

**ASM<sup>®</sup> HANDBOOK**

Volume  
**13A**

**Corrosion:  
Fundamentals, Testing,  
and Protection**



# Contents

<b>Fundamentals of Corrosion</b> .....	1	Kinetics of Aqueous Corrosion Processes .....	44
Introduction to the Fundamentals of Corrosion .....	3	Activation Control of Corrosion .....	45
Thermodynamics .....	3	Mass Transport Control .....	47
Kinetics .....	3	Influence of Corrosion Product Deposits .....	49
Gaseous Corrosion .....	4	Kinetics of Corrosion of Passive Metals .....	49
Constructive Uses of Corrosion .....	4	Aqueous Corrosion Reaction Mechanisms .....	52
Conclusions .....	4	Fundamental Aspects of Electrode Kinetics .....	52
<b>Fundamentals of Corrosion Thermodynamics</b>		Electrode Kinetics near the Corrosion Potential .....	54
Introduction to Fundamentals of Corrosion Thermodynamics .....	5	Mechanisms of Cathodic Processes .....	56
Electrochemical Reactions .....	5	Mechanisms of Anodic Processes .....	56
Molten Salt Corrosion Thermodynamics .....	5	Passivity .....	61
Geochemical Modeling .....	5	General Aspects .....	61
Electrode Processes .....	6	Kinetics of Passivity .....	62
Electrode Reactions .....	6	Thermodynamics of Passivity .....	62
Electrode Potentials .....	8	Kinetics of Passivity .....	62
Thermodynamics of Chemical Equilibria .....	8	Nature of the Passive Film .....	63
Reactions in Aqueous Solutions .....	8	Passive-Film Formation and Dissolution .....	64
Thermodynamics of Electrochemical Equilibria .....	10	Breakdown of the Passive Film .....	65
Cell Potentials and the Electromotive Force Series .....	11	Methods for Determining Aqueous Corrosion Reaction Rates .....	68
Potential Measurements with Reference Electrodes .....	13	Electrochemical Methods .....	68
The Three-Electrode Device .....	13	Electrode Reaction Thermodynamics and Kinetics in	
Electrode Selection Characteristics .....	13	Corrosion .....	68
Operating Conditions for Reference Electrodes .....	15	Electrochemical Methods for the Study of Uniform	
Potential versus pH (Pourbaix) Diagrams .....	17	Corrosion: Polarization Methods .....	70
Calculation and Construction of <i>E</i> -pH Diagrams .....	18	Polarization Resistance Methods .....	71
Practical Use of <i>E</i> -pH Diagrams .....	22	Electrochemical Impedance Methods .....	72
<i>E</i> -pH Diagrams for Ternary Systems .....	23	Frequency Modulation Methods .....	73
<i>E</i> -pH Diagrams for High-Temperature Aqueous Solutions .....	24	Electrochemical Noise Resistance .....	74
<i>E</i> -pH Diagrams for Adsorbed Species .....	27	Electrochemical Methods for the Study of Galvanic	
Molten Salt Corrosion Thermodynamics .....	31	Corrosion Rates .....	75
Thermodynamics of Cells .....	31	Electrochemical Methods for the Definition of	
Electrodes for Molten Salts .....	31	Conditions Where Corrosion Rates Are High .....	76
Thermodynamics of Molten Salt Corrosion .....	32	Evaluation of Intergranular Corrosion Rates .....	79
Geochemical Modeling .....	34	Electrochemical Methods for Evaluation of Corrosion	
History of Geochemical Modeling .....	35	Rates under Paints .....	80
Principles of Geochemical Modeling .....	35	Nonelectrochemical Methods That Determine	
Limitations in Geochemical Modeling .....	36	Cumulative Mass Loss .....	80
Describing Equilibrium .....	37	<b>Fundamentals of Gaseous Corrosion</b>	
Applications of Geochemical Modeling to Corrosion .....	37	Introduction to Fundamentals of Corrosion in Gases .....	87
Geochemical Modeling Features .....	39	Fundamental Data .....	87
<b>Fundamentals of Aqueous Corrosion Kinetics</b>		Thermodynamics of Gaseous Corrosion .....	90
Kinetics of Aqueous Corrosion .....	42	Fundamental Data .....	90
Basis of Corrosion Reactions .....	42	Free Energy of Reaction .....	90
