

## CORROSION DETECTION AND DIAGNOSIS

**E. Bardal**

*Norwegian University of Science and Technology, Norway*

**J. M. Drugli**

*SINTEF Materials Technology, Norway*

**Keywords:** Corrosion monitoring, inspection methods, corrosion failures, detection, failure description, analysis, diagnosis, corrosion forms, further examination.

### Contents

1. Introduction
2. Inspection Organization
3. Inspection, Detection and Monitoring Methods
  - 3.1. Overview
  - 3.2. Visual Inspection
  - 3.3. Radiography
  - 3.4. Ultrasonic Testing
  - 3.5. Eddy Currents
  - 3.6. Magnetic Particle Inspection (MPI)
  - 3.7. Liquid Penetrant
  - 3.8. The Electric Field Signature Method (FSM)
  - 3.9. Acoustic Emission
  - 3.10. Leak Detection
  - 3.11. Corrosion Monitoring
  - 3.12. Pigging Devices
4. Treatment and Analysis of Inspection Results
  - 4.1. Description and Evaluation of Observations and Conditions
  - 4.2. Diagnosis Based on Description of Attack and Service Conditions—Definition of Corrosion Forms
  - 4.3. Characteristic Features and Conditions of Various Corrosion Forms
    - 4.3.1. Uniform (General) Corrosion
    - 4.3.2. Galvanic (Two-metal) Corrosion
    - 4.3.3. Thermogalvanic Corrosion
    - 4.3.4. Crevice and Deposit Corrosion
    - 4.3.5. Pitting Corrosion
    - 4.3.6. Intergranular Corrosion (IC) and Exfoliation Corrosion
    - 4.3.7. Selective Corrosion (SC) (Selective Leaching)
    - 4.3.8. Erosion Corrosion
    - 4.3.9. Cavitation Corrosion
    - 4.3.10. Fretting Corrosion
    - 4.3.11. Stress Corrosion and Hydrogen Assisted Cracking
    - 4.3.12. Corrosion Fatigue
    - 4.3.13. Corrosion under some Special Environmental Conditions
  - 4.4. Further Analysis

5. From Diagnosis to Determination of Solution(s), Recommendations and Preventive Actions  
Glossary  
Bibliography  
Biographical Sketches

## Summary

This article is introduced by a presentation of different conditions and situations in which corrosion attacks are detected. Inspection and detection procedures depend strongly on the expected risk and consequences of failure as well as on various service conditions.

In the first half of the article, inspection organization and programs are briefly dealt with. This is followed by a more detailed review of inspection, detection and monitoring methods, which comprises visual inspection, radiography, ultrasonic testing, eddy current technique, magnetic particle inspection, the use of liquid penetrant, the electric field signature method, acoustic emission, leak detection, corrosion monitoring methods and pigging devices.

The second half of the article comprises the treatment and analysis of inspection results. Included in this are the various steps of description and evaluation of observations and conditions. It is shown how corrosion diagnosis can be based upon the description of attack and the service conditions. An important part of this is the classification of corrosion, where the corrosion forms are characterized by the appearance of the attack, possibly combined with information about the most significant service conditions. Characteristic features and conditions of the various corrosion forms are presented.

Possible need for further analysis by external experts and advanced laboratory equipment is briefly commented upon. Finally, the way from diagnosis to determination of solutions, recommendations and preventive actions is summarized.

## 1. Introduction

Corrosion can cause serious failures, which lead to large economic loss, sometimes combined with environmental pollution, or risk of personnel injuries. The most important steps in order to hinder or reduce the extent of such failures are sufficiently early detection, proper diagnosis and effective prevention measures.

Corrosion attacks are detected under quite different conditions and situations:

- When the expected risk and/or consequences of corrosion failure are great, systematic, periodic inspection, or continuous corrosion monitoring, has to be carried out. For such equipment, for example, for pressurized vessels and pipes, inspection techniques and intervals are often defined by legal code requirements. Code regulations and specifications ensure that proper materials are selected, that a responsible design of the equipment is obtained, and that adequate fabrication

methods are used. When the equipment has been installed on the site, operating procedures, maintenance procedures, inspection and control shall ensure safe performance and operation of the particular items. The main objective of the periodic inspection is to determine whether the equipment is still conforming to the safe design parameters. It has to be established whether corrosion, erosion or abrasion has consumed the “corrosion allowance” or if there are indications of mechanical or corrosion-influenced cracking that can lead to failure. If the quality, periodicity, and extent of inspection or monitoring are carried out efficiently, the probability of detecting attacks before they cause serious failures is very high.

