and fluids.

The avionic systems on aircraft are not isolated "black boxes" sealed against the environment. There are many compartments, switches, lights, relays, terminal boards, circuit-breaker panels, and so forth that make up a complete system. In addition, a sophisticated aircraft may contain miles of wire and coaxial cables and hundreds of electrical connectors. Corrosion attack on the various elements making up the total avionic system can create numerous problems in relation to reliability and maintainability. Table 4-1 summarizes the effects of corrosion on avionic components.

Corrosion of land vehicles is another problem that the Army encounters. The extent of land-vehicle corrosion depends a lot on the geographical location (see Figure 4-1). Corrosion is more severe in humid areas near the seashores and in the snow-belt regions. This problem is addressed by using anticorrosion coatings. The military (127) recognized the need for additional rustproofing to prolong the useful life of its vehicles. The average age of the commercial utility cargo vehicle is now 12 years. Other than the visual inspection, there is no other NDT inspection performed. This is because the cost of an NDT inspection cannot be justified for a $15,000 vehicle compared to $10 million missiles or a $200 million aircraft.

Downs and Gorak of the U.S. Army Tropic Center (134) conducted corrosion performance tests of several military items in the Panama Canal Zone. These included tactical radios, batteries, V-belts, automobile roller bearings, POL products, windshield wiper motors, windshield wiper blades, interval timers, barrier material (plastic bags), and practice rockets (90 mm). One of the objectives of their study was to learn how and when to apply nondestructive test instrumentation and techniques to test items. They were, however, unable to accomplish this objective and recommended a state-of-the-art investigation

Table 4-1

EFFECTS OF CORROSION ON AVIONIC COMPONENTS

[Ref. (133), reproduced by permission of AGARD]

Component	Failure Mode
Antenna Systems	Shorts or changes in circuit constants and structural deterioration
Chassis, Housing, Covers, and Mounting Frames	Contamination, pitting, loss of finish, and structural deterioration
Shock Mounts and Supports	Deterioration and loss of shock effectiveness
Control-Box Mechanical and Electrical-Tuning Linkage and Motor Contacts	Intermittent operation and faulty frequency selection
Water Traps	Structural deterioration
Relay and Switching Systems	Mechanical failure, intermittent operation, signal loss, and shorts
Plugs, Connectors, Jacks, and Receptacles	Shorts, increased resistance, intermittent operation, and reduced system reliability
Multipin Cable Connectors	Shorts, increased resistance, intermittent operation, and water seal deterioration
Power Cables	Disintegration of insulation and wire/ connector deterioration
Display Lamps and Wing Lights	Intermittent operation and mechanical and electrical failures
Waveguides	Loss of integrity against moisture, reduction of efficiency, and structural deterioration
Radar Plumbing Joints	Failure of gaskets, power loss, and pitting
Printed and Microminiature Circuits	Shorts, increased resistance, and component system failures
Batteries	High resistance at terminals, failure of electrical contact points, and structural deterioration of mounting
Bus Bars	Structural and electrical failures
Coaxial Lines	Impedance fluctuations, loss of signal, and structural deterioration of connectors

of NDT techniques for application to tropic application to tropic development and surveillance testing.

Corrosion of munitions can occur during their storage. During storage, corrosion can result in leakage of chemicals. Such leaks were detected in an expendable rocket-powered target missile drone AQM-37A (135). Leak studies performed over a 5-year period on such missiles showing extensive corrosion of shear fittings could potentially create an extremely serious leak problem. The U.S. Army Aberdeen Proving Grounds have prepared a document that describes a range of nondestructive test methods for a range of applications for materials testing (136). These methods are applicable to cannon tubes, cast armor plate, welded joints, projectile fuses, and vehicle track shoes.

B. Air Force Corrosion Problems

A workshop on NDE of aircraft corrosion organized by the USAF in 1983 recognized the corrosion problems that needed immediate attention. The workshop presented an overview of the many types of corrosion problems encountered in practice. Teal (128) discussed NDE needed for corrosion detection. These included detection and determination of the extent of corrosion without disassembly; detection of corrosion in multiple layers, under sealant, and beneath paint; identification of suspected corrosion by scanning large areas; and severity of corrosion inspection in complex geometries (see Figure 4-2). He also presented successfully applied NDE methods for detecting corrosion, including detection of single-layer corrosion by ultrasonics, tubular corrosion by radiography, disbonds in honeycombs by ultrasonics, and moisture in honeycombs by acoustic emission.

Cooke and Meyer (131) identified corrosion problems in the Air Force and performed an assessment of the NDT methods (see Table 4-2). His assessment criterion for NDT methods is rated by their ability to determine, in the following decreasing order of importance, the extent of corrosion in the surface area (highest priority), severity of attack in depth, site corroding activity, rate of attack, and type of corrosion (lowest priority).

Doruk (71) studied the kinds and causes of corrosion observed primarily in Type F-5A aircraft (see Figures 4-3 and 4-4). He reports cases of pitting corrosion in wing and fuselage skins and the drain-cavity section of jet-engine compressor casings (INCONEL W), and crevice corrosion in areas adjacent to nonmetallic components such as fiberglass antennas. Exfoliation corrosion was present in the vertical stabilizer attach angle (combined with stress corrosion) (7075-T6), vertical stabilizer along the edge of the radome (combined with stress corrosion), and inside the air inlet ducts.

Stress corrosion cracking was detected in the wing-to-body joint fitting (7075-T6), main landing-gear uplock support rib (7075-T6), eye bolt of the landing-gear strut, and H-link connected to the landing gear strut (Figure 4-5). Bimetallic corrosion was found in holes in the vertical stabilizer attach angle, holes under the wings through which the jaw bolts were placed, holes in the magnesium alloy covering plates under the fuselage, wing skins adjacent to countersunk fastener heads, and access panels and covers of magnesium in contact with aluminum. Honeycomb assembly damage at the leading-edge sections of wings was detected.

Hardy and Holloway (132) have identified key technology needs for airframe corrosion. The items in the priority of ranking are:

1. Faying Surface/Stackups: Rapid coverage of large areas, improved discrimination between defects and geometry changes, location of the layer containing the defect, and image damage (C-scan) (characterization of the extent) with provision for permanent records.