Thermodynamic Basis for Corrosion .....	43	Richardson-Jeffes Diagrams .....	92
		Phase Sequence in the Multilayered Scale .....	93
		Kellogg Diagrams .....	94

Determination of Partial Pressures of Gas Mixtures .....	94	Electrochemical Allied Processes .....	153
Partial Pressures of Volatile Oxidation Products .....	95	Electrochemical Deburring .....	153
Kinetics of Gaseous Corrosion Processes .....	97	Electrochemical Deep-Hole Drilling .....	154
Defect Structure of Oxide .....	97	Pulse Electrochemical Machining .....	155
Solid-State Diffusion .....	98	Electrochemical Hybrid Processes .....	157
Oxide Texture .....	101	Electrochemical Grinding .....	157
Oxidation Kinetics .....	101	The ECG Machine Tool .....	158
Thin-Film Mechanisms .....	102	Process Characteristics .....	158
Gaseous Corrosion Mechanisms .....	106	Applications .....	159
Properties of Scales .....	106	Electrochemical Refining .....	160
Stresses in Scales .....	107	Electrochemical Cell .....	160
Stress Relief .....	108	Metals Purified .....	160
Sulfidation .....	112	Principles of the Electrochemical Reactions .....	160
Metal Dusting .....	113	Physical Properties of Electrochemical Cells .....	161
Chlorine Corrosion .....	113	Engineering Considerations in the Refining Process .....	161
Summary Outline of Alloy Oxidation .....	113	Chemical-Mechanical Planarization for Semiconductors .....	164
Methods for Measuring Gaseous Corrosion Rates .....	115	History .....	164
Discontinuous Methods .....	115	Chemical-Mechanical Planarization Overview .....	164
Continuous Methods .....	115	Chemistry of Metal CMP .....	164
 		Electrochemical Theories and Methods in CMP .....	166
<b>Fundamentals Applied to Specific Environments</b>		Uncontrolled Corrosion—Chemically Induced Defects .....	167
Corrosion in Molten Salts .....	117	Conclusions .....	168
Phase Stability and Salt Chemistry .....	117	Anodes for Batteries .....	170
Electrochemistry and Fused Salt Corrosion .....	119	Constructive versus Destructive Corrosion in Batteries .....	170
Scale Fluxing: A Hot Corrosion Mechanism .....	120	Constructive Corrosion as Part of Power Generation .....	171
Consequences of Salt Chemistry on Corrosion .....	121	Constructive Corrosion as Part of Battery	
Conclusions .....	122	Manufacturing .....	175
Corrosion by Molten Nitrates, Nitrites, and Fluorides .....	124	Destructive Corrosion .....	175
Test Methods .....	124	Conclusions .....	176
Purification .....	124	Fuel Cells .....	178
Nitrates/Nitrites .....	124	Performance .....	178
Fluorides .....	125	Fuel-Cell Technology Overview .....	179
Conclusions .....	128	 	
Corrosion by Liquid Metals .....	129	<b>Forms of Corrosion .....</b>	<b>187</b>
Corrosion Reactions in Liquid-Metal Environments .....	129	Introduction to Forms of Corrosion .....	189
Considerations in Materials Selection .....	133	Uniform Corrosion .....	189
 		Localized Corrosion .....	189
<b>Fundamentals of Corrosion for Constructive Purposes</b>		Metallurgically Influenced Corrosion .....	189
Introduction to Corrosion for Constructive Purposes .....	135	Mechanically Assisted Degradation .....	189
Reversible Cell Potential .....	135	Environmentally Induced Cracking .....	189
Irreversible Cell Potential .....	136	Microbiologically Influenced Corrosion .....	189
Electropolishing .....	139	 	
Electrical Circuits .....	139	<b>Uniform Corrosion</b>	
Anodic Processes .....	139	Aqueous Corrosion .....	190
Selection of Electrolytes .....	140	Effect of pH (Acidity) .....	190
Kinetics of Electropolishing .....	140	Oxidizing Power (Electrochemical Potential) .....	192
Properties of Electropolished Surfaces .....	141	Temperature and Heat Transfer .....	193