- The inspection schedules for medium consequences of failure are set by proprietor policy in response to real safety and cost factors.
- In other cases, the consequences of corrosion are minor, or significant corrosion may not be expected. When corrosion attacks are developed in such cases, they are usually detected casually, or in inspection routines for other purposes, but sometimes they are not detected before leakage, fracture, malfunction or some other indication of damage occurs.

The inspection program (see Section 2) and methods (Section 3) depend very much on the aforementioned conditions and situations, but also on type of structure, equipment, design, and process. In systematic inspection and monitoring, a range of techniques of varying sophistication are used.

The diagnosis, i.e., the identification of the form of corrosion and the ascertainment of the cause of it (Section 4), is based on the inspection results, the knowledge of materials data and service conditions, and qualified analysis of this information.

The final goal of the detection and diagnosis is to facilitate decisions on appropriate repair/replacement and corrosion prevention measures, which may include improved materials selection or design, change of environment, electrochemical protection, or use of a coating.

## **2. Inspection Organization**

Inspection plays an important role in modern engineering. As indicated, it shall start even before the equipment is fabricated by: checking materials selection, drawings, welding procedures, and capability of producers and suppliers. The fabrication and the acceptance of the finished product would also be inspected and quality controlled.

To be able to perform the inspection in a systematic way, an inspection program has to be worked out. The program shall specify the frequency of inspection, timing, and recording of service and equipment condition. To devise a proper inspection program, knowledge of the process and the material performance is needed. The inspection of the various parts of the system and the type of inspection methods shall be specified. The frequency of inspection shall be evaluated, based both on the risk of failure occurring and on the consequences if failure occurs. It is recommended that critical equipment operating at high pressure and/or at severe corrosive conditions shall be inspected at least once a year.

Experiences from similar equipment, or from previous inspection of the same equipment, will often give valuable information about the most critical sites for corrosion attacks. These sites must then be inspected more frequently than sites where the probability for corrosion damage is less. Critical sites may, for example, be bends, welds, or obstacles in pipe systems with corrosive medium flowing in the system. It is important that the inspection department has access to the past history of the equipment or of similar units, so that a proper inspection may be made.

The individual inspector or inspection department has to be reliable. Quality control or assurance programs shall involve professional licensing for inspection personnel. Inspection personnel, who are educated and trained in inspection techniques, such as radiography, ultrasonics, magnetic particles, and dye penetrants, should be certificated by government or institutions. The inspection and quality control is the foundation of a good preventive maintenance program.

### 3. Inspection, Detection and Monitoring Methods

#### 3.1. Overview

In Table 1, the most important inspection methods and their relative ability to detect corrosion defects are summarized.

- (0)The method is not used, or it is not applicable.
- (1)The method is possible, but not suitable.
- (2)The method is suitable, however, there are other methods that are preferable.
- (3)The method is suitable.

Some monitoring methods are also listed in Table 1. These can give an indication of the corrosion rates.

In the following sections, a brief summary of some inspection and monitoring methods is given. Detailed descriptions can be found in books listed in the bibliography.

Method	Ability to detect crack-like defects		Ability to detect general corrosion and pits	
	Accessible surfaces	Non accessible	Accessible surfaces	Non accessible
<b>General inspection methods</b>				
Visual inspection	1	0	3	0
Radiography	1	1	3	3
Ultrasonic, manual	3	3	0	2
Ultrasonic, automatic	3	3	0	3
Eddy current	2	1 (3*)	0	1 (3*)
Magnetic particle	3	0	0	0
Liquid penetrant	3	0	0	0
Acoustic emission	2	2	0	0

Leak detection	0	1	0	2
Field signature method	3	3	0	3
<b>Corrosion probe monitoring</b>				
Weight loss coupons	—	—	—	—
Electric resistance	—	—	—	—
Linear polarization resistance coupons	—	—	—	—
Electrochemical impedance	—	—	—	—

Table 1. Inspection and Monitoring Methods

### 3.2. Visual Inspection

Visual inspection in the simplest form can be performed without any accomplishing aids when there is physical access to the object. The experienced inspector can often determine the type of corrosion, such as general corrosion, pitting corrosion, crevice corrosion, weld and heat affected zone corrosion, and erosion corrosion from visual inspection. The degree of corrosion can be measured and described and documented by use of sketches or photographs. For exact measurements of local corrosion penetration caused, for example, by pitting corrosion, various types of mechanical or optical measuring instruments can be used.