2a. A/C Wheels: Crack detection with paint on. (The polyurethane coating

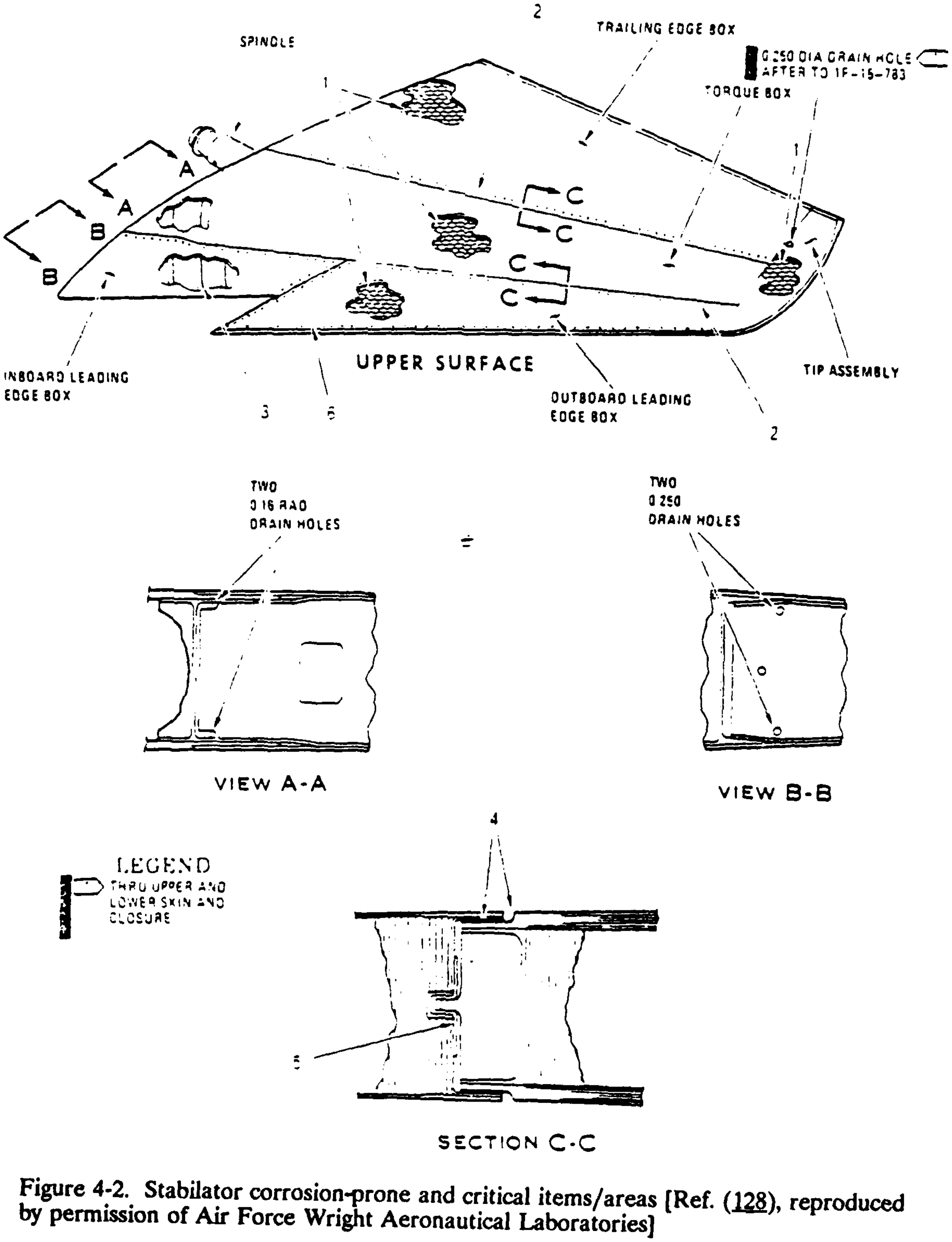


Figure 4-2. Stabilator corrosion-prone and critical items/areas [Ref. (128), reproduced by permission of Air Force Wright Aeronautical Laboratories]

Table 4-2

CORROSION DETECTION ASSESSMENT

[Ref. (131), reproduced by permission of Air Force Wright Aeronautical Laboratories]

Structure Type	Suggested Technique	Corrosion Assessment Characteristics						Ease of Use	Availability		
		Δ (X-Y) Extent	Δ (Z) Severity	Actively Corroding	Rate of Attack	Type of Corrosion	Portable		1-2 Years	3-5 Years	>5 Years
A. Skin & Stringer	Double-wall x-ray	G	A	N/A	N/A	P	G	A	current x-ray	digital x-ray	
	Neutron radiography	G	A	G	N/A	P	P	A to P		✓	
	Probe	P to G	P to G	G	G	N/A	N/A	[illegible]	P	A	
	Fiber optics	G	N/A	P	N/A	P	G	[illegible]	✓		
B. Hollow Tubes	Horseshoe shaped probe	G	P	N/A	N/A	N/A	G	G	✓		
	Fiber optics	G	N/A	P	N/A	P	G	G	✓		
	Neutron radiography (N-ray)			(See	above	under	Part A.)				
	Gamma attenuation	G	G	N/A	N/A	N/A	G	G to A	✓		
C. Honeycomb	X-ray N-ray			(See	above	under	Part A.)				
	Harmonic Bond Tester	P to G	N/A	N/A	N/A	N/A	G	G	current		
	Ultrasonic NDI on Bond Line	P to G	N/A	N/A	N/A	N/A	G	G			
	IR Reflectivity w. chopped Laser	G	A to P	?	?	A	G	A		✓	
	Electrographic Photography			(Limited	application)				✓		
	Ultrasonic Bubbler		(Limited application to bond integrity)						current		
	Acoustic emission	P	P	A	A to P	N/A	A	A			
D. Circuit Boards	Imbedded probe	P to G	P to G	N/A	G	N/A	N/A	G	✓		
	Signal harmonics		(Limited application)						?		
	Thermography		(Used for QA in manufacturing)						✓		

G = good, A = average, P = poor, N/A = not applicable

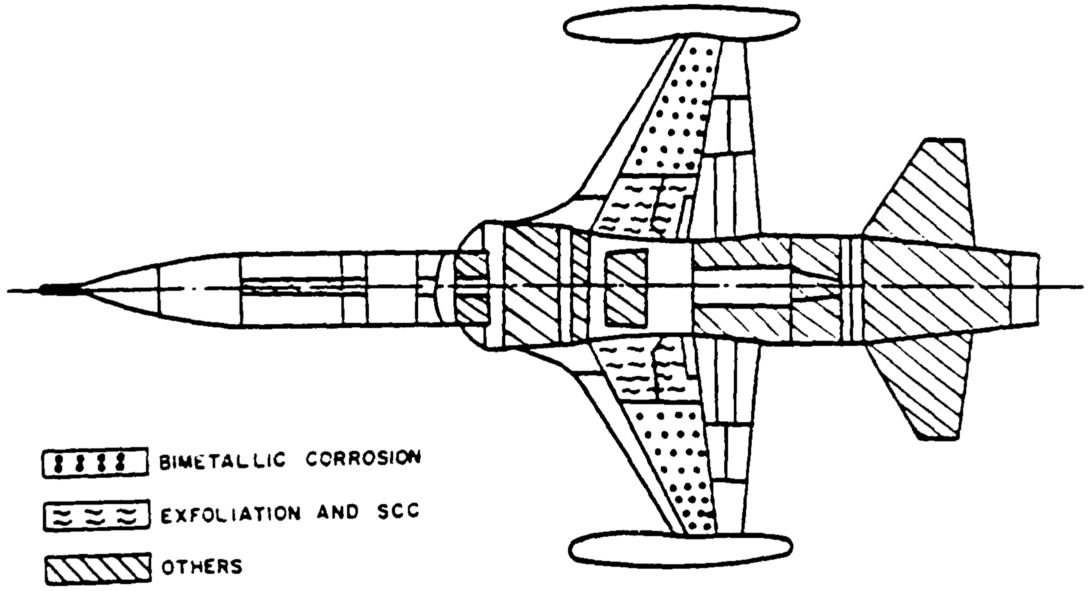


Figure 4-3. Locations of concentration of corrosion on the under section of the aircraft body (F-5A). [Exfoliation and stress-corrosion cracking indicated on the figure are those found on parts incorporating the landing gears (71)].

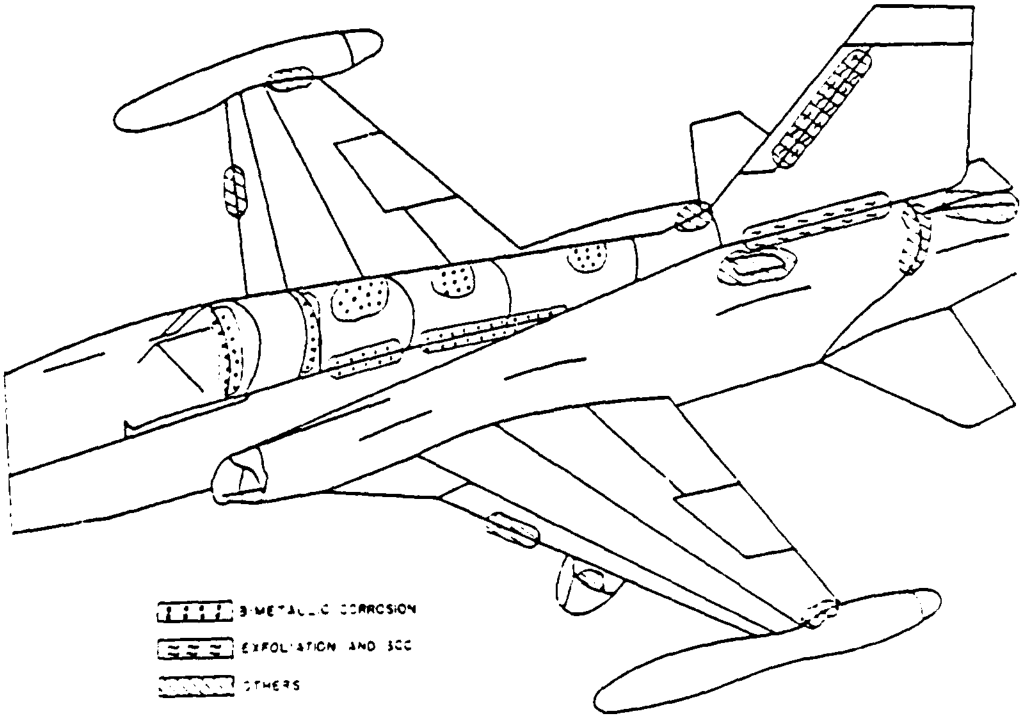


Figure 4-4. Locations of concentration of corrosion on the center and aft section of the aircraft body (F-5A)(71)

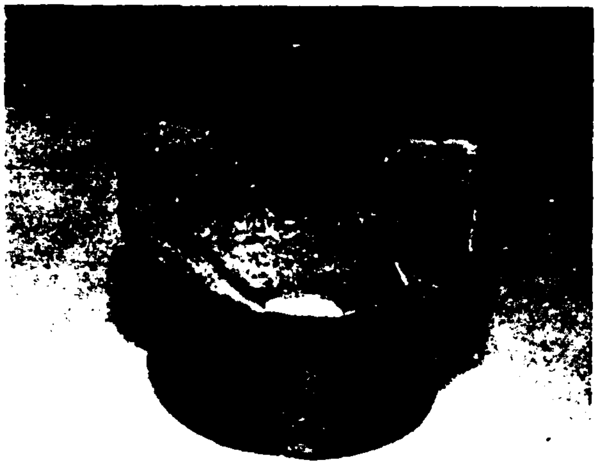


Figure 4-5. Stress-corrosion crack in the H-link connected to the landing-gear strut, which was made visible using a fluorescent penetrant (71).

is being removed solely to facilitate penetrant inspections. Eddy current is specific to bead seat. A similar situation exists for baked resin coatings for low-temperature engine components and for coated landing gears. Rapid, full coverage is needed.) (The inspection technique must easily adapt to the different size rims that must be inspected.)

2b. Honeycomb Panels: Rapid coverage of large areas (e.g., large transports), image damage (C-scan), more realistic accept/reject criteria recorded, detection of face/core corrosion, fluid entrapment (close-out damage leads to water intrusion), and adaptable to complex geometry. (Infrared was suggested. Currently, visual and "con tap" methods are being used.)

3. Corrosion Around Fasteners: Provide rapid coverage of large areas (which areas require a second look?), provide indication of potential corrosion, establish detectability requirements, and provide inspection data for interpretation by structural engineers.

4. Quantification of Corrosion: Depth/area of corrosion (i.e., determine the extent of intergranular corrosion before grinding a component down by "brute force" past minimum acceptable thickness). (Should an electrochemical approach be used or early detection of corrosion?)

5. Measurement of Coating Adequacy: Remaining coating life (in original condition and after a repair), adequacy of application, and applicable to paints/primers/platings/conversion coatings/ion-vapor-deposited (IVD) coatings/anodic coatings/etc. (Are the protective barriers broken?) (For example, the capability of current eddy current techniques is 0.005 mm to measure cadmium plating thickness on high-strength steel components due to magnetic permeability and electrical conductivity variations in plating and substrate. The question is: How can these variations be compensated for when the critical plating thickness required may be 0.008 mm? Signal averaging by a microprocessor may be one possible method to reduce such errors. Specifications for preservation systems and coatings are not applied as rigidly for replacement parts as they are for initial procurement. Uniform buy standards are needed.)

6. Munitions/War Readiness Material: Storage in "sealed" containers and potential application for corrosion

probe. (How can stored munitions be inspected without removal from containers or, minimally, without disassembly?)

7. Corrosion Under Paint: Not a problem. (Filiform and corrosion under a sound coating system are not problems.)

8. Grinding Damage Under Platings (e.g., Chrome Plating): More discrimination for base-metal damage. (For example, sometimes techniques are too sensitive to grinding patterns without there being any damage in the base metal.)

9. Need for Standards, Qualified Inspectors Knowledgeable in Corrosion and Structural Mechanics, and Sufficient Equipment Appropriate for the Depot or ALC Level and for the Field Level.

To develop a suitable NDT technique for corrosion detection, the USAF funded a project (84) in 1984. The objective of this project was to develop nondestructive evaluation techniques for locating and characterizing corrosion hidden in aluminum alloy airframe structures. The candidate NDT techniques were realtime x-ray, realtime neutron radiography, and low-frequency eddy current (84). The Air Force is now in the process of funding another NDT project in new corrosion NDT techniques in fiscal year 1988. Hardy and Holloway (132) have reported key needs in technology for corrosion detection.

C. Navy Corrosion Problems

Navy's corrosion problems are intensified by their close association with seawater. Navy's seagoing vessels such as ships and submarines are directly affected by seawater corrosion. The waterfront facilities also deteriorate by corrosion. The Navy's aircraft are exposed to the salt and moisture and, therefore, corrode more than their counterparts in the Air Force.

Corrosion maintenance expenditures in FY82 and FY83 for different types of aircraft are listed in Table 4-3 (133). This list includes most of the aircraft in the Navy's inventory. A labor rate of $19 per hour, obtained through the VAMOSC (Visibility and Management of Operating and Support Costs) AIR program, was used for these calculations. While admittedly understated, the sum for just these aircraft amounts to over $120 million.

In an effort to control the corrosion problem, the Navy washes all squadron aircraft every 14 days. The Navy also inspects their aircraft for intergranular, galvanic, filiform, pitting, and surface corrosion. Some of the examples of corrosion and the applied inspection methods are as follows (129) (see Figures 4-6 to 4-8).

Holland, from Naval Air Systems Command (129), has cited some of the current NDT test procedures (see Table 4-4). In most cases, components must be removed for aircraft to be examined. Corrosion must also be at a fairly advanced stage before it is detectable. The currently used equipment is manually operated, is subject to operator interpretation, and lacks permanent records. Certain cases also require paint stripping. Because current inspection methods are very slow; the inspections are usually limited to small areas. NDT methods and systems are, therefore, required to overcome the above limitations. The Navy is also interested in pursuing work in methods to detect interface corrosion, corrosion under paint, automatic corrosion mapping, real-time radiography, neutron radiography, and phase-sensitive eddy current for far-side corrosion.

A comprehensive investigation of corrosion-related failures in the Canadian Maritime has been prepared by Hollingshead and Hanlan (137). Their investigations are divided into three categories: machinery, seawater systems, and general. The machinery category includes examples of corrosion problems with desuperheater tubes, gas-turbine engine-fuel manifolds, and waste heat and auxiliary boilers. The seawater category describes the erosion/

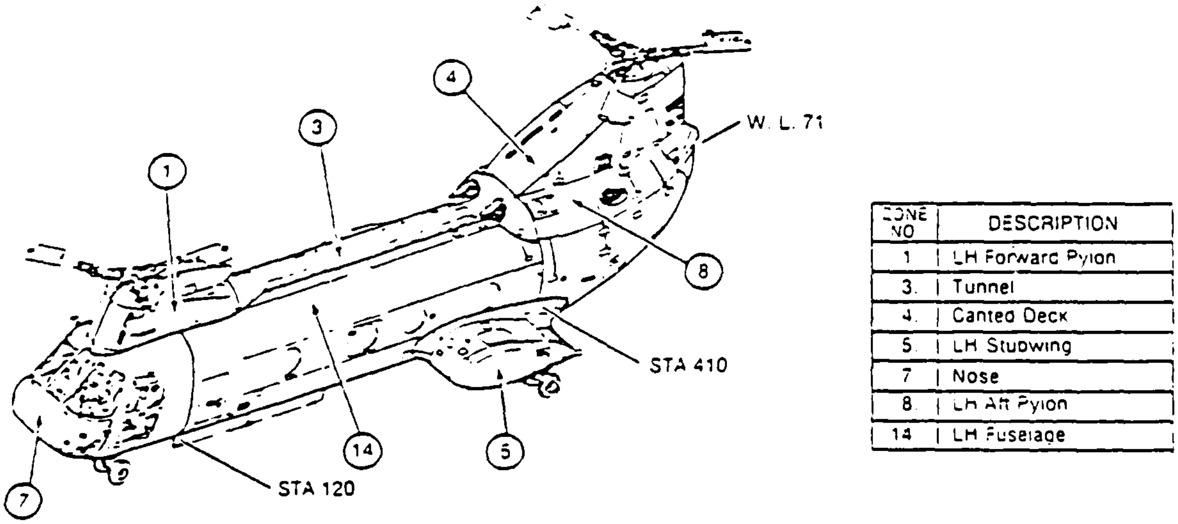
Table 4-3

COST OF NAVAL AIRCRAFT CORROSION*
[Ref. (133), reproduced by permission of AGARD]

Aircraft	FY82	FY83
A-6	18.1	17.8
A-7	16.8	18.6
C-130	2.0	2.6
E-2	4.3	4.8
F/A-18	0.1	0.5
F-4	9.6	7.4
F-14	12.0	14.2
H-2	4.1	4.4
H-3	8.4	9.1
H-46	7.0	7.5
H-53	3.4	4.5
P-3	14.9	19.4
S-3	7.9	8.7
AV-8A	0.5	0.5
TOTALS	109.1	120.0 (10 percent increase)

Labor Rate = $19/DMMH

*Includes only organizational and intermediate levels of maintenance



ZONE NO	DESCRIPTION
1	LH Forward Pylon
3.	Tunnel
4.	Canted Deck
5	LH Stubwing
7	Nose
8	LH Aft Pylon
14	LH Fuselage

Figure 4-6. Identification of inspection zones - H-46 [Ref. (129), reproduced by permission of Air Force Wright Aeronautical Laboratories]

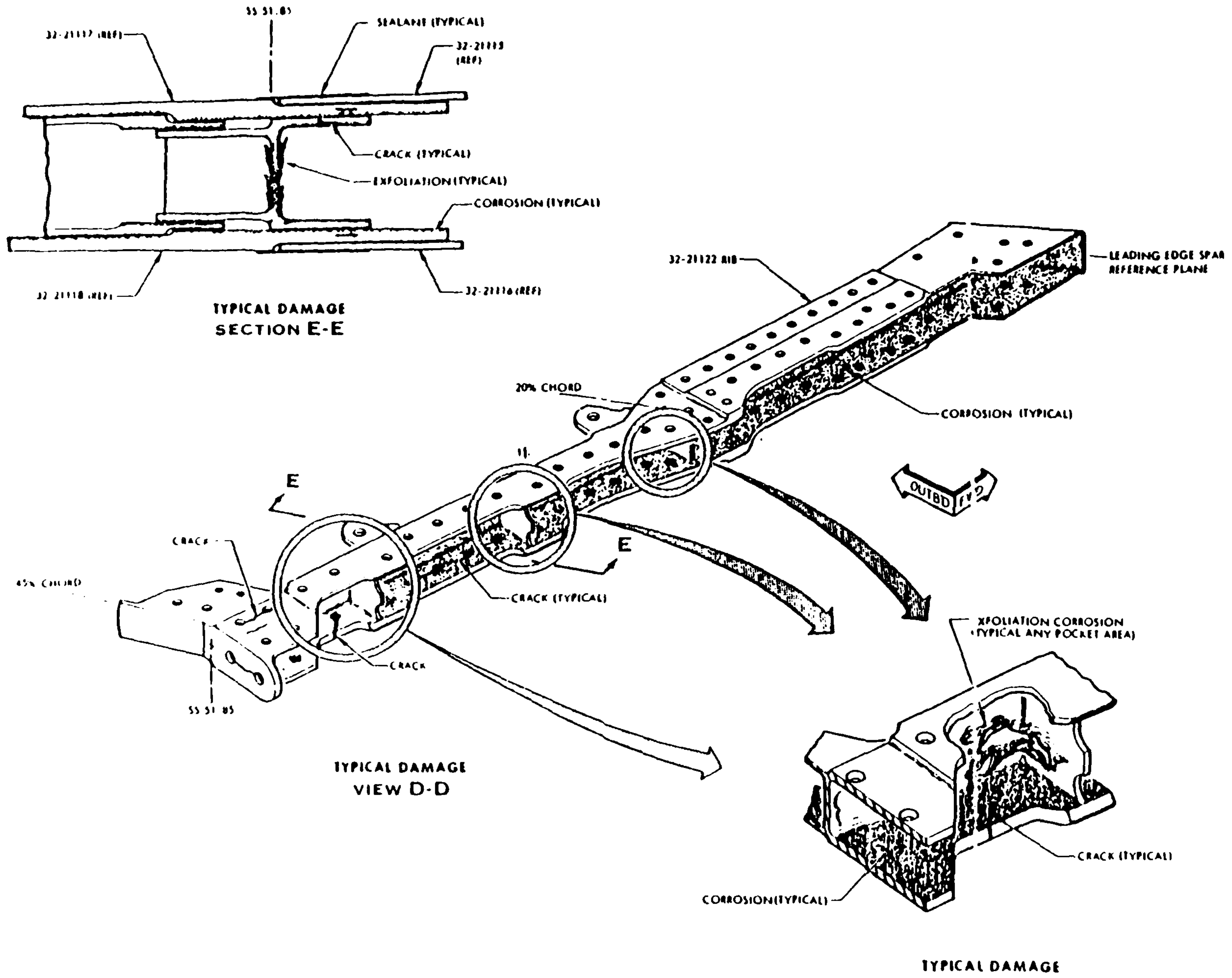


Figure 4-7. Stabilator main-box upper skin and lower skin [Ref. (129), reproduced by permission of Air Force Wright Aeronautical Laboratories]

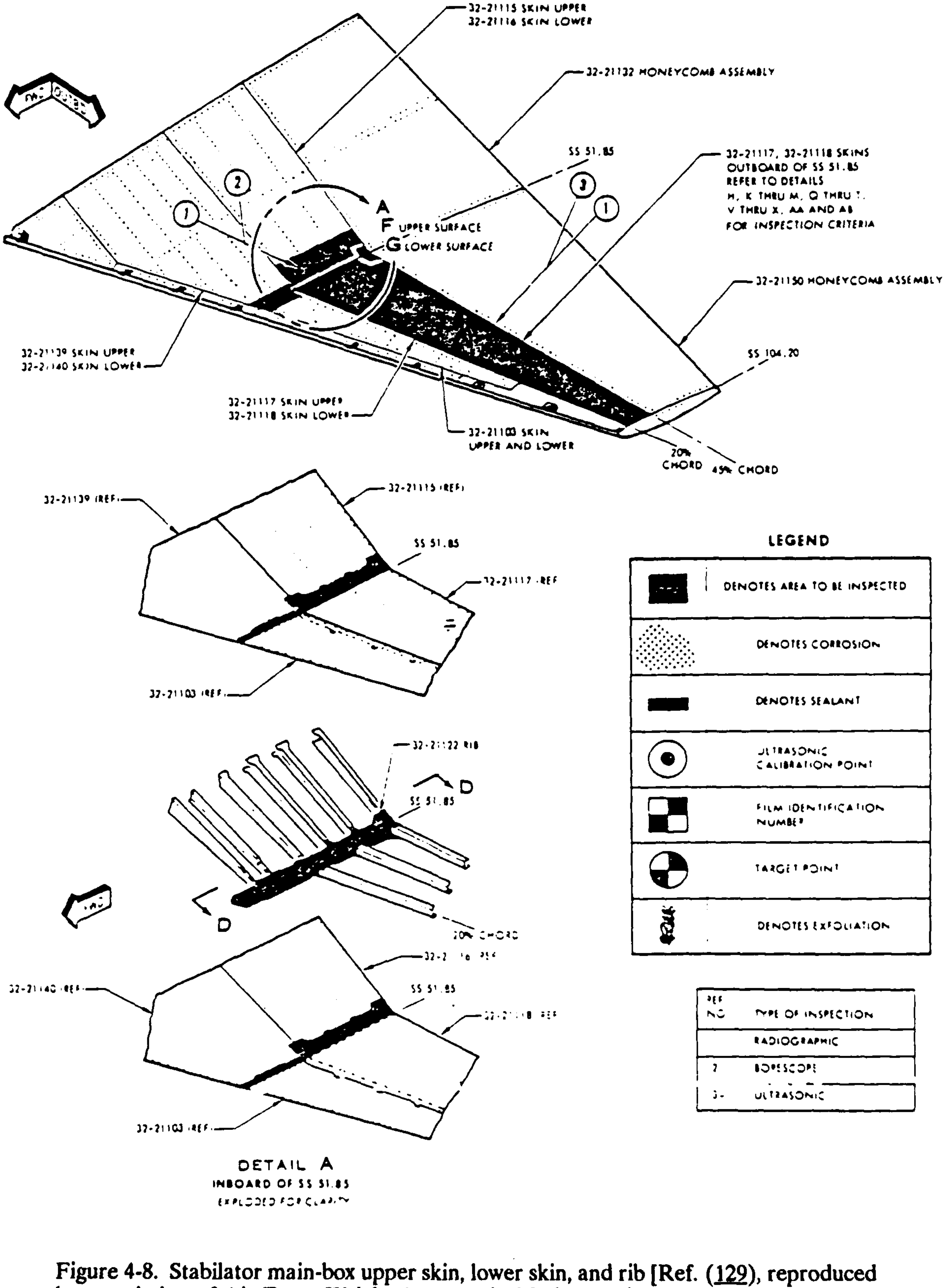


Figure 4-8. Stabilator main-box upper skin, lower skin, and rib [Ref. (129), reproduced by permission of Air Force Wright Aeronautical Laboratories]

Table 4-4

CORROSION EXAMPLES AND NDE METHODS APPLIED)
[Ref. (129), reproduced by permission of Air Force Wright Aeronautical Laboratories]

Component	NDT Method	Type of Corrosion	Corrosion-Proof Areas
1. H-46 Rotor Blade	X-Ray	Galvanic	Spar Back Wall, Interior of Spar, STA 286
2. H-46 Engine Exhaust Device	Ultrasonics	Galvanic	Mounting Flange
3. H-46 Stub Wing	Eddy Current	Multiple Mechanisms	Stub-Wing Fittings
4. H-46 - H-53 Device Shaft	Ultrasonics	Exfoliation	Drive Shaft
5. Landing Gear on Navy Aircraft	Ultrasonics	Exfoliation/ Pitting	Inside of Telescopic Mechanism
6. F-4 Stabilizer Rib	X-Ray	Intergranular	Center Rib
7. H-4 Stabilizer Skin	X-Ray and Ultrasonics	Exfoliation	Skin
8. H-1 and H-2 Main Rotor Blade	Ultrasonics and Harmonic Band Tests	Pitting	Doubles and Span

corrosion of copper/nickel pipes and pump impellers and crevice corrosion of pump shaft. The general category includes corrosion problems with hulls and fasteners.

Hollingshead and Hanlan (137) have emphasized the role of corrosion training in combating corrosion. The more personnel are aware of elementary fundamentals, the more chances there are for preventing corrosion. A summary of the corrosion problems in the Canadian naval fleet follows (137).

Avionic corrosion is also a major problem for the Navy (133). This aspect was covered in Army Problems, Section IVA (see Table 4-1).

Component	Type of Corrosion
1. Solar Saturn Fuel Manifold in Destroyers	Chloride SCC
2. Desuperheater Tubes in Ships	Sensitization Carbide Precipitation
3. Waste Heat and Auxiliary Boilers	Chloride SCC Oxygen Pitting
4. Dealuminification of Aluminum-Si-Bronze Valves and Pittings in Destroyers	Dealuminification
5. Firemain Brazolets (Si-Mg-Bronze)	Erosion/Corrosion
6. Seawater Pump-Shaft Stainless Steels	Crevice Corrosion
7. Pump Impellers	Erosion/Corrosion Cavitation
8. Firemain Pipe Corrosion	Erosion/Corrosion
9. Weld Corrosion in Bilges	Electrochemical Potential
10. Fitting from Helo Hauldown	*Stress-Corrosion Cracking (SCC)*
11. Pelican Hooks	SCC of High-Strength Alloy
12. Aluminum Landing Craft Hulls	Exfoliation Corrosion

Brackett (138) has reported the extensive corrosion in the naval waterfront facilities that were mostly built in the early 1950s. Most of these facilities have reached or exceeded their original design life, resulting in escalating maintenance and repair costs. A study on the factors influencing ultrasonic inspection offshore structures was performed by Birring for the U.S. Coast Guard (139). This study outlines the various factors such as surface roughness, temperature, scale, water salinity, and pressure that effect ultrasonic inspection.

Corrosion of steel reinforcement in concrete structures reduces the strength of civil engineering structures, including waterfront facilities, bridges, and buildings. Damage from corrosion of reinforcement occurs when the corrosion products cause the volume of the structural element to expand, resulting in tensile stresses and cracking. As corrosion progresses, the corrosion products expand, causing more cracking; eventually spalling occurs, exposing the steel reinforcement. Rust stains on the surface of the concrete are usually the first visual indications of corrosion of the reinforcement; however, once these visual signs are evident, corrosion is well advanced, requiring costly repair or replacement of the structure.

Other tests on the concrete structure include surface hardness, rebound hammer, penetration techniques, pullout techniques, magnetic perturbation, and tomography. A description of various NDE methods for inspection of reinforcements is given in Ref. 140. However, none of the techniques has proven to be accurate and reliable for inspection of the reinforcement. X-ray tomography has been applied for such inspection with some success. The inspection system is, however, not practical because of its high initial costs and portability problems, and the need to waterproof the electronics of the system.

D. Conclusions

A number of NDE methods for detection and evaluation of corrosion are presently available. While these methods can be applied for a number of corrosion inspection problems, a large number of areas are still too difficult or too expensive to inspect. Inspections can only be justified if their costs are lower relative to the replacement costs. From the available information, the conclusion can be reached that the present corrosion NDE methods are not sufficient to fulfill the demands of the Army, Air Force, and Navy. This report also states that the corrosion problems of the DoD services overlap and are common in several cases. To address these needs, a cooperative effort should be established to develop and improve NDE methods for corrosion evaluation.

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APPENDIX A

SCOPE AND LANGUAGE OF CORROSION

technical
practices
committee

NACE Glossary of Corrosion Related Terms

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National Association of Corrosion Engineers,
Houston, Texas, 1986)

Corrosion related terms used in NACE publications shall be consistent with the definitions in this glossary. Special usage terms and terms not included in the glossary shall be defined in each publication as appropriate.

History and background

This glossary, published by the National Association of Corrosion Engineers, was prepared by the Reference Publications Committee (RPC) of the Technical Practices Committee (TPC). The TPC approved this glossary for use by NACE members, other organizations, and the public.

The committee presented a first draft of the glossary to the TPC at CORROSION/84 for review and revision. The Group Committee Chairmen then presented the glossary to their membership for general comment. The TPC RPC modified the glossary based on these comments and prepared it for presentation to the TPC at Fall Committee Week/85. The TPC approved publication of the initial glossary on September 18, 1985 after a review of the document by the Group Chairmen who made up the TPC, the membership of the TPC RPC, and the TPC officers.

NACE's Technical Committees are currently working with the TPC RPC to revise the glossary to broaden the base of technology encompassed within the document and expand upon the definitions as necessary. NACE will solicit future review of the glossary in cooperation with other professional, technical, and trade organizations to maximize the degree of consistency.

Please forward your comments and suggestions for improvement of the glossary to the Technical Activities Department at NACE Headquarters (P.O. Box 218340, Houston, Texas 77218) for consideration in the next edition of the NACE Glossary of Corrosion Related Terms.

Acrylic: Resin polymerized from acrylic acid, methacrylic acid, esters of these acids, or acrylonitrile.

Active: The negative direction of electrode potential. Also used to describe a metal that is corroding without significant influence of reaction product.

Aeration Cell (Oxygen Cell): See Differential Aeration Cell.

Alkyd: Resin used in coatings. Reaction products of polyhydric alcohols and polybasic acids.

Alligatoring: Pronounced wide cracking over the entire surface of a coating having the appearance of alligator hide.

Anaerobic: Free of air or uncombined oxygen.

Anion: A negatively charged ion which migrates through the electrolyte toward the anode under the influence of a potential gradient.

Anode: The electrode of an electrolyte cell at which oxidation occurs. (Electrons flow away from the anode in the external circuit. It is usually at the electrode that corrosion occurs and metal ions enter solution.)

Anode Corrosion Efficiency: The ratio of the actual corrosion (weight loss) of an anode to the theoretical corrosion (weight loss) calculated by Faraday's law from the quantity of electricity that has passed.

Anodic Inhibitor: A chemical substance or mixture that prevents or reduces the rate of the anodic or oxidation reaction.

Anodic Polarization: The change of the electrode potential in the noble (positive) direction due to current flow. (See Polarization).

Anodic Protection: Polarization to a more oxidizing potential to achieve a reduced corrosion rate by the promotion of passivity.

Anodizing: Oxide coating formed on a metal surface (generally aluminum) by an electrolytic process.

Anolyte: The electrolyte adjacent to the anode of an electrolytic cell.

Anti-Fouling: Intended to prevent fouling of underwater structures (such as the bottoms of ships).

Auger Spectroscopy: Analytical technique in which the sample surface is irradiated with low energy electrons and the energy spectrum of electrons emitted from the surface is measured.

Austenite: A face-centered cubic crystalline phase of iron-base alloys.

Auxiliary Electrode: An electrode commonly used in polarization studies to pass current to or from a test electrode. It is usually made from a noncorroding material.

Backfill: Material placed in the drilled hole to fill space around anodes, vent pipe, and buried components of a cathodic protection system.

Beach Marks: A term used to describe the characteristic fracture markings produced by fatigue crack propagation. Known also as clamshell, conchoidal, and arrest marks.

Bituminous Coating: Coal tar or asphalt based coating.

Blow Down: (1) Injection of air or water under high pressure through a tube to the anode area for the purpose of purging the annular space and possibly correcting high resistance caused by gas blocking. (2) In conjunction with boilers or cooling towers, the process of discharging a significant portion of the aqueous solution in order to remove accumulated salts, deposits, and other impurities.

Blushing: Whitening and loss of gloss of a usually organic coating caused by moisture; blooming.

Calcareous Coating or Deposit: A layer consisting of a mixture of calcium carbonate and magnesium hydroxide deposited on surfaces being cathodically protected because of the increased pH adjacent to the protected surface.

Case Hardening: Hardening a ferrous alloy so that the outer portion, or case, is made substantially harder than the inner portion, or core. Typical processes are carburizing, cyaniding, carbon-nitriding, nitriding, induction hardening, and flame hardening.

Cathode: The electrode of an electrolytic cell at which reduction is the principal reaction. (Electrons flow toward the cathode in the external circuit.) Typical cathodic processes are cations taking up electrons and being discharged, oxygen being reduced, and the reduction of an element or group of elements from a higher to a lower valence state.

Cathodic Corrosion: Corrosion resulting from a cathodic condition of a structure usually caused by the reaction of an amphoteric metal with the alkaline products of electrolysis.

Cathodic Disbondment: The destruction of adhesion between a coating and its substrate by products of a cathodic reaction.

Cathodic Inhibitor: A chemical substance or mixture that prevents or reduces the rate of the cathodic or reduction reaction.

Cathodic Polarization: The change of the electrode potential in the active (negative) direction caused by current flow. (See Polarization.)

Cathodic Protection: Reduction of corrosion rate by shifting the corrosion potential of the electrode toward a less oxidizing potential by applying an external electromotive force.

Catholyte: The electrolyte adjacent to the cathode of an electrolytic cell.

Cation: A positively charged ion which migrates through the electrolyte toward the cathode under the influence of a potential gradient.

Caustic Embrittlement: An obsolete historical term denoting stress corrosion cracking of steel exposed to alkaline solutions.

Cavitation: The formation and rapid collapse within a liquid of cavities or bubbles that contain vapor or gas or both.

Cavitation Damage: Damage of a material associated with collapse of cavities in the liquid at a solid/liquid interface under conditions of severe turbulent flow.

Cell: Electrochemical system consisting of an anode and a cathode immersed in an electrolyte. The anode and cathode may be separate metals or dissimilar areas on the same metal. The cell includes the external circuit which permits the flow of electrons from the anode toward the cathode. (See Electrochemical Cell.)

Chalking: The development of loose removable powder at the surface of an organic coating usually caused by weathering.

Checking: The development of slight breaks in a coating which do not penetrate to the underlying surface.

Chemical Conversion Coating: A protective or decorative coating produced in situ by chemical reaction of a metal with a chosen environment.

Chevron Pattern: A V-shaped pattern on a fatigue or brittle fracture surface. The pattern can also be one of straight radial lines on cylindrical specimens.

Concentration Cell: An electrolytic cell, the electromotive force of which is caused by a difference in concentration of some component in the electrolyte. (This difference leads to the formation of discrete cathode and anode regions.)

Concentration Polarization: That portion of the polarization of a cell produced by concentration changes resulting from passage of current through the electrolyte.

Contact Corrosion: A term mostly used in Europe to describe galvanic corrosion between dissimilar metals.

Continuity Bond: A metallic connection that provides electrical continuity between metal structures.

Corrosion: The deterioration of a material, usually a metal, by reaction with its environment.

Corrosion Fatigue: Fatigue type cracking of metal caused by repeated or fluctuating stresses in a corrosive environment characterized by shorter life than would be encountered as a result of either the repeated or fluctuating stress alone or the corrosive environment alone.

Corrosion Inhibitor: See Inhibitor.

Corrosion Potential (E_{corr}): The potential of a corroding surface in an electrolyte, relative to a reference electrode. Also called rest potential, open circuit potential, freely corroding potential.

Corrosion Rate: The rate at which corrosion proceeds, expressed as either weight loss or penetration per unit time.

Corrosion Resistance: Ability of a metal to withstand corrosion in a given corrosion system.

Corrosivity: Tendency of an environment to cause corrosion in a given corrosion system.

Counter Electrode: See Auxiliary Electrode.

Couple: See Galvanic Corrosion.

Cracking (of Coating): Breaks in a coating that extend through to the underlying surface.

Crazing: A network of checks or cracks appearing on the surface.

Creep: Time-dependent strain occurring under stress.

Crevice Corrosion: A form of localized corrosion occurring at locations where easy access to the bulk environment is prevented, such as at the mating surfaces of metals or assemblies of metal and nonmetal.

Critical Humidity: The relative humidity above which the atmospheric corrosion rate of some metals increases sharply.

Critical Pitting Potential (E_{cp}, E_p, E_{pp}): The lowest value of oxidizing potential at which pits nucleate and grow. It is dependent on the test method used.

Current Density: The current flowing to or from a unit area of an electrode surface.

Current Efficiency: The ratio of the electrochemical equivalent current density for a specific reaction to the total applied current density.

Dealloying: The selective corrosion of one or more components of a solid solution alloy (also known as parting).

Decomposition Potential (or Voltage): The potential of a metal surface necessary to decompose the electrolyte of a cell or a component thereof.

Deep Groundbed: One or more anodes installed vertically at a nominal depth of 50 feet or more below the earth's surface in a drilled hole for the purpose of supplying cathodic protection for an underground or submerged metallic structure.

Depolarization: The removal of factors resisting the flow of current in a cell.

Deposit Attack: Corrosion occurring under or around a discontinuous deposit on a metallic surface (also called poultice corrosion).

Dezincification: A corrosion phenomenon resulting in the selective removal of zinc from copper-zinc alloys. (This is the most common form of dealloying.)

Dielectric Shield: In a cathodic protection system, an electrically nonconductive material, such as a coating, plastic sheet, or pipe, that is placed between an anode and an adjacent cathode to avoid current wastage and to improve current distribution, usually on the cathode.

Differential Aeration Cell: An electrolytic cell, the electromotive force of which is due to a difference in air (oxygen) concentration at one electrode as compared with that at another electrode of the same material.

Diffusion Limited Current Density: The current density, often referred to as limiting current density, that corresponds to the maximum transfer rate that a particular species can sustain because of the limitation of diffusion.

Disbondment: The destruction of adhesion between a coating and the surface coated.

Double Layer: The interface between an electrode or a suspended particle and an electrolyte created by charge-charge interaction leading to an alignment of oppositely charged ions at the surface of the electrode or particle. The simplest model is represented by a parallel plate condenser.

Drainage: Conduction of electric current from an underground metallic structure by means of a metallic conductor. (1) Forced Drainage: Drainage applied to underground metallic structures by means of an applied electromotive force or sacrificial anode. (2) Natural Drainage: Drainage from an underground structure to a more negative (more anodic) structure, such as the negative bus of a trolley substation.

Drying Oil: An oil capable of conversion from a liquid to a solid by slow reaction with oxygen in the air.

Electrical Isolation: The condition of being electrically separated from other metallic structures or the environment.

Electrochemical Cell: An electrochemical system consisting of an anode and a cathode in metallic contact and immersed in an electrolyte. (The anode and cathode may be different metals or dissimilar areas on the same metal surface.)

Electrochemial Equivalent: The weight of an element or group of elements oxidized or reduced at 100% efficiency by the passage of a unit quantity of electricity. Usually expressed as grams per coulomb.

Electrochemical Potential: The partial derivative of the total electrochemical free energy of a constituent with respect to the number of moles of this constituent where all factors are kept constant. It is analogous to the chemical potential of a constituent except that it includes the electric as well as chemical contributions to the free energy. The potential of an electrode in an electrolyte relative to a reference electrode measured under open circuit conditions.

Electrode: An electronic conductor used to establish electrical contact with an electrolytic part of a circuit.

Electrode Potential: The potential of an electrode in an electrolyte as measured against a reference electrode. (The electrode potential does not include any resistance losses in potential in either the solution or the external circuit. It represents the reversible work to move a unit charge from the electrode surface through the solution to the reference electrode.)

Electrokinetic Potential: This potential, sometimes called zeta potential, is a potential difference in the solution caused by residual, unbalanced charge distribution in the adjoining solution producing a double layer. The electrokinetic potential is different from the electrode potential in that it occurs exclusively in the solution phase, i.e., it represents the reversible work necessary to bring a unit charge from infinity in the solution up to the interface in question but not through the interface.

Electrolysis: The process that produces a chemical change in an electrolyte resulting from the passage of electricity.

Electrolyte: A chemical substance or mixture, usually liquid, containing ions which migrate in an electric field.

Electrolytic Cleaning: A process for removing soil, scale, or corrosion products from a metal surface by subjecting it as an electrode to an electric current in an electrolytic bath.

Electromotive Force Series (Emf Series): A list of elements arranged according to their standard electrode potentials, the sign being positive for elements whose potentials are cathodic to hydrogen and negative for those anodic to hydrogen.

Ellipsometry: An optical analytical technique employing plane polarized light to study thin films.

Embrittlement: Loss of ductility of a material resulting from a chemical or physical change.

Endurance Limit: The maximum stress that a material can withstand for an infinitely large number of fatigue cycles. (See Fatigue Strength.)

Environment: The surroundings or conditions (physical, chemical, mechanical) in which a material exists.

Environmental Cracking: Brittle fracture of a normally ductile material in which the corrosive effect of the environment is a causative factor. Environmental cracking is a general term that includes all of the terms listed below. The definitions of these terms are listed elsewhere in the glossary.

Corrosion Fatigue
High Temperature Hydrogen Attack
Hydrogen Blistering
Hydrogen Embrittlement
Hydrogen Induced Cracking
Liquid Metal Cracking
Stress Corrosion Cracking
Sulfide Stress Cracking

The following terms have been used in the past in connection with environmental cracking but are now obsolete and should not be used:

Caustic Embrittlement
Delayed Fracture
Liquid Metal Embrittlement
Season Cracking
Static Fatigue
Stepwise Cracking
Sulfide Corrosion Cracking
Sulfide Stress Corrosion Cracking

Epoxy: Resin formed by the reaction of bisphenol and epichlorohydrin.

Equilibrium (Reversible) Potential: The potential of an electrode in an electrolytic solution when the forward rate of a given reaction is exactly equal to the reverse rate. The electrode potential with reference to a standard equilibrium, as defined by the Nernst equation.

Erosion: Destruction of materials by the abrasive action of moving fluids, usually accelerated by the presence of solid particles.

Erosion Corrosion: A corrosion reaction accelerated by the relative movement of the corrosive fluid and the metal surface.

Exchange Current: When an electrode reaches dynamic equilibrium in a solution, the rate of anodic dissolution balances the rate of cathodic plating. The rate at which either positive or negative charges are entering or leaving the surface at this point is known as the exchange current.

Exfoliation Corrosion: Localized subsurface corrosion in zones parallel to the surface that result in thin layers of uncorroded metal resembling the pages of a book.

External Circuit: The wires, connectors, measuring devices, current sources, etc. that are used to bring about or measure the desired electrical conditions within the test cell. It is this portion of the cell through which electrons travel.

Fatigue: The phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material.

Fatigue Strength: The stress to which a material can be subjected for a specified number of fatigue cycles.

Ferrite: A body-centered cubic crystalline phase of iron-base alloys.

Filiform Corrosion: Corrosion that occurs under some coatings in the form of randomly distributed threadlike filaments.

Film: A thin, not necessarily visible layer of material.

Foreign Structure: Any metallic structure that is not intended as part of a cathodic protection system of interest.

Fouling: An accumulation of deposits. This term includes accumulation and growth of marine organisms on a submerged metal surface and also includes the accumulation of deposits (usually inorganic) on heat exchanger tubing.

Fractography: Descriptive treatment (photographs) of fracture, especially in metals.

Fracture Mechanics: A quantitative analysis for evaluating structural reliability in terms of applied stress, crack length, and specimen geometry.

Free Machining: The machining characteristics of an alloy to which an ingredient has been introduced to give small broken chips, lower power consumption, better surface finish, and longer tool life.

Fretting Corrosion: Deterioration at the interface of two contacting surfaces under load, accelerated by relative motion between them of sufficient amplitude to produce slip.

Furan: Resin formed from reactions involving furfuryl alcohol alone or in combination with other constituents.

Galvanic Anode: A metal which, because of its relative position in the galvanic series, provides sacrificial protection to metals that are more noble in the series, when coupled in an electrolyte.

Galvanic Corrosion: Corrosion associated with the current resulting from the electrical coupling of dissimilar electrodes in an electrolyte.

Galvanic Couple: A pair of dissimilar conductors, commonly metals, in electrical contact in electrolyte. (See Galvanic Corrosion.)

Galvanic Current: The electric current that flows between metals or conductive nonmetals in a galvanic couple.

Galvanic Series: A list of metals arranged according to their corrosion potentials in a given environment.

Galvanostatic: A constant current technique of applying current to a specimen in an electrolyte. Also called intentiostatic.

General Corrosion: A form of deterioration that is distributed more or less uniformly over a surface.

Graphitic Corrosion: Deterioration of gray cast iron in which the metallic constituents are selectively leached or converted to corrosion products leaving the graphite intact.

Graphitization: A metallurgical term describing the formation of graphite in iron or steel, usually from decomposition of iron carbide at elevated temperatures. Not recommended as a term to describe Graphitic Corrosion.

Ground Bed: A buried item, such as junk steel or graphite rods, that serves as the anode for the cathodic protection of pipelines or other buried structures.

Heat Affected Zone (HAZ): That portion of the base metal that was not melted during brazing, cutting, or welding, but whose microstructure and properties were altered by the heat of these processes.

High Temperature Hydrogen Attack: A loss of strength and ductility of steel by high temperature reaction of absorbed hydrogen with carbides in the steel resulting in decarburization and internal fissuring.

Holiday: Any discontinuity or bare spot in a coated surface.

Hydrogen Blistering: Subsurface voids produced in a metal by hydrogen absorption in (usually) low strength alloys with resulting surface bulges.

Hydrogen Embrittlement (HE): A loss of ductility of a metal resulting from absorption of hydrogen.

Hydrogen Induced Cracking (HIC): A form of hydrogen blistering in which stepwise internal cracks are created that can affect the integrity of the metal.

Hydrogen Overvoltage: Overvoltage associated with the liberation of hydrogen gas.

Hydrogen Stress Cracking: A cracking process that results from the presence of hydrogen in a metal in combination with tensile stress. It occurs most frequently with high strength alloys.

Impingement Attack: Corrosion associated with turbulent flow of liquid and may be accelerated by entrained gas bubbles. (See also Erosion Corrosion.)

Impressed Current: Direct current supplied by a device employing a power source external to the electrode system of a cathodic protection installation.

Inclusion: A nonmetallic phase such as an oxide, sulfide, or silicate particle in a metal.

Inhibitor: A chemical substance or combination of substances which, when present in the environment, prevents or reduces corrosion without significant reaction with the components of the environment.

Inorganic Zinc Rich Paint: Coating containing a zinc powder pigment in an inorganic vehicle.

Intentiostatic: See Galvanostatic.

Intercrystalline Corrosion: See Intergranular Corrosion.

Interdendritic Corrosion: Corrosive attack of cast metals that progresses preferentially along interdendritic paths.

Intergranular Corrosion: Preferential corrosion at or along the grain boundaries of a metal. Also called intercrystalline corrosion.

Intergranular Stress Corrosion Cracking (IGSCC): Stress corrosion cracking in which the cracking occurs along grain boundaries.

Internal Oxidation: The formation of isolated particles of corrosion products beneath the metal surface.

Intumescence: The swelling or bubbling of a coating usually because of heating (term currently used in space and fire protection applications).

Ion: An electrically charged atom or group of atoms.

Iron Rot: Deterioration of wood in contact with iron-based alloys.

K_{ISCC}: Abbreviation for the critical value of the plane strain stress intensity factor that will produce crack propagation by stress corrosion cracking of a given material in a given environment.

Knife-Line Attack: Intergranular corrosion of an alloy, usually stabilized stainless steel, along a line adjoining or in contact with a weld after heating into the sensitization temperature range.

Lamellar Corrosion: See Exfoliation Corrosion.

Langelier Index: A calculated saturation index for calcium carbonate that is useful in predicting scaling behavior of natural water.

Liquid Metal Cracking: Cracking of a metal caused by contact with a liquid metal.

Long-Line Current: Current flowing through the earth between an anodic and a cathodic area that returns along an underground metallic structure.

Luggin Probe: A small tube or capillary filled with electrolyte, terminating close to the metal surface under study, and used to provide an ionically conducting path without diffusion between an electrode under study and a reference electrode.

Martensite: Metastable body-centered phase of iron supersaturated with carbon, produced from austenite by shear transformation during quenching or deformation.

Metal Dusting: The catastrophic deterioration of metals in carbonaceous gases at elevated temperatures.

Metallizing: The coating of a surface with a thin metal layer by spraying, hot dipping, or vacuum deposition.

Mill Scale: The heavy oxide layer formed during hot fabrication or heat treatment of metals.

Mixed Potential: A potential resulting from two or more electrochemical reactions occurring simultaneously on one metal surface.

Nernst Equation: An equation that expresses the exact electromotive force of a cell in terms of the activities of products and reactants of the cell.

Nernst Layer and Nernst Thickness: The diffusion layer or the hypothetical thickness of this layer as given by the theory of Nernst. It is defined by:

$$i_d = n F D \frac{C_o - C}{\delta}$$

where, i_d = the diffusion limited current density, D = the diffusion coefficient, C_o = the concentration at the electrode surface, and δ = the Nernst thickness (0.5 mm in many cases of unstirred aqueous electrolytes).

Noble: The positive direction of electrode potential, thus resembling noble metals such as gold and platinum.

Noble Metal: A metal that occurs commonly in nature in the free state. Also a metal or alloy whose corrosion products are formed with a low negative or a positive free energy change.

Noble Potential: A potential more cathodic (positive) than the standard hydrogen potential.

Normalizing: Heating a ferrous alloy to a suitable temperature above the transformation range (austenizing), holding at temperature for a suitable time, and then cooling in still air to a temperature substantially below the transformation range.

Open-Circuit Potential: The potential of an electrode measured with respect to a reference electrode or another electrode when no current flows to or from it. (See Corrosion Potential.)

Organic Zinc Rich Paint: Coating containing zinc powder pigment and an organic resin.

Overvoltage: The change in potential of an electrode from its equilibrium or steady state value when current is applied.

Oxidation: Loss of electrons by a constituent of a chemical reaction. (Also refers to the corrosion of a metal that is exposed to an oxidizing gas at elevated temperatures.)

Oxygen Concentration Cell: See Differential Aeration Cell.

Parting: See Dealloying.

Passivation: A reduction of the anodic reaction rate of an electrode involved in corrosion.

Passive: A metal corroding under the control of a surface reaction product.

Passive-Active Cell: A cell, the electromotive force of which is caused by the potential difference between a metal in an active state and the same metal in a passive state.

Passivity: The state of being passive.

Patina: The coating, usually green, which forms on the surface of metals such as copper and copper alloys exposed to the atmosphere. Also used to describe the appearance of a weathered surface of any metal.

pH: A measure of hydrogen ion activity defined by

$$pH = \log_{10} \frac{1}{a_{H^+}},$$

where a_{H^+} = hydrogen ion activity = the molar concentration of hydrogen ions multiplied by the mean ion activity coefficient.

Pickle: A solution or process used to loosen or remove corrosion products such as scale or tarnish.

Pits, Pitting: Localized corrosion of a metal surface that is confined to a small area and takes the form of cavities.

Pitting Factor: The ratio of the depth of the deepest pit resulting from corrosion divided by the average penetration as calculated from weight loss.

Polarization: The deviation from the open circuit potential of an electrode resulting from the passage of current.

Polarization Admittance: The reciprocal of polarization resistance (di/dE).

Polarization Curve: A plot of current density versus electrode potential for a specific electrode-electrolyte combination.

Polarization Resistance: The slope (dE/di) at the corrosion potential of a potential (E)-current density (i) curve. Also used to describe the method of measuring corrosion rates using this slope.

Polyester: Resin formed by condensation of polybasic and monobasic acids with polyhydric alcohols.

Potential-pH Diagram (also known as Pourbaix Diagram): A graphic method of representing the regions of thermodynamic stability of species for metal-electrolyte systems.

Potentiodynamic (Potentiokinetic): The technique for varying the potential of an electrode in a continuous manner at a preset rate.

Potentiostat: An instrument for automatically maintaining an electrode at a constant potential or controlled potential with respect to a reference electrode.

Potentiostatic: The technique for maintaining a constant electrode potential.

Poultice Corrosion: See Deposit Attack.

Pourbaix Diagram: See Potential-pH Diagram.

Precipitation Hardening: Hardening caused by the precipitation of a constituent from a supersaturated solid solution.

Primer: The first coat of paint applied to a surface. Formulated to have good bonding and wetting characteristics; may or may not contain inhibitive pigments.

Primary Passive Potential (Passivation Potential): The potential corresponding to the maximum active current density (critical anodic current density) of an electrode that exhibits active-passive corrosion behavior.

Profile: Anchor pattern on a surface produced by abrasive blasting or acid treatment.

Redox Potential: The equilibrium electrode potential for a reversible oxidation-reduction reaction in a given electrolyte.

Reduction: Gain of electrons by a constituent of a chemical reaction.

Reference Electrode: A reversible electrode used for measuring the potentials of other electrodes.

Relative Humidity: The ratio, expressed as a percentage, of the amount of water vapor present in a given volume of air at a given temperature to the amount required to saturate the air at that temperature.

Rest Potential: See Corrosion Potential

Riser: That section of pipeline extending from the ocean floor up the platform. Also the vertical tube in a steam generator convection bank that circulates water and steam upwards.

Rust: Corrosion product consisting primarily of hydrated iron oxide; a term properly applied only to iron and ferrous alloys.

Sacrificial Protection: Reduction of corrosion of a metal in an electrolyte by galvanically coupling it to a more anodic metal; a form of cathodic protection.

Scaling: (1) The formation at high temperatures of thick corrosion product layers on a metal surface. (2) The deposition of water insoluble constituents on a metal surface.

Scanning Electron Microscope (SEM): An electron optical device that images topographical details with maximum contrast and depth of field by the detection, amplification, and display of secondary electrons.

Season Cracking: An obsolete historical term usually applied to stress corrosion cracking of brass.

Sensitizing Heat Treatment: A heat treatment, whether accidental, intentional, or incidental (as during welding), which causes precipitation of constituents at grain boundaries, often causing the alloy to become susceptible to intergranular corrosion or intergranular stress corrosion cracking.

Sigma Phase: An extremely brittle Fe-Cr phase in Fe-Ni-Cr alloys which can form at elevated temperatures.

Slip: A deformation process involving shear motion of a specific set of crystallographic planes.

Slow Strain Rate Technique: An experimental technique for evaluating susceptibility to stress corrosion cracking. It involves pulling the specimen to failure in uniaxial tension at a controlled slow strain rate while the specimen is in the test environment and examining the specimen for evidence of stress corrosion cracking.

Slushing Compound: An obsolete term describing oil or grease coatings used to provide temporary protection against atmospheric corrosion.

Solution Heat Treatment: Heating a metal to a suitable temperature and holding at that temperature long enough for one or more constituents to enter into solid solution, then cooling rapidly enough to retain the constituents in solution.

Spalling: The spontaneous chipping, fragmentation, or separation of a surface or surface coating.

Standard Electrode Potential: The reversible potential for an electrode process when all products and reactions are at unit activity on a scale in which the potential for the standard hydrogen half-cell is zero.

Stray Current: Current flowing through paths other than the intended circuit.

Stray Current Corrosion: Corrosion resulting from direct current flow through paths other than the intended circuit. For example, by any extraneous current in the earth.

Stress Corrosion Cracking (SCC): Cracking of a metal produced by the combined action of corrosion and tensile stress (residual or applied).

Subsurface Corrosion: See Internal Oxidation.

Sulfidation: The reaction of a metal or alloy with a sulfur-containing species to produce a sulfur compound that forms on or beneath the surface of the metal or alloy.

Sulfide Stress Cracking (SSC): Brittle failure by cracking under the combined action of tensile stress and corrosion in the presence of water and hydrogen sulfide.

Tafel Line, Tafel Slope, Tafel Diagram: When an electrode is polarized, it frequently will yield a current/potential relationship over a region that can be approximated by:

$$\eta = \pm B \log \frac{i}{i_0}$$

where η = change in open circuit potential, i = the current density, B and i_0 = constants. The constant (B) is also known as the Tafel slope. If this behavior is observed, a plot on semilogarithmic coordinates is known as the Tafel line and the overall diagram is termed a Tafel diagram.

Tarnish: Surface discoloration of a metal resulting from formation of a thin film of corrosion product.

Thermal Spraying: A group of processes by which finely divided metallic or nonmetallic materials are deposited in a molten or semimolten condition to form a coating. (The coating material may be in the form of powder, ceramic rod, wire, or molten material.)

Thermogalvanic Corrosion: Corrosion resulting from an electrochemical cell caused by a thermal gradient.

Throwing Power: The relationship between the current density at a point on a surface and its distance from the counter electrode. The greater the ratio of the surface resistivity shown by the electrode reaction to the volume resistivity of the electrolyte, the better is the throwing power of the process.

Transpassive: The noble region of potential where an electrode exhibits a higher than passive current density.

Tuberculation: The formation of localized corrosion products scattered over the surface in the form of knoblike mounds called tubercles.

Underfilm Corrosion: Corrosion that occurs under organic films in the form of randomly distributed threadlike filaments or spots. In many cases this is identical to filiform corrosion. (See Filiform Corrosion.)

Voids: A term generally applied to paints to describe holidays, holes, and skips in the film. Also used to describe shrinkage in castings or welds.

Wash Primer: A thin, inhibiting paint, usually chromate pigmented with a polyvinyl butyrate binder.

Weld Decay: Not a preferred term. Intergranular corrosion, usually of stainless steel or certain nickel-base alloys, that occurs as the result of sensitization in the heat affected zone during the welding operation.

Working Electrode: The test or specimen electrode in an electrochemical cell.

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