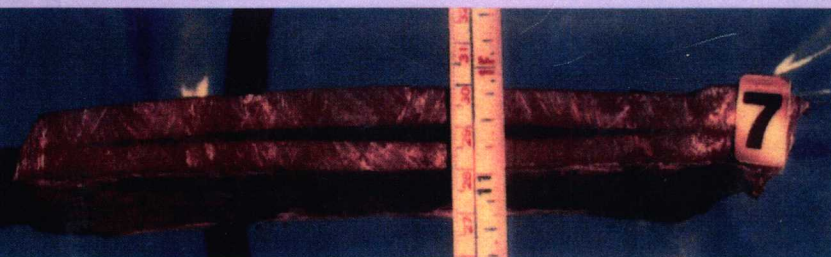
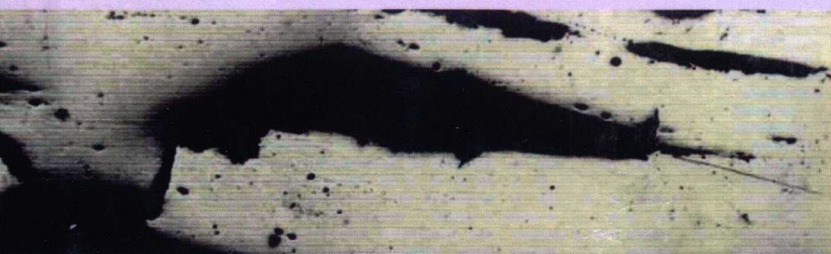


Wiley Series in Corrosion

R. Winston Revie, Series Editor

CORROSION FAILURES

**THEORY, CASE STUDIES,
AND SOLUTIONS**



**K. ELAYAPERUMAL
V. S. RAJA**

WILEY

CORROSION FAILURES

Theory, Case Studies, and Solutions

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Dr. K. Elayaperumal holds degrees in Metallurgical Engineering from Indian Institute of Science, Bangalore, India, and Massachusetts Institute of Technology, Cambridge, Massachusetts, USA. He has acquired vast R&D experience in the field of corrosion of metallic materials in the nuclear power industry and the related chemical process industry in his two-decade career in the Department of Atomic Energy, Government of India, Bhabha Atomic Research Centre. His advisory consultancy services in the field of analysis of corrosion failure in chemical process industries have generated a great amount of interesting case studies and brought out in this book. He is a recipient of National Metallurgist Award by Govt. of India and Life Time Achievement Award by NACE India Section.

Prof. V. S. Raja received his doctoral degree from Indian Institute of Science, Bangalore, India. He is a Professor of Corrosion Science and Engineering in the Department of Metallurgical Engineering and Materials Science and also Institute Chair Professor in the Indian Institute of Technology Bombay, India. For the past 28 years, he taught several corrosion and materials related courses, supervising about 20 doctoral students. His main research lies in understanding the interrelation between metallurgy and corrosion, especially passivity, localized corrosion, and stress corrosion cracking. He is also actively involved in solving industrial problems related to corrosion. He has received several awards for his contribution to teaching, research, and industry and is a NACE International Fellow.

FOREWORD

In this unique book, the authors provide a concise presentation of the essence of corrosion principles with an orientation toward corrosion failures and management of corrosion to prevent failures. By appropriate design, construction, operation, and maintenance, the cost of failure can, indeed, be avoided. The book is divided into the following six chapters that are essential reading for any person concerned with the use of materials in applications where safety, integrity, and reliable, cost-effective operation are required:

1. Introduction: The significance of corrosion failures is described in economic and engineering terms.
2. Thermodynamics and kinetics of corrosion: The basic principles of corrosion are presented along with an outline of techniques for assessing the extent of corrosion in engineering installations.
3. Forms of corrosion: Ten basic forms of corrosion are described, including the critical controlling factors for each form. The authors present a valuable collection of photographs to illustrate the forms of corrosion.
4. Materials of construction for chemical process industries: An extensive discussion of the materials available is presented, along with properties on which materials selection is based. The discussion includes not only metallic materials but also nonmetals – ceramics, glasses, and polymers.
5. Failure analysis procedures with reference to corrosion failures: The steps involved in failure analysis are succinctly described from the

perspective of developing an understanding of the cause of failure as necessary to prevent future failures.

6. Case studies: Eighty case studies are photographically illustrated, presented, and discussed. Each case study includes a description of the type of service involved, the specific problem, the material, observations, diagnosis, and remedy.

I am delighted to commend this book to all readers with an interest in reliable application of engineering materials, and I congratulate the authors on their success in achieving the completion of this valuable book.

R. Winston Revie
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PREFACE

Corrosion cuts across almost all industries, and the corroded components prematurely fail and/or operate at suboptimal level. It affects productivity, safety, and environments and devours nonrenewable natural resources and therefore is of great concern to society. Although industrial components do fail by other mechanisms such as mechanical overload, fatigue, creep, brittle fracture, corrosion remains the single most destruction causing the highest damage to all industrial components. For example, in chemical processing industries, corrosion of process equipment vessels and the associated piping, tubing, and utility components such as boilers, heat exchangers, and condensers is the most predominant damage-causing mechanism among the others mentioned earlier. Corrosion takes place on the inside surface of the vessels and other components because of the action of process chemicals and also on the outside surfaces because of the atmospheric moisture laden with chemical vapors and also by wet insulation materials. On the other hand, corrosion damage in aerospace and other transportation industry is relatively less, though found to be critical in life and safety and in the cost of the components. It is estimated that corrosion causes loss of about 3.5% of GNP of a nation. Hence, corrosion control becomes an important subject of science and engineering.