Material thinning due to general corrosion may be difficult to determine exactly, without use of additional non-destructive inspection methods, such as ultrasonics.

Initial cracks caused by stress corrosion or corrosion fatigue, are often difficult to detect visually. If such defects are likely, then methods to make the cracks visible are needed (magnetic particles, liquid penetrant, eddy current). Mirrors, boroscopes, flexible fiber-optic instruments, or small video cameras can be used together with light sources, to look inside small pipes or narrow spaces in the equipment.

### 3.3. Radiography

Radiography makes use of the penetrating quality of short wave electromagnetic beams, which may be X-rays generated by X-ray equipment or  $\gamma$ -rays from radioactive isotopes. These beams are similar to light, but are not visible. The wavelengths are much shorter and the energy much higher and thus the beams are able to penetrate solid materials, including metals. When the beam passes through a test specimen, some energy is absorbed in the material. The thicker the material, the larger the amount of energy absorbed. Furthermore, different materials attenuate the beam to various degrees. For example, air and corrosion products are much more easily penetrated than solid metals. The principle of radiography is shown in Figure 1. The beam from X-ray equipment or an isotope penetrates a piece of metal, and the amount the beam is attenuated depends on the thickness of the material, and hence the intensity of the transmitted beam varies with position. A photographic film at the back side of the specimen will, after development, be dark behind the thin parts where the transmitted

beam intensity was high, and light behind the thick parts of the specimen where the intensity was low, i.e., pits and thinning of the material will be visible as dark areas on the film. Pit depths and the degree of thinning can be determined to a certain degree by density measurements of the film and use of proper geometrical correction factors. Radiography is commonly used for control of weld quality, because most weld defects can be detected by this method.

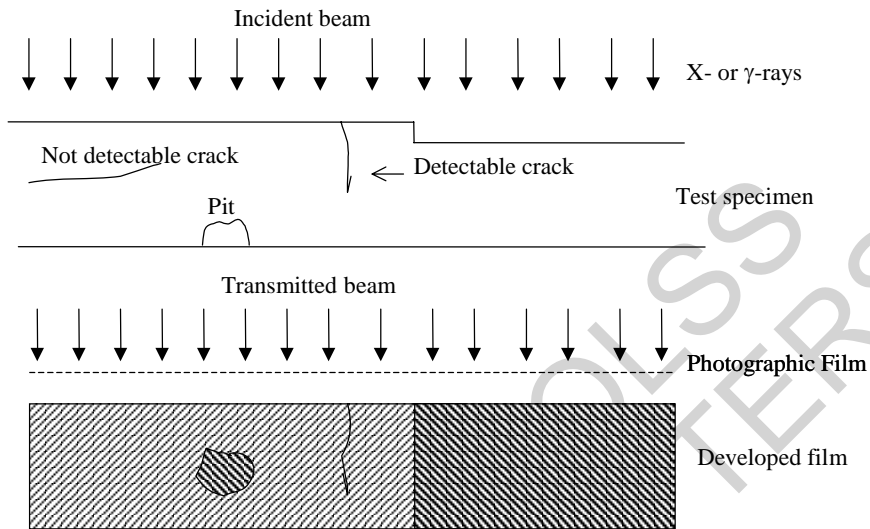


Figure 1. The Principle of Radiography

The minimum variation of the thickness in the direction of beam that can be detected is ~1–2% of the sample thickness, which means that narrow cracks are difficult to detect if they are oriented in directions other than parallel to the beam. Another limitation of radiography is that both sides of the part must be accessible. However, the interior of pipes can be investigated by the so-called double wall technique.

Advantages of radiography in the assessment of corrosion are:

- The radiograph is a permanent record, which, if required, can be evaluated later by more competent personnel than the operator.
- The inside of complex small parts, which are not accessible, can be evaluated.
- The radiograph can give some indication of the nature and degree of attack.

-  
-  
-

TO ACCESS ALL THE 21 PAGES OF THIS CHAPTER,  
Visit: <http://www.eolss.net/Eolss-sampleAllChapter.aspx>

## Bibliography

American Society of Testing and Materials (ASTM) (2000). ASTM standard G46: standard recommended practice for examination and evaluation of pitting corrosion. In *Wear and Erosion: Metal Corrosion* (Vol. 03.02.) of *Annual Book of ASTM Standards*. pp. 175-181. Conshohocken, PA: American Society of Testing and Materials [Provides, e.g., descriptions of various pit forms.]