Electrochemical Machining .....	143	Velocity and Fluid Movement .....	193
Electrochemical Machining System .....	143	Component Concentration and Composition .....	194
Theory of ECM .....	144	Atmospheric Corrosion .....	196
Metal-Removal Rate .....	145	Elements of the Process .....	196
Interelectrode Gap .....	146	Atmospheric Parameters and Their Influence .....	198
Electrolyte Conductivity .....	146	Air Chemistry and Principal Pollutants Inducing	
Process Control .....	146	Corrosion .....	199
Electrolytes .....	146	Thermodynamics of Atmospheric Corrosion and Use of	
Workpiece Shape Prediction .....	147	Pourbaix Diagrams .....	200
Tool Design .....	148	Models for Prediction of Atmospheric Corrosion .....	203
Integrated Approach for Tool Design in ECM .....	148	Atmospheric Corrosion and Precipitation Runoff from	
Process Capabilities and Limitations .....	150	Corroded Metals .....	204
Application Examples .....	150	Biologically Influenced Atmospheric Corrosion .....	205

Trends in Atmospheric Corrosion Research and Methods .....	205	Effects of Metallurgical Variables on the Corrosion of Aluminum Alloys .....	275
Galvanic Corrosion .....	210	Effect of Constituent Alloys on Pitting Corrosion of Aluminum .....	275
Galvanic Series .....	210	1xxx Series Alloys .....	275
Polarization .....	210	2xxx Series Alloys .....	275
Area, Distance, and Geometric Effects .....	210	3xxx Series Alloys .....	276
Modes of Attack .....	211	4xxx Series Alloys .....	276
Predicting Galvanic Corrosion .....	211	5xxx Series Alloys .....	276
Performance of Alloy Groupings .....	211	6xxx Series Alloys .....	276
Methods of Control .....	213	7xxx Series Alloys .....	277
Stray-Current Corrosion .....	214	Effects of Metallurgical Variables on the Corrosion of High-Nickel Alloys .....	279
Sources of Stray Currents .....	214	Heat-Resistant Alloys .....	279
Prevention of Stray-Current Corrosion .....	215	Effect of Chemical Composition on the Corrosion Behavior of Nickel Corrosion-Resistant Alloys .....	279
Molten Salt Corrosion .....	216	Factors Affecting the Corrosion Behavior of Nickel-Base Alloys .....	281
Mechanisms of Molten Salt Corrosion .....	216	Changes in Microstructure .....	281
Types of Molten Salts .....	217	Conclusions .....	285
Prevention of Molten Salt Corrosion .....	218	Effects of Metallurgical Variables on Dealloying Corrosion .....	287
Liquid Metal Corrosion .....	220	Dealloying in Aqueous Environments .....	287
Experience in Systems Exposed to Liquid Metals .....	220	The Critical Potential .....	289
Forms of Liquid-Metal Corrosion .....	220	Below the Critical Potential .....	289
Safety Considerations .....	223	Morphology Above the Critical Potential .....	289
High-Temperature Gaseous Corrosion .....	228	Mechanisms .....	289
High-Temperature Oxidation .....	230	Corrosion of Carbon Steel Weldments .....	294
Sulfidation .....	230	Influence of Weld Microstructure .....	294
Carburization .....	231	Residual Stress .....	294
Other Forms of High-Temperature Corrosion .....	232	Geometrical Factors .....	294
		Preferential Heat-Affected Zone Corrosion .....	294
<b>Localized Corrosion</b>		Preferential Weld Metal Corrosion .....	295
Pitting Corrosion .....	236	Galvanic Corrosion .....	295
Phenomenology of Pitting Corrosion .....	236	Mitigation of Preferential Weldment Corrosion .....	295
Stages of Pitting .....	239	Industrial Case Studies .....	296
Crevice Corrosion .....	242	Stress-Corrosion Cracking .....	297
Critical Factors .....	242	Corrosion of Stainless Steel Weldments .....	301
Selected Examples .....	244	Metallurgical Factors .....	301
Testing .....	245	Corrosion of Austenitic Stainless Steel Weldments .....	301
Prevention or Mitigation of Crevice Corrosion .....	245	Corrosion of Ferritic Stainless Steel Weldments .....	311
Filiform Corrosion .....	248	Corrosion of Duplex Stainless Steel Weldments .....	313
Occurrence of Attack .....	248	Corrosion of Nonferrous Alloy Weldments .....	317
Mechanism of Attack .....	249	Metallurgical Factors .....	317
Filiform Corrosion of Steels .....	249	Corrosion of Aluminum Alloy Weldments .....	317
Tests for Filiform Corrosion .....	249	Corrosion of Titanium Alloy Weldments .....	318
Filiform Corrosion of Coated Aluminum and Magnesium .....	250	Corrosion of Tantalum Alloy Weldments .....	319
Prevention of Filiform Corrosion .....	254	Corrosion of Nickel and High-Nickel Alloy Weldments .....	320
		<b>Mechanically Assisted Degradation</b>	
<b>Metallurgically Influenced Corrosion</b>		Forms of Mechanically Assisted Degradation .....	322
Introduction to Metallurgically Influenced Corrosion .....	257	Erosion .....	322
Stainless Steel and Nickel Alloys .....	257	Fretting Corrosion .....	324
Aluminum .....	257	Fretting Fatigue .....	325
Factors Influencing Corrosion .....	257	Cavitation Erosion and Water Drop Impingement .....	326
Effects of Metallurgical Variables on Aqueous Corrosion .....	258	Corrosion Fatigue .....	328
Fundamentals of Pure Metals, Impure Metals, and Alloys .....	258	Aqueous Corrosion-Wear Interactions .....	331
Influence on Corrosion .....	260	Methods of Wear Measurements .....	331
Effects of Metallurgical Variables on the Corrosion of Stainless Steels .....	266	Model of Corrosive Wear .....	332
Austenitic Stainless Steels .....	266	Polarization Curve Measurements under Abrasion .....	332
Ferritic Stainless Steels .....	268	Effect of Galvanic Interactions on Flotation .....	332
Duplex Stainless Steels .....	271	Mechanism of Electrochemical Interaction .....	333
High-Performance Stainless Steels .....	272	Relative Significance of Corrosion and Abrasion in Wear .....	333

Galvanic Interactions in Multielectrode Systems .....	334	Simulated Service Corrosion Testing .....	419
Case History on Material Selection for Grinding Balls ....	335	In-Service Techniques for Damage Detection and	
Gaseous Corrosion Wear Interactions .....	338	Monitoring .....	419
Mechanisms .....	338	Evaluating Forms of Corrosion .....	419
Measurement .....	342		
Control .....	343		
<b>Environmentally Induced Cracking</b>		<b>Planning Corrosion Tests and Evaluating Results</b>	
Introduction to Environmentally Induced Cracking .....	345	Designing, Planning, and Preparing Corrosion Tests .....	420
Stress-Corrosion Cracking .....	346	Test Objectives and Conditions .....	420
The Phenomenon of SCC .....	346	Design of Experiments .....	421
Overview of SCC Mechanisms .....	347	Examples of Experimental Designs Applied to Corrosion	
Controlling Parameters .....	348	Testing .....	423
Important Fracture Features .....	349	Statistical Interpretation of Corrosion Test Results .....	425
Phenomenology of Crack Initiation Processes .....	349	Complexity of Test Conditions .....	425
Crack Initiation Mechanisms .....	350	Mechanistic Aspects .....	426
Phenomenology of Crack Propagation Processes .....	351	Probabilistic Aspects .....	426
Crack Propagation Mechanisms .....	360	Statistical Analysis .....	429
Hydrogen Damage .....	367	Modeling Corrosion Processes .....	430
Classification of Hydrogen Processes .....	367	Mechanistic Models .....	430
Theories for Hydrogen Damage .....	368	Risk-Based Models .....	438
Hydrogen Damage in Iron-Base Alloys .....	370	Knowledge Models .....	442
Nickel Alloys .....	374		
Aluminum Alloys .....	375	<b>Laboratory Corrosion Tests</b>	
Copper Alloys .....	375	Electrochemical Methods of Corrosion Testing .....	446
Titanium Alloys .....	376	Fundamentals .....	446
Zirconium Alloys .....	377	Preparing an Electrochemical Polarization Experiment ....	447
Vanadium, Niobium, Tantalum and Their Alloys .....	378	No-Applied-Signal Tests .....	449
Intermetallic Compounds .....	379	Small-Signal Polarization Tests .....	451
Liquid Metal Induced Embrittlement .....	381	Large-Signal Polarization Tests .....	455
Mechanisms of Embrittlement .....	382	Scanning Electrode Techniques .....	459
Role of Liquid in Crack Propagation .....	383	Miscellaneous Techniques .....	460
Occurrence of LMIE .....	383	Immersion Testing .....	463
Effects of Metallurgical, Mechanical, and Physical		Total Immersion .....	463
Factors .....	385	Autoclave Tests .....	465
Fatigue in Liquid Metal Environments .....	387	Partial Immersion to Vapor Phase .....	466
Decrease or Elimination of LMIE Susceptibility .....	387	Intermittent Immersion .....	466
Embrittlement of Nonferrous Metals and Alloys .....	387	Specimen Preparation Duration of Tests .....	467
Embrittlement of Ferrous Metals and Alloys .....	388	Calculation of Corrosion Rate .....	468
Solid Metal Induced Embrittlement .....	393	Reporting the Data .....	468
Characteristics of SMIE .....	393	Cabinet Testing .....	470
Investigations of SMIE .....	394	Applications and Use of Salt Spray (Fog) Testing .....	470
Delayed Failure and Mechanism of SMIE .....	394	Static Atmosphere Condition Salt Spray (Fog) Tests .....	473
		Cyclic and Other Atmosphere Condition Salt Spray	
		(Fog) Tests .....	474
		Combining Weathering (Light Exposure Apparatus)	
		and Salt Spray (Fog) Type Corrosion Tests .....	474
<b>Microbiologically Influenced Corrosion</b>		Test Specimen Procedures for Salt Spray (Fog)	
Microbiologically Influenced Corrosion .....	398	Corrosion Tests .....	474
General Characteristics of Microbes .....	399	Pretest Specimen Preparation for Salt Spray	
Organisms Involved in Biological Corrosion .....	399	Corrosion Tests .....	474
Formation of Biofilms .....	400	Salt Spray Test Chamber Apparatus .....	475
General Mechanisms by Which Biological Organisms		Microbiologically Influenced Corrosion Testing .....	478
Influence Corrosion .....	402	Biofilm Formation .....	478
Industries Affected .....	404	Mechanisms .....	479
Microbiologically Influenced Corrosion of Various		Electrochemical Techniques .....	480
Materials .....	404		
Testing for Microbiologically Influenced Corrosion .....	409	<b>Simulated Service Corrosion Testing</b>	
Prevention of MIC .....	410	Simulated Service Testing in the Atmosphere .....	487
Further Reading .....	413	Atmospheric Corrosion .....	487
		Types of Atmospheres .....	487
<b>Corrosion Testing and Evaluation</b> .....	417	Relative Corrosivity .....	488
Introduction to Corrosion Testing and Evaluation .....	419	Environmental Factors .....	488
Planning Corrosion Tests and Evaluating Results .....	419	Conducting Atmospheric Corrosion Tests .....	488
Laboratory Corrosion Testing .....	419	Analyzing Atmospheric-Corrosion Tests .....	491

Simulated Service Testing in Water .....	495	Strategies in Corrosion Monitoring .....	539
Test Method Selection and Precautions .....	496	Interpretation and Reporting .....	540
Test Specimens .....	496		
Effect of Water Variables .....	496	<i>Evaluating Forms of Corrosion</i>	
Simulated Service Testing in Soil .....	497	Evaluating Uniform Corrosion .....	542
Soil Characteristics .....	497	Mass-Loss Tests .....	542
Test Approach .....	498	Other Test and Evaluation Methods .....	544
Specimen Preparation .....	498	Evaluating Pitting Corrosion .....	545
Specimen Burial .....	498	Test Methods .....	545
Corrosion Measurements .....	499	Examination of Pits .....	546
Specimen Retrieval .....	500	Evaluation of Pitting .....	546
Conclusions .....	500	Evaluating Crevice Corrosion .....	549
<i>In-Service Techniques for Damage Detection and Monitoring</i>		Aspects of Crevice Corrosion Testing .....	549
In-Service Techniques—Damage Detection and Monitoring .....	501	Guidelines for Crevice Corrosion Testing .....	549
Electrochemical Methods .....	501	General Considerations .....	549
Electromagnetic and Sonic Methods .....	503	Specific Crevice Corrosion Tests .....	550
Optical and Fiber-Optic Sensing .....	504	Multiple-Crevice Assembly Testing .....	551
Fluorescence Methods .....	504	Continuous Crevice Formers .....	552
Other Corrosion-Detection Methods .....	505	Evaluating Cylindrical Materials and Products .....	554
Data Management and Expert System .....	506	Component Testing .....	556
Simulation and Modeling .....	506	Electrochemical Tests .....	557
Electrochemical Techniques for In-Service Corrosion Monitoring .....	509	Mathematical Modeling .....	559
Direct Current Electrochemical Techniques .....	509	Evaluating Galvanic Corrosion .....	562
Electrochemical Impedance Spectroscopy .....	510	Component Testing .....	562
Corrosion Monitoring Techniques .....	514	Modeling .....	562
On-Line Corrosion Monitoring Techniques .....	514	Laboratory Testing .....	563
Direct Techniques .....	514	Evaluating Intergranular Corrosion .....	568
Indirect Techniques .....	515	The Purpose of Testing .....	568
System Considerations .....	516	Tests for Stainless Steels and Nickel-Base Alloys .....	568
Examples of On-Line Corrosion Monitoring .....	517	Tests for Aluminum Alloys .....	569
Monitoring of Localized Corrosion .....	519	Tests for Other Alloys .....	570
Initiation of Localized Corrosion .....	519	Evaluating Exfoliation Corrosion .....	572
Electrochemical Noise Method .....	519	Spray Tests .....	572
Galvanically Coupled Differential Flow Cell .....	519	Immersion Tests .....	573
Galvanically Coupled Crevice Cell .....	520	Visual Assessment of Exfoliation .....	574
Coupled Multielectrode Sensors .....	521	Evaluating Stress-Corrosion Cracking .....	575
Electrochemical Biofilm Activity Sensor .....	522	General State-of-the-Art .....	575
Nonelectrochemical Methods .....	523	Static Loading of Smooth Specimens .....	576
Conclusions .....	523	Static Loading of Precracked (Fracture Mechanics)	
Infrared Imaging for Corrosion, Disbondments, and Cracks .....	525	Specimens .....	583
Infrared Thermography Equipment .....	525	Dynamic Loading: Slow-Strain-Rate Testing .....	591
Thermographic Process .....	526	Selection of Test Environments .....	592
Imaging Results .....	527	Testing of Aluminum Alloys .....	596
Sonic Thermography for Crack Detection .....	527	Testing of Copper Alloys (Smooth Specimens) .....	599
Corrosion Monitoring Using Microwave and Guided Wave		Testing of Carbon and Low-Alloy Steels .....	601
Nondestructive Evaluation .....	529	Testing of High-Strength Steels .....	602
Microwave NDE Devices .....	529	Testing of Non-Heat-Treatable Stainless Steels .....	603
Guided Wave Ultrasonic Devices .....	530	Testing of Magnesium Alloys .....	605
Corrosion Monitoring for Industrial Processes .....	533	Testing of Nickel Alloys .....	605
Selecting a Corrosion-Monitoring Method .....	533	Testing of Titanium Alloys .....	605
Direct Testing of Coupons .....	533	Special Considerations for Testing of Weldments .....	607
Electrical-Resistance Probes .....	536	Surface Preparation of Smooth Specimens .....	607
Ultrasonic Thickness Measurements .....	536	Interpretation of Test Results .....	608
Polarization-Resistance Measurement .....	537	Selection of Test Method .....	611
Measurement of Corrosion Potentials .....	537	Evaluating Hydrogen Embrittlement .....	617
Alternating Current Impedance Measurements .....	537	Toward a Definition .....	617
Electrochemical Noise .....	538	Sources of Hydrogen .....	618
Hydrogen Probe .....	538	Source of Stress .....	618
Analysis of Process Streams .....	538	Testing .....	618
Sentry Holes .....	539	Interpretation of Test Results .....	622
Side-Stream (Bypass) Loops .....	539	Prevention and Control .....	623

Evaluating Corrosion Fatigue .....	625	Effects of Alloying on Active Anodic Corrosion of Titanium .....	706
Relationship between Corrosion-Fatigue Cracking, Stress-Corrosion Cracking, and Hydrogen Embrittlement Cracking .....	625	Effects of Alloying Additions on Titanium Passivity .....	707
Prediction of Corrosion-Fatigue Life .....	625	Formation of Amorphous or Vitreous Oxide .....	707
Types of Corrosion-Fatigue Tests .....	625	Reduction of the Potential Gradient across Surface Film ..	708
Standards and Recommended Practices for Fatigue Testing .....	625	Enhancement of Atomic Bond Strength .....	708
Cycles-to-Failure Tests .....	626	Lowering of the pH of Zero Charge .....	709
Environmental Effects and Fatigue .....	630	Repassivation Behavior of Titanium and Titanium-Base Alloys .....	709
Crack Propagation Tests .....	631	<b>Surface Treatments and Conversion Coatings</b>	
Evaluating Erosion Corrosion, Cavitation, and Impingement .....	639	Phosphate Conversion Coatings .....	712
Standard Test Methods .....	639	Structure and Function of the Phosphate Film .....	712
Other Tests .....	642	Phosphating Steps .....	714
Effects of Test Parameters .....	642	Physical and Chemical Properties .....	717
Data Correlations .....	643	Processing Equipment and Control .....	718
Evaluating Microbiologically Influenced Corrosion .....	644	Chromate and Chromate-Free Conversion Coatings .....	720
Attack by Sulfate-Reducing Bacteria .....	644	Historical Perspective .....	720
Attack by Organisms Other Than SRB .....	645	Chromate Conversion Coating Formation .....	720
Testing for Microbiological Activity .....	647	Morphology, Structure, and Composition .....	722
Risk Assessment Based on Operating Conditions .....	648	Coating Properties .....	723
High-Temperature Gaseous Corrosion Testing .....	650	Chromate-Free Conversion Coatings .....	727
Factors Affecting High-Temperature Corrosion and Materials Properties .....	650	Chromate-Free Processes .....	727
Measurement of High-Temperature Degradation .....	657	Aluminum Anodizing .....	736
High-Temperature Corrosion and Degradation Processes .....	659	Structure of Anodic Oxide Films .....	736
High-Temperature Materials .....	663	Anodizing .....	738
Testing Methods Used for Materials at High Temperatures .....	665	Testing of Film Properties .....	740
<b>Methods of Corrosion Protection .....</b>	<b>683</b>	Surface Modification Using Energy Beams .....	741
Introduction to Methods of Corrosion Protection .....	685	Ion Implantation .....	741
Factors Affecting Corrosion Behavior .....	685	Laser Surface Processing .....	744
Galvanic Couples .....	685	<b>Ceramic, Glass, and Oxide Coatings</b>	
Coatings .....	685	Porcelain Enamels .....	750
Inhibitors .....	686	Types of Porcelain Enamels .....	750
<b>Corrosion Resistance of Bulk Materials</b>		Frits for Porcelain Enameling .....	750
Introduction to Corrosion Resistance of Bulk Materials .....	687	Properties of Porcelain Enamels .....	751
Alloying .....	687	Corrosion Resistance of Porcelain Enamels .....	752
Metallurgical Factors .....	687	Evaluation of Porcelain-Enameled Surfaces .....	752
Mechanical Treatments .....	688	Chemical-Setting Ceramic Linings .....	755
Corrosion Resistance of Aluminum Alloys .....	689	History of Chemical-Setting Silicates .....	755
Alloying to Improve Corrosion Resistance .....	689	Advantages and Disadvantages .....	755
Mechanical Treatments to Improve Corrosion Resