I dedicate this book to students, teachers, engineers and any other theoreticians and practitioners of corrosion science in general, who are trying hard to make this world a better place. I also acknowledge International Zaman University of Phnom Penh, Cambodia for their willingness to support my studies.
Contents

Preface xv

Part 1 Corrosion Chemistry

1 Corrosion and its Definition 3

2 The Corrosion Process and Affecting Factors 5

3 Corrosion Types Based on Mechanism 7
   3.1 Uniform Corrosion 7
   3.2 Pitting Corrosion 7
   3.3 Crevice Corrosion 8
   3.4 Galvanic Corrosion 8
   3.5 Intergranular Corrosion 8
   3.6 Selective Corrosion 9
   3.7 Erosion or Abrasion Corrosion 9
   3.8 Cavitation Corrosion 9
   3.9 Fretting Corrosion 9
   3.10 Stress Corrosion Cracking 9
   3.11 Microbial Corrosion 9

4 Corrosion Types of Based on the Media 11
   4.1 Atmospheric Corrosion 11
   4.2 Corrosion in Water 12
   4.3 Corrosion in Soil 13

5 Nature of Protective Metal Oxide Films 15

6 Effect of Aggressive Anions on Corrosion 17

7 Corrosion Prevention Methods 19

8 Commonly Used Alloys and their Properties 21
   8.1 Aluminum 2024 Alloy 21
   8.2 Aluminum 7075 Alloy 22
   8.3 Aluminum 6061 Alloy 22

9 Cost of Corrosion and Use of Corrosion Inhibitors 23

10 Types of Corrosion Inhibitors 25
   10.1 Anodic Inhibitors 25
   10.2 Cathodic Inhibitors 25

11 Chromates: Best Corrosion Inhibitors to Date 27
   11.1 Limitations on the Use of Chromates due to Toxicity 27
   11.2 Corrosion Inhibition Mechanism of Chromates 29
# Contents

12 **Chromate Inhibitor Replacements: Current and Potential Applications**
   12.1 Nitrites
   12.2 Trivalent Chromium Compounds
   12.3 Oxyanions Analogous to Chromate
   12.4 Synergistic Use of Oxyanions Analogues of Chromate

13 **Sol-Gels (Ormosils): Properties and Uses**
   13.1 Types of Sol-Gels
   13.2 Corrosion Inhibition Mechanism of Sol-Gel Coatings
   13.3 Synthesis of Sol-Gels
   13.4 Incorporation of Corrosion Inhibitive Pigments into Sol-Gel Coatings

14 **Corrosion in Engineering Materials**
   14.1 Introduction
   14.2 Steel Structures
   14.3 Concrete Structures
   14.4 Protection Against Corrosion in Concrete Construction
   14.5 Corrosion of Unbonded Prestressing Tendons
   14.6 Cathodic Protection
   14.7 Corrosion in Industrial Projects

References

**Part 2  Cathodic Protection**

15 **Corrosion of Materials**
   15.1 Deterioration or Corrosion of Ceramic Materials
   15.2 Degradation or Deterioration of Polymers
   15.3 Corrosion or Deterioration of Metals

16 **Factors Influencing Corrosion**
   16.1 Nature of the Metal
   16.2 Nature of the Corroding Environment

17 **Corrosion Mechanisms**
   17.1 Direct Chemical Attack or Chemical or Dry Corrosion
   17.2 Electrochemical or Aqueous or Wet Corrosion
   17.3 Differences between Chemical and Electrochemical Corrosion

18 **Corrosion Types**
   18.1 Uniform Corrosion
   18.2 Non-Uniform Corrosion

19 **Thermodynamics of Corrosion**
   19.1 Gibbs Free Energy (ΔG)
   19.2 Passivity
   19.3 Pourbaix Diagrams
   19.4 Corrosion Equilibrium and Adsorptions
   19.5 Concentration Corrosion Cells
   19.6 Polarization
   19.7 Polarization Curves
20 Corrosion Prevention and Protection
20.1 Proper Design
20.2 Choice of Material
20.3 Protective Coatings
20.4 Changing the Environmental Factors that Accelerate Corrosion
20.5 Changing the Electrochemical Characteristic of the Metal Surface

21 Cost of Corrosion
21.1 Corrosion Preventative Measures
21.2 Lost Production Due to Plants Going out of Service or Shutdowns
21.3 Product Loss Due to Leakages
21.4 Contamination of the Product
21.5 Maintenance Costs
21.6 Overprotective Measures

22 Cathodic Protection
22.1 Sacrificial Anode Cathodic Protection Systems
22.2 Impressed Current Cathodic Protection Systems
22.3 Cathodic Protection Current Need
22.4 Effect of Coatings on Cathodic Protection
22.5 Effect of Passivation on Cathodic Protection
22.6 Automated Cathodic Protection Systems
22.7 Cathodic Protection Criteria
22.8 Reliability of Cathodic Protection Criteria
22.9 Interference Effects of Cathodic Protection Systems
22.10 Criteria for Cathodic Protection Projects
22.11 Cost of Cathodic Protection
22.12 Comparison of Cathodic Protection Systems

23 Sacrificial Anode or Galvanic Cathodic Protection Systems
23.1 Anodic Potentials and Anodic Polarization
23.2 Galvanic Cathodic Protection Current Need
23.3 Anodic Current Capacity and Anodic Current Efficiency
23.4 Service Life of an Anode
23.5 Minimum Number of Galvanic Anodes
23.6 Commonly Used Galvanic Anodes
23.7 Performance Measurements of Galvanic Anodes
23.8 Galvanic Anodic Beds
23.9 Sacrificial Anode Cathodic Protection Projects
23.10 Maintenance of Sacrificial Anode Cathodic Protection Systems

24 Impressed Current Cathodic Protection Systems
24.1 T/R Units
24.2 Types of Anodes
24.3 Anodic Bed Resistance
24.4 Types of Anodic Beds
24.5 Cable Cross-Sections
24.6 Impressed Current Cathodic Protection Projects
24.7 Maintenance of Impressed Current Cathodic Protection Systems

25 Corrosion and Corrosion Prevention of Concrete Structures
25.1 Concrete’s Chemical Composition
25.2 Corrosion Reactions of Concrete
### Contents

25.3 Factors Affecting Corrosion Rate in Reinforced Concrete Structures 160
25.4 Corrosion Measurements in Reinforced Concrete Structures 164
25.5 Corrosion Prevention of Reinforced Concrete 166

26 Cathodic Protection of Reinforced Concrete Steels 167
   26.1 Current Needed for Cathodic Protection of Steel Structures 168
   26.2 Cathodic Protection Criteria 168
   26.3 Determination of Protection Potential 168
   26.4 Cathodic Protection Methods for Reinforced Concrete Steels 168
   26.5 Cathodic Protection of Pre-Stressed Steel Concrete Pipes 169

27 Corrosion in Petroleum Industry 171
   27.1 Hydrochloric Acid (HCl) and Chlorides 172
   27.2 Hydrogen (H₂) Gas 172
   27.3 Hydrogen Sulfide (H₂S) and Other Sulfur Compounds 173
   27.4 Sulfuric Acid (H₂SO₄) 173
   27.5 Hydrogen Fluoride (HF) 173
   27.6 Carbon Dioxide (CO₂) 173
   27.7 Dissolved Oxygen (O₂) and Water (H₂O) 174
   27.8 Organic Acids 175
   27.9 Nitrogen (N₂) Compounds and Ammonia (NH₃) 175
   27.10 Phenols 175
   27.11 Phosphoric Acid (H₃PO₄) 175
   27.12 Caustic Soda (NaOH) 176
   27.13 Mercury (Hg) 176
   27.14 Aluminum Chloride (AlCl₃) 176
   27.15 Sulfate Reducing Bacteria (SRB) 176

28 Corrosion in Pipeline Systems 177
   28.1 Pipes Made of Iron and its Alloys 177
   28.2 Petroleum or Crude Oil Pipeline Systems 178
   28.3 Water Pipeline Systems 179

29 Cathodic Protection of Pipeline Systems 181
   29.1 Measurement of Terrain’s Resistivity 181
   29.2 Potential Measurements 182
   29.3 Determination of Coating Failures Based on Potential Measurements 183
   29.4 Measuring Potential Along the Pipeline 183
   29.5 Maintenance of Pipeline Cathodic Protection Systems 183
   29.6 Measurement Stations 184
   29.7 Cathodic Protection of Airport Fuel Distribution Lines 185
   29.8 Cathodic Protection of Water Pipelines 185

30 Corrosion and Cathodic Protection of Crude Oil or Petroleum Storage Tanks 187
   30.1 Cathodic Protection of Inner Surfaces of Crude Oil Storage Tanks 187

31 Corrosion and Cathodic Protection of Metallic Structures in Seawater 191
   31.1 Factors Affecting Corrosion Rate of Metallic Structures in Seawater 191
   31.2 Cathodic Protection of Metallic Structures in the Sea 193
   31.3 Cathodic Protection of Ships 193
   31.4 Cathodic Protection of Pier Poles with Galvanic Anodes 196

32 Cathodic Protection of the Potable Water Tanks 197
### Contents

33  **Corrosion and Corrosion Prevention in Boilers**  
   33.1 Corrosion in Boilers  
   33.2 Corrosion Prevention in Boilers  

34  **Corrosion and Corrosion Prevention in Geothermal Systems**  
   34.1 Corrosion in Geothermal Systems  
   34.2 Corrosion Prevention in Geothermal Systems  

References  

Part 3  **Corrosion Engineering**  

35  **Corrosion of Materials**  
   35.1 Deterioration or Corrosion of Ceramic Materials  
   35.2 Degradation or Deterioration of Polymers  
   35.3 Corrosion or Deterioration of Metals  

36  **Cost of Corrosion**  
   36.1 Corrosion Preventative Measures  
   36.2 Lost Production Due to Plants Going out of Service or Shutdowns  
   36.3 Product Loss Due to Leakages  
   36.4 Contamination of the Product  
   36.5 Maintenance Costs  
   36.6 Overprotective Measures  

37  **Factors Influencing Corrosion**  
   37.1 Nature of the Metal  
   37.2 Nature of the Corroding Environment  

38  **Corrosion Mechanisms**  
   38.1 Direct Chemical Attack or Chemical or Dry Corrosion  
   38.2 Electrochemical or Aqueous or Wet Corrosion  
   38.3 Differences between Chemical and Electrochemical Corrosion  

39  **Types of Corrosion**  
   39.1 Uniform Corrosion  
   39.2 Non-Uniform Corrosion  

40  **The Thermodynamics of Corrosion**  
   40.1 Gibbs Free Energy (∆G)  
   40.2 Passivity  
   40.3 Pourbaix Diagrams  
   40.4 Corrosion Equilibrium and Adsorptions  
   40.5 Concentration Corrosion Cells  
   40.6 Polarization  
   40.7 Polarization Curves  

41  **Corrosion Prevention and Protection**  
   41.1 Proper Design  
   41.2 Choice of Material  
   41.3 Protective Coatings  
   41.4 Changing the Environmental Factors that Accelerate Corrosion  
   41.5 Changing the Electrochemical Characteristic of the Metal Surface
### Contents

**42 Corrosion and Corrosion Prevention of Concrete Structures**  
295  
42.1 Concrete's Chemical Composition  
295  
42.2 Corrosion Reactions of Concrete  
296  
42.3 Factors Affecting Corrosion Rate in Reinforced Concrete Structures  
296  
42.4 Corrosion Measurements in Reinforced Concrete Structures  
300  
42.5 Corrosion Prevention of Reinforced Concrete  
302

**43 Corrosion and Corrosion Prevention of Metallic Structures in Seawater**  
305  
43.1 Factors Affecting Corrosion Rate of Metallic Structures in Seawater  
305  
43.2 Cathodic Protection of Metallic Structures in the Sea  
307

**44 Corrosion and Corrosion Prevention in Petroleum Industry**  
309  
44.1 Chemicals that Cause Corrosion in Petroleum Industry  
310  
44.2 Petroleum or Crude Oil Pipeline Systems  
314  
44.3 Crude Oil or Petroleum Storage Tanks  
315

**45 Corrosion and Corrosion Prevention in Water Transportation and Storage Industry**  
317  
45.1 Water Pipeline Systems  
317  
45.2 Cooling Water Systems  
319  
45.3 Potable Water Tanks  
319  
45.4 Boilers  
319  
45.5 Geothermal Systems  
322

**References**  
325

**Part 4 Questions and Answers**

**46 Corrosion: Definition and History**  
341  
Questions  
341  
Answers & Solutions  
343  
Answer Key  
344

**47 Corrosion of Materials**  
345  
Questions  
345  
Answers & Solutions  
356  
Answer Key  
364

**48 Cost of Corrosion**  
365  
Questions  
365  
Answers & Solutions  
367  
Answer Key  
369

**49 Factors Influencing Corrosion**  
371  
Questions  
371  
Answers & Solutions  
375  
Answer Key  
380

**50 Corrosion Mechanisms**  
381  
Questions  
381  
Answers & Solutions  
383  
Answer Key  
386
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>51</td>
<td>Types of Corrosion</td>
<td>387</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>387</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Solutions</td>
<td>409</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>431</td>
</tr>
<tr>
<td>52</td>
<td>Corrosion Prevention</td>
<td>433</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>433</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Solutions</td>
<td>467</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>502</td>
</tr>
<tr>
<td>53</td>
<td>Corrosion in Engineering Materials</td>
<td>503</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>503</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Solutions</td>
<td>526</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>548</td>
</tr>
<tr>
<td>54</td>
<td>Corrosion and Corrosion Prevention of Concrete Structures</td>
<td>551</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>551</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Solutions</td>
<td>564</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>574</td>
</tr>
<tr>
<td>55</td>
<td>Corrosion and Corrosion Prevention of Metallic Structures in Seawater</td>
<td>575</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>575</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Solutions</td>
<td>578</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>580</td>
</tr>
<tr>
<td>56</td>
<td>Corrosion and Corrosion Prevention in Petroleum Industry</td>
<td>581</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>581</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Solutions</td>
<td>591</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>601</td>
</tr>
<tr>
<td>57</td>
<td>Corrosion and Corrosion Prevention in Water Transportation and Storage Industry</td>
<td>603</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>603</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Solutions</td>
<td>610</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>617</td>
</tr>
<tr>
<td>58</td>
<td>Thermodynamics of Corrosion</td>
<td>619</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>619</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Solutions</td>
<td>626</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>633</td>
</tr>
<tr>
<td>59</td>
<td>Cathodic Protection</td>
<td>635</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>635</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Solutions</td>
<td>648</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>660</td>
</tr>
<tr>
<td>60</td>
<td>Sacrificial Anode or Galvanic Cathodic Protection Systems</td>
<td>661</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>661</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Solutions</td>
<td>671</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>681</td>
</tr>
<tr>
<td>61</td>
<td>Impressed Current Cathodic Protection Systems</td>
<td>683</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>683</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Questions</td>
<td>693</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>702</td>
</tr>
<tr>
<td>Chapter</td>
<td>Title</td>
<td>Pages</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------------------</td>
<td>---------</td>
</tr>
<tr>
<td>62</td>
<td>Cathodic Protection of Reinforced Concrete Steels</td>
<td>703</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>703</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Solutions</td>
<td>707</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>710</td>
</tr>
<tr>
<td>63</td>
<td>Cathodic Protection of Pipeline Systems</td>
<td>711</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>711</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Solutions</td>
<td>717</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>722</td>
</tr>
<tr>
<td>64</td>
<td>Cathodic Protection of Crude Oil or Petroleum Storage Tanks</td>
<td>723</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>723</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Solutions</td>
<td>726</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>729</td>
</tr>
<tr>
<td>65</td>
<td>Cathodic Protection of Metallic Structures in the Sea</td>
<td>731</td>
</tr>
<tr>
<td></td>
<td>Questions</td>
<td>731</td>
</tr>
<tr>
<td></td>
<td>Answers &amp; Solutions</td>
<td>737</td>
</tr>
<tr>
<td></td>
<td>Answer Key</td>
<td>741</td>
</tr>
<tr>
<td></td>
<td>Index</td>
<td>743</td>
</tr>
</tbody>
</table>
Preface

My rationale for writing this book was to assist students, teachers and engineers of corrosion science in asking questions and having answers about corrosion science and its subdisciplines, considering the absence of such a resource in the market.

The questions and solutions provided in the book focus on broader corrosion science and are categorized into subdisciplines such as corrosion and its prevention in petroleum or construction industries, etc.

It is intended that this book be utilized as a resource for related courses in the upper grade levels of undergraduate education, i.e., junior and senior years, as well as in master’s or doctorate level programs.

The book consists of a total of 1,399 multiple choice questions and answers categorized in 20 chapters and numerous subsections about corrosion. The questions and answers refer to certain chapters in my previous books published by Scrivener Publishing, Corrosion Chemistry, Cathodic Protection and Corrosion Engineering the full text of which is included in this volume, to produce a valuable reference guide for engineers and students.
Part 1
CORROSION CHEMISTRY
Corrosion and its Definition

According to American Society for Testing and Materials’ corrosion glossary, corrosion is defined as “the chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its properties.”

Other definitions include Fontana’s description that corrosion is the extractive metallurgy in reverse, which is expected since metals thermodynamically are less stable in their elemental forms than in their compound forms as ores. Fontana states that it is not possible to reverse fundamental laws of thermodynamics to avoid corrosion process; however, he also states that much can be done to reduce its rate to acceptable levels as long as it is done in an environmentally safe and cost-effective manner.

In today’s world, a stronger demand for corrosion knowledge arises due to several reasons. Among them, the application of new materials requires extensive information concerning corrosion behavior of these particular materials. Also the corrosivity of water and atmosphere have increased due to pollution and acidification caused by industrial production. The trend in technology to produce stronger materials with decreasing size makes it relatively more expensive to add a corrosion allowance to thickness. Particularly in applications where accurate dimensions are required, widespread use of welding due to developing construction sector has increased the number of corrosion problems. Developments in other sectors such as offshore oil and gas extraction, nuclear power production and medicinal health have also required stricter rules and control. More specifically, reduced allowance of chromate-based corrosion inhibitors due to their toxicity constitutes one of the major motivations to replace chromate inhibitors with environmentally benign and efficient ones.
The Corrosion Process and Affecting Factors

There are four basic requirements for corrosion to occur. Among them is the anode, where dissolution of metal occurs, generating metal ions and electrons. These electrons generated at the anode travel to the cathode via an electronic path through the metal, and eventually they are used up at the cathode for the reduction of positively charged ions. These positively charged ions move from the anode to the cathode by an ionic current path. Thus, the current flows from the anode to the cathode by an ionic current path and from the cathode to the anode by an electronic path, thereby completing the associated electrical circuit. Anode and cathode reactions occur simultaneously and at the same rate for this electrical circuit to function. The rate of anode and cathode reactions (that is the corrosion rate), is defined by American Society for Testing and Materials as material loss per area unit and time unit.

In addition to the four essentials for corrosion to occur, there are secondary factors affecting the outcome of the corrosion reaction. Among them there are temperature, pH, associated fluid dynamics, concentrations of dissolved oxygen and dissolved salt. Based on pH of the media, for instance, several different cathodic reactions are possible. The most common ones are:

Hydrogen evolution in acid solutions,

\[ \text{2H} + 2\text{e}^- \rightarrow \text{H}_2 \quad (2.1) \]

Oxygen reduction in acid solutions,

\[ \text{O}_2 + 4\text{H} + 4\text{e}^- \rightarrow 2\text{H}_2\text{O} \quad (2.2) \]

Hydrogen evolution in neutral or basic solutions,

\[ 2\text{H}_2\text{O} + 2\text{e}^- \rightarrow \text{H}_2 + 2\text{OH}^- \quad (2.3) \]

Oxygen reduction in neutral or basic solutions,

\[ \text{O}_2 + 2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 4\text{OH}^- \quad (2.4) \]

The metal oxidation is also a complex process and includes hydration of resulted metal cations among other subsequent reactions.

\[ \text{M}^{n+} \rightarrow \text{M}^{n+} + \text{ne}^- \quad (2.5) \]

In terms of pH conditions, this book has emphasized near neutral conditions as the media leading to less emphasis on hydrogen evolution and oxygen reduction reactions, since both hydrogen evolution and oxygen reduction reactions that take place in acidic conditions are less common.

Among cathode reactions in neutral or basic solutions, oxygen reduction is the primary cathodic reaction due to the difference in electrode potentials. Thus, oxygen supply to the system, in which corrosion takes place, is of utmost importance for the outcome of corrosion reaction. Inhibitors are
commonly tested in stagnant solutions for the purpose of weight-loss tests, thus ruling out the effects of varying fluid dynamics on corrosion. Weight-loss tests are performed at ambient conditions, thus effects of temperature and dissolved oxygen amounts are not tested as well, while for salt fog chamber tests, temperature is varied for accelerated corrosion testing. For both weight loss tests and salt fog chamber tests, however, dissolved salt concentrations are commonly kept high for accelerated testing to be possible.

When corrosion products such as hydroxides are deposited on a metal surface, a reduction in oxygen supply occurs, since the oxygen has to diffuse through deposits. Since the rate of metal dissolution is equal to the rate of oxygen reduction, a limited supply and limited reduction rate of oxygen will also reduce the corrosion rate. In this case the corrosion is said to be under cathodic control. In other cases corrosion products form a dense and continuous surface film of oxide closely related to the crystalline structure of metal. Films of this type prevent primarily the conduction of metal ions from metal-oxide interface to the oxide-liquid interface, resulting in a corrosion reaction that is under anodic control. When this happens, passivation occurs and metal is referred as a passivated metal. Passivation is typical for stainless steels and aluminum.
Corrosion Types Based on Mechanism

Brief definitions of major types of corrosion will be given in this section in the order of commonalities and importance of these corrosion types for the metal alloys, which are mild steel, and Aluminum 2024, 6061 and 7075 alloys.

3.1 Uniform Corrosion

Uniform corrosion occurs when corrosion is quite evenly distributed over the surface, leading to a relatively uniform thickness reduction. Metals without significant passivation tendencies in the actual environment, such as iron, are liable to this form. Uniform corrosion is assumed to be the most common form of corrosion and responsible for most of the material loss. However, it is not a dangerous form of corrosion because prediction of thickness reduction rate can be done by means of simple tests. Therefore, corresponding corrosion allowance can be added, taking into account strength requirements and lifetime.

3.2 Pitting Corrosion

Pitting corrosion is one of the most observed corrosion types for aluminum and steel, and it is the most troublesome one in near neutral pH conditions with corrosive anions, such as Cl⁻ or SO₄²⁻ present in the media. It is characterized by narrow pits with a radius of equal or lesser magnitude than the depth. Pitting is initiated by adsorption of aggressive anions, such as halides and sulfates, which penetrate through the passive film at irregularities in the oxide structure to the metal-oxide interface. It is not clear why the breakdown event occurs locally. In the highly disordered structure of a metal surface, aggressive anions enhance dissolution of the passivating oxide. Also, adsorption of halide ions causes a strong increase of ion conductivity in the oxide film so that the metal ions from the metal surface can migrate through the film.

Thus, locally high concentrations of aggressive anions along with low solution pH values strongly favor the process of pitting initiation. In time, local thinning of the passive layer leads to its complete breakdown, which results in the formation of a pit. Pits can grow from a few nanometers to the micrometer range. In the propagation stage, metal cations from the dissolution reaction diffuse toward the mouth of the pit or crevice (in the case of crevice corrosion), where they react with OH⁻ ions produced by the cathodic reaction, forming metal hydroxide deposits that may cover the pit to a varying extent. Corrosion products covering the pits facilitate faster corrosion because they prevent exchange of the interior and the exterior electrolytes, leading to very acidic and aggressive conditions in the pit. Stainless steels have high resistance to initiation of pitting. Therefore, rather few pits are formed, but when a pit has been formed, it may grow very fast due to large cathodic areas and a thin oxide film that has considerable electrical conductance. Conversely for several aluminum alloys, pit initiation can be accepted under many circumstances. This is so because numerous pits are formed, and the oxide is insulating and has, therefore,
low cathodic activity. Thus, corrosion rate is under cathodic control. However, if the cathodic reaction can occur on a different metal because of galvanic connection as for deposition of Cu on the aluminum surface, pitting rate may be very high. Therefore, the nature of alloying elements is very important.13

### 3.3 Crevice Corrosion

Crevice corrosion occurs underneath deposits and in narrow crevices that obstruct oxygen supply.14-16 This oxygen is initially required for the formation of the passive film and later for repassivation and repair. Crevice corrosion is a localized corrosion concentrated in crevices in which the gap is wide enough for liquid to penetrate into the crevice but too narrow for the liquid to flow. A special form of crevice corrosion that occurs on steel and aluminum beneath a protecting film of metal or phosphate, such as in cans exposed to atmosphere, is called filiform corrosion.14 Provided that crevice is sufficiently narrow and deep, oxygen is more slowly transported into the crevice than it is consumed inside it. When oxygen has been completely consumed, OH– can no longer be produced there. Conversely, dissolution of the metal inside the crevice continues, driven by the oxygen reduction outside of the crevice. Thus, the concentration of metal ions increases and, with missing OH– production in the crevice, electrical neutrality is maintained by migration of negative ions, such as Cl– into the crevice.15 This way, an increasing amount of metal chlorides or other metal salts are produced in the crevice. Metal salts react with water and form metal hydroxides, which are deposited, and acids such as hydrochloric acid, which cause a gradual reduction of pH down to values between 0 and 4 in the crevice, while outside of crevice it is 9 to 10, where oxygen reduction takes place. This autocatalytic process leads to a critical corrosion state. Thus reduction of hydronium ions takes place in very acidic conditions in addition to the primary cathodic reaction that is reduction of oxygen16

\[
2H^+ + 2e^- \rightarrow H_2 \quad (3.1)
\]

\[
O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (3.2)
\]

### 3.4 Galvanic Corrosion

Galvanic corrosion occurs when a metallic contact is made between a more noble metal and a less noble one.17-19 A necessary condition is that there is also an electrolytic condition between the metals, so that a closed circuit is established. The area ratio between cathode and anode is very large and, therefore, the corrosion rate can be high. The most familiar example of intergranular corrosion is associated with austenitic steels.20 A typical form of intergranular corrosion is associated with stainless steels.21 It is most common in AlCuMg alloys, but it is also observed in other aluminum alloys with no copper present. Both exfoliation corrosion and other types of intergranular corrosion are efficiently prevented with a coating of a more resistant aluminum alloy, such as an alclad alloy or commercially pure aluminum, which is the reason alclad 2024-T3 alloy is used in most modern aircrafts.22

### 3.5 Intergranular Corrosion

Intergranular corrosion is the localized attack with propagation into the material structure with no major corrosion on other parts of the surface.6,22-25 The main cause of this type of corrosion is the presence of galvanic elements due to differences in concentration of impurities or alloying elements.6 In most cases, there is a zone of less noble metal at or in the grain boundaries, which acts as an anode, while other parts of the surface form the cathode.22 The area ratio between the cathode and anode is very large and, therefore, the corrosion rate can be high. The most familiar example of intergranular corrosion is associated with austenitic steels.20 A typical form of intergranular corrosion in aluminum alloys is exfoliation corrosion.21 It is most common in AlCuMg alloys, but it is also observed in other aluminum alloys with no copper present. Both exfoliation corrosion and other types of intergranular corrosion are efficiently prevented with a coating of a more resistant aluminum alloy, such as an alclad alloy or commercially pure aluminum, which is the reason alclad 2024-T3 alloy is used in most modern aircrafts.22
3.6 Selective Corrosion

Selective corrosion or selective leaching occurs in alloys in which one element is clearly less noble than the others. As a result of this form of corrosion, the less noble metal is removed from the material, leading to a porous material with very low strength and ductility. However, regions that are selectively corroded are sometimes covered with corrosion products or other deposits. Thus, the component keeps exactly the same shape, making the corrosion difficult to discover.

3.7 Erosion or Abrasion Corrosion

Erosion or abrasion corrosion occurs when there is a relative movement between a corrosive fluid and a metallic material immersed in it. In such cases, the material surface is exposed to mechanical wear, leading to metallically clean surfaces, which result in a more active metal. Most sensitive materials are those normally protected by passive oxide layers with inferior strength and adhesion to the substrate, such as lead, copper, steel and some aluminum alloys. When wearing particles move parallel to the material surface, the corrosion is called abrasion corrosion. On the other hand, erosion corrosion occurs when the wearing particles move with an angle to the substrate surface.

3.8 Cavitation Corrosion

Cavitation corrosion occurs at fluid dynamic conditions, causing large pressure variations due to high velocities, as often is the case for water turbines, propellers, pump rotors and external surfaces of wet cylinder linings in diesel engines. While erosion corrosion has a pattern reflecting flow direction, cavitation attacks are deep pits grown perpendicularly to the surface. Pits are often localized close to each other or grown together over smaller or larger areas, making a rough, spongy surface.

3.9 Fretting Corrosion

Fretting corrosion occurs at the interface between two closely fitting components when they are subjected to repeated slight relative motion. The relative motion may vary from less than a nanometer to several micrometers in amplitude. Vulnerable objects are fits, bolted joints and other assemblies where the interface is under load.

3.10 Stress Corrosion Cracking

Stress Corrosion Cracking is defined as crack formation due simultaneous effects of static tensile strength and corrosion. Tensile stress may originate from an external load, centrifugal forces, temperature changes or internal stress induced by cold working, welding or heat treatment. The cracks are generally formed in planes normal to the tensile stress, and they propagate intergranularly or transgranularly and may be branched.

Corrosion fatigue is crack formation due to varying stresses combined with corrosion. This is different from stress corrosion cracking because stress corrosion cracking develops under static stress while corrosion fatigue develops under varying stresses.

3.11 Microbial Corrosion

Another type of corrosion occurs when organisms produce an electron flow, resulting in modification of the local environment to a corrosive one. An example is when microbial deposits accumulate on the surface of a metal. They can be regarded as inert deposits on the surface, shielding the area below from the corrosive electrolyte. The area directly under the colony will become the anode, and the metallic surface just outside the contact area will support the reduction of oxygen reaction and become the cathode. Metal dissolution will occur under the microbial deposit and, in that regard, would resemble to pits, but the density of local dissolution areas should match closely with the colony density.

Another case is when microbial deposits produce components, such as inorganic and organic acids, that will change the local environment and thereby induce corrosion. Specifically, the production of inorganic acids leads to hydrogen ion production, which may contribute to hydrogen embrittlement of the colonized metal.
Corrosion types can also be categorized based on what type of environment they take place. Accordingly, major corrosion types are atmospheric corrosion, corrosion in fresh water, corrosion in seawater, corrosion in soils, corrosion in concrete and corrosion in the petroleum industry.

4.1 Atmospheric Corrosion

In general for atmospheric corrosion, dusts and solid precipitates are hygroscopic and attract moisture from air. Salts can cause high conductivity, and carbon particles can lead to a large number of small galvanic elements since they act as efficient cathodes after deposition on the surface.\(^{32,33}\) The most significant pollutant is \(\text{SO}_2\), which forms \(\text{H}_2\text{SO}_4\) with water.\(^{34,35}\) Water that is present as humidity bonds in molecular form to even the cleanest and well-characterized metal surfaces.\(^{32,33}\) Through the oxygen atom it bonds to the metal surface or to metal clusters and acts as a Lewis base by adsorbing on electron deficient adsorption sites. Water may also bond in dissociated form, in which case the driving force is the formation of metal-oxygen or metal-hydroxyl bonds. The end products resulting from water adsorption are then hydroxyl and atomic hydrogen groups adsorbed on the substrate surface.\(^{36}\) Atmospheric corrosion rate is influenced by the formation and protective ability of the corrosion products formed. The composition of corrosion products depends on participating dissolved metal ions and anions dissolved in the aqueous layer. According to the hard and soft acids and bases theory, hard metal ions such as \(\text{Al}^{3+}\) and \(\text{Fe}^{3+}\) prefer \(\text{H}_2\text{O}, \text{OH}^-, \text{O}^-, \text{SO}_4^{2-}, \text{NO}_3^-, \text{CO}_3^{2-}\) while intermediate metals such as \(\text{Fe}^{2+}, \text{Zn}^{2+}, \text{Ni}^{2+}, \text{Cu}^{2+}, \text{Pb}^{2+}\) prefer softer bases, such as \(\text{SO}_3^{2-}\) or \(\text{NO}_2^-\) and soft metals such as \(\text{Cu}^+\) or \(\text{Ag}^+\) prefer soft bases as \(\text{R}_2\text{S}, \text{RSH}\) or \(\text{RS}^-\).\(^{34–35}\)

In the specific case of iron or steel exposed to dry or humid air, a very thin oxide film composed of an inner layer of magnetite (\(\text{Fe}_3\text{O}_4\)) forms, covered by an outer layer of \(\text{FeOOH}\) (rust).\(^{37–38}\) Atmospheric corrosion rates for iron are relatively high and exceed those of other structural metals. They range (in \(\mu\text{m/ year}\)) from 4 to 65 in rural, 26 to 104 in marine, 23 to 71 in urban and 26 to 175 in industrial areas.\(^{39}\)

In the case of aluminum, the metal initially forms a few nm thick layer of aluminum oxide, \(\gamma\text{-Al}_2\text{O}_3\), which in humidified air is covered by aluminum oxyhydroxide, \(\gamma\text{-AlOOH}\), eventually resulting in a double-layer structure.\(^{40–42}\) The probable composition of the outer layer is a mixture of \(\text{Al}_2\text{O}_3\) and hydrated \(\text{Al}_2\text{O}_3\), mostly in the form of \(\text{Al(OH)}_3\). However, the inner layer is mostly composed of \(\text{Al}_2\text{O}_3\) and small amounts of hydrated aluminum oxide mostly in the form of \(\text{AlOOH}\).\(^{43–45}\) This oxide layer is insoluble in the pH interval of 4 to 9.\(^{46}\) Lower pH values result in the dissolution of \(\text{Al}^{3+}\). Rates of atmospheric corrosion of aluminum outdoors (in \(\mu\text{m/ year}\)) are substantially lower than for most other structural metals and are from 0.0 to 0.1 in rural, from 0.4 to 0.6 in marine, and \(\sim 1\) in urban areas.\(^{47, 48}\)
In general, anodic passivity of metals, regardless of type of corrosion, is associated with the formation of a thin oxide film, which isolates the metal surface from the corrosive environment. Films with semiconducting properties, such as Fe, Ni, Cu oxides, provide inferior protection compared to metals as Al, which has an insulating oxide layer.49

An alternative explanation of differences between oxide films of different metals based on their conducting properties is the networkforming oxide theory, in which covalent bonds connect the atoms in a three-dimensional structure. Due to nature of covalent bonding, there is short-range order on the atomic scale, but no long-range order. These networks of oxides can be broken up by the introduction of a network modifier.50 When a network modifier is added to a networkforming oxide, they break the covalent bonds in the network, introducing ionic bonds, which can change the properties of mixed oxides, such as Cu/CuO or Al/Al2O3, where rate of diffusion of Cu in Cu2O is 10,000 times larger than Al in Al2O3.51 Depending on single oxide bond strengths, metal oxides can be classified as network formers, intermediates or modifiers. Network formers tend to have single oxide strengths greater than 75 kcal/mol, intermediates lie between 75 and 50 and modifiers lie below this value.52,53 Iron is covered by a thin film of cubic oxide of γ-Fe2O3/Fe3O4 in the passive region. The consensus is that the γ-Fe2O3 layer, as a network former, is responsible for passivity, while Fe3O4, as a network modifier, provides the basis for formation of higher oxidation states but does not directly contribute toward passivity.54 The most probable reason for iron being more difficult to passivate is that it is not possible to go directly to the passivating species of γ-Fe2O3. Instead, a lower oxidation state film of Fe3O4 is required, and this film is highly susceptible to chemical dissolution. Until the conditions are established whereby the Fe3O4 phase can exist on the surface for a reasonable period of time, the γ-Fe2O3 layer will not form and iron dissolution will continue.55-56 Impurities such as water also modify the structure of oxide films. Water acts as a modifying oxide when added to network-forming oxides and thus weakens the structure.57,58 In conclusion, metals, which fall into network-forming or intermediate classes, tend to grow protective oxides, such as Al or Zn. Network formers are non-crystalline, while the intermediates tend to be microcrystalline at low temperatures. The metals, which are in the modifier class, have been observed to grow crystalline oxides, which are thicker and less protective.59 A partial solution is to alloy the metal with one that forms a network-forming oxide, in which the alloying metal tends to oxidize preferentially and segregates to the surface as a glassy oxide film.60 This protects the alloy from corrosion. For example, the addition of chromium to iron causes the oxide film to change from polycrystalline to non-crystalline as the amount of chromium increases, making it possible to produce stainless steel.61-63

Alloying is important such that pure Al has a high resistance to atmospheric uniform corrosion, while the aerospace alloy Al 2024, containing 5 percent Cu, among others, is very sensitive to selective aluminum leaching in aqueous environments. It is, on the other hand, less sensitive to pitting. In the case of steel, the addition of chromium as an alloying element substantially decreases the amount of pitting corrosion in addition to other corrosion types.64

4.2 Corrosion in Water

Second to atmospheric corrosion is corrosion in water. The rate of attack is greatest if water is soft and acidic and the corrosion products form bulky mounds on the surface as in the case of iron.23 The areas where localized attack is occurring can seriously reduce the carrying capacity of pipes. In severe cases iron oxide can cause contamination, leading to complaints of “red water.”65 In seawater the bulk pH is 8 to 8.3; however, due to cathodic production of OH· the pH value at the metal surface increases sufficiently for deposition of CaCO3 and a small extent of Mg(OH)2 together with iron hydroxides. These deposits form a surface layer that reduces oxygen diffusion. Due to this and other corrosion inhibiting compounds, such as phosphates, boric acid, organic salts, that are present, the average corrosion rate in seawater is usually less than that of soft fresh water. However, the rate is higher than it is for hard waters due their higher Ca and Mg content.66 An exception occurs when a material is in the splash zone in seawater, where a thin water film that frequently washes away the layer of corrosion deposits exists on the surface a majority of the time, resulting in the highest oxygen supply and leading to the highest corrosion rate.67 In slowly flowing seawater, the corrosion rate of aluminum is 1 to 5 μm/year, whereas for carbon steel it is 100 to 160 μm/year.68 Additionally, even when the oxygen supply is limited, corrosion can occur in waters where SRB (sulfate-reducing bacteria) are active.69 Other surface contamination, such as oil, mill scale (a surface layer of ferrous oxides of FeO and Fe2O3 that forms on steel or iron during hot rolling)70 or deposits, may not increase the overall rate of corrosion, but it can lead to pitting and pin-hole corrosion in the presence of aggressive anions.70,71

4.2.1 Cooling Water Systems

Cooling water systems are employed to expel heat from an extensive variety of applications, ranging from large power stations down to small air conditioning units associated with hospitals and office blocks.80 Corrosion inhibitors extend the life of these systems by minimizing corrosion of heat exchange, receiving vessels and pipework that would otherwise possess a safety risk, reducing plant life and impairing process efficiency.63 Based on the type of system present, that is, either open or closed, once-through or recirculated systems, different amounts and types of corrosion inhibitors are employed. In potable waters, for example, since the