Atkinson J. T. N. and Droffelaar H. van (1982). *Corrosion and its Control*, pp. 121–127; 191–202. Houston, Texas: NACE. [Chapters on detecting and monitoring corrosion and failure analysis.]

Bardal E., Drugli J. M., and Gartland P. O. (1993). The Behavior of Corrosion Resistant Steels in Seawater: A Review. *Corrosion Science* **35**(1–4), 257–267. [On behavior of stainless steels in seawater.]

Bardal, E (2001): Corrosion in seawater – biological effects. www.desware.net. Oxford: EOLSS Publishers. [Main emphasis on corrosion resistant materials.]

Efird K. D. (1977). Effects of Fluid Dynamics on the Copper and Copper-Base Alloys in Seawater. *Corrosion* **33**(Jan), 3–8. [Determination of critical velocities for erosion corrosion of copper alloys.]

Fontana M. G. and Greene N. (1978). Corrosion Forms. In *Corrosion Engineering*, pp. 28-115. New York: McGraw-Hill [Excellent and comprehensive description of various corrosion forms.]

Lees D. J. (1982). Characteristics of Stress-Corrosion Fracture Initiation and Protection. *Metallurgist and Materials Technologist*, **14** (1), 29-38 [Comprehensive review of stress corrosion cracking.]

Perkins A. (1996). Corrosion monitoring. *Corrosion Engineering Handbook*, (ed. P. A. Schweitzer), pp. 623–652. New York: Marcel Dekker. [Description of various corrosion monitoring methods]

Ashbaugh W.G. (1986). Corrosion Failures. In *Metals Handbook. Failure analysis and prevention*. Vol. 11 (ed. K. Mills). pp.172-202. Metals Park, Ohio: ASM International. [Deals with corrosion failure analysis in detail. The same volume contains a special article on analysis of corrosion fatigue failures.]

Craig B. and Pohlman S.L. (1987). Forms of Corrosion. In *Metals Handbook. Corrosion*, Vol. 13 (ed. J. R. Davis), pp. 77-190. Metals Park, Ohio: ASM International. [A section with many articles by different authors, with description of corrosion forms.]

Wood J.D. (1989). Guide to Nondestructive evaluation techniques. In *Metals Handbook. Non-destructive evaluation and quality control.*, Vol. 17 (ed. J. R. Davis), pp. 49-51. Metals Park, Ohio: ASM International. [This is an introduction that is followed by a series of articles by many different authors, with detailed description of inspection and monitoring methods.]

## Biographical Sketches

**Einar Bardal** graduated at the Faculty of Mechanical Engineering of The Norwegian Institute of Technology in Trondheim, Department of Materials and Metal Forming in 1964, and obtained his dr.ing. degree with a scientific investigation in corrosion at the same department in 1968. He was senior lecturer from 1969 to 1977 and part time professor in materials properties 1979-94 at this department.

He was initiator of SINTEF Corrosion Centre and head of the centre 1975-94. Since 1994 he has been professor in Corrosion and Coating Technology at the Norwegian University of Science and Technology, Trondheim, Department of Machine Design and Materials Technology, and in the same period scientific adviser at SINTEF Materials Technology. In 30 years he has been responsible for corrosion education at the faculties of Mechanical Engineering and Marine Technology at the university. Bardal has published a large number of papers in corrosion, corrosion fatigue and surface technology. He is member of the Norwegian Academy of Science and Technology, and was winner of Statoil's research prize in 1993 and the European Federation of Corrosion Medal 2001. He has been member of several international committees and was chairman of the European Corrosion Congress in 1997 (Eurocorr'97)

**John M. Drugli** is educated at Trondheim Technical College as mechanical engineer in 1958. He was engineer at the Ship Towing Tanks and the Cavitation Tunnel, Division of Marine Hydrodynamics, Norwegian Institute of Technology till 1961. In the time period 1962-1970 he accomplished courses in

Physical Metallurgy, Welding, Metallurgy and Metals Working and Corrosion at the Norwegian Institute of Technology in Trondheim. He was laboratory engineer at the same institute from 1961 to 1976. After that time he worked as Research Scientist and from 1990 as Senior Research Scientist at SINTEF Corrosion Centre

He has background in research work in the fields of Welding and Welding Metallurgy, Materials Testing, Corrosion and Corrosion Testing with particular emphasis on experimental techniques, evaluating of materials, cathodic protection design and material selection for various corrosion conditions. Drugli has published more than 30 papers in corrosion, corrosion testing and material selection. He was winner of SINTEF's research prize in 1995.

UNESCO – EOLSS  
SAMPLE CHAPTERS