Corrosion is a multidisciplinary subject that calls for greater/concurrent understanding of electrochemical concepts, materials science, especially metallurgy and design. Teaching corrosion requires not only a sound understanding of these subjects but also better appreciation of actual corrosion problems that industries encounter. On the other hand, industrial corrosion problems are typically handled by mechanical engineers, chemical engineers, and at times

metallurgical engineers. What makes solving corrosion problems on the field difficult is that environmental and operating conditions are usually diverse and there is no list of do's and don'ts and nor there exist simple mathematical equations that could correlate the failures to these conditions that alone let the prediction of corrosion failures. In a vast majority of industries, barring a few nuclear power plants and pipelines carrying crude and petrochemicals where the environments are reasonably defined, controlling corrosion is primarily phenomenological in nature. Thus, effective corrosion control by these field engineers can be possible only if they can understand the complex concepts of electrochemistry and metallurgy that govern the corrosion processes. The main objectives of this book are twofold: enable the students to appreciate how the concepts of electrochemistry and metallurgy are intimately related to corrosion failures and empower the practicing engineers (involved in design and manufacturing of industrial components and those involved in process control, inspection, and maintenance) to tackle corrosion problems through simplifying electrochemical concepts and corrosion mechanisms and give exposure to metallurgy and failure analysis methodology and the relevant tools needed for the analysis. The book therefore can serve as text books as much as a reference one. In this sense, this book is considered unique and different from the normal text and failure analysis books published in the subject of corrosion.

The book brings out the phenomenon, importance, and cost of corrosion in various industrial sectors and infrastructures in the first chapter in order to emphasize the need to seriously consider corrosion control. Corrosion processes start with electron transfer from metallic surface to chemical species of the environment, which forms the basis for all types of corrosion. The governing electrochemical thermodynamics decides if a metal can corrode at all in a given environment, while the corrosion rates are decided by electrochemical kinetics. These concepts and the governing equations are simplified and presented in Chapter 2. Of particular importance is the role of polarization (overvoltage), passivity, and their dependence on environment and its relation to corrosion rate and electrochemical corrosion testing and monitoring techniques. The reader is expected to get clarity on these aspects of corrosion.

Chapter 3 covers the different manifestations (can also be called mechanisms) of corrosion that arise out of complexities in environments and metallic structures. For example, corrosive environment can be quiescent or under flow in relation to the metallic structures and it may contain chlorides, foulants, and microbes. On the other hand, the metallic structures could have been fabricated through joining methods such as flange/riveting/welding, they could be under applied stresses or residual stresses, and could be bimetallic in nature. Such situations lead to different forms of corrosion, such as pitting corrosion, crevice corrosion, galvanic corrosion, intergranular

corrosion (IGC), flow-assisted corrosion, and environmentally assisted cracking. This chapter is expected to give strong basis for implementing various corrosion control measures such as materials selection as well as for corrosion failure analysis.

Among the corrosion preventive methods such as industrial painting, adding corrosion inhibitors, cathodic protection, and materials selection, the most often considered method for chemical process equipments demanding corrosion resistance and in many cases heat transfer as well is the materials selection. The Chapter 4 deals with this aspect in great detail, starting from plain carbon steels through stainless steels, copper-based alloys, and nickel-based alloys to metals such as titanium and tantalum in the order of increasing corrosion resistance and the accompanying increase in unit cost. To give a broad perspective, light alloy such as aluminum and nonmetallic materials similar to engineering plastics such as polytetrafluoroethylene, fiber-reinforced plastics, ceramics, and glasses are covered.

As mentioned earlier in this preface, detailed analysis of every unexpected corrosion failure is very important and a must to arrive at the root cause of the failure and to take appropriate preventive measures. The process namely failure analysis needs to be done in a systematic scientific way. Chapter 5 deals with systematic scientific procedures of conducting failure analysis starting with field inspection through sample testing and analysis to report writing.

Chapter 6, the longest chapter in the book, presents a set of 80 real-time case studies of actual corrosion failures that occurred in chemical process industries in the very recent past and analyzed by the authors. For each case, details such as the industry group, the equipment identification, the experienced corrosion phenomenon, material of construction (MOC), chemical service condition, tests carried out, diagnostic analysis, and finally recommendations for remedial actions are provided. The needed explanation such as description/mechanisms/characteristics of the particular form of corrosion in question, detailed composition of the MOC used, if needed, can be found in the preceding chapters, that is, Chapters 2–5. This chapter also gives its own content list in which the reader can choose a specific case study of his/her interest and read it in detail.

In summary, the book is an attempt to spread in detail the practical aspects of corrosion failures of chemical process equipments supported by scientific background and explanation of each corrosion phenomenon experienced and reported in the case studies. One can notice a good number of cases for most prominent forms of corrosion occurred in a variety of industries.

It is hoped that the book would serve as a useful practical guide for practicing engineers in their endeavor to control corrosion and also see theory in each and every corrosion failures they encounter, and an inspiring textbook for undergraduate/masters students to see the immediate application of

theory in practice. In essence, the authors will be happy if this book can synergize theory and practice. The authors express many thanks to Dr. Winston Revie for encouraging us to write this book as well for writing a foreword and to E. Shanmuganathan, Naresh Ingle and Farooq Mohamed Khan for their assistance in preparing this book and M/s John Wiley & Sons, Inc., for publishing this book.

K. Elayaperumal

V. S. Raja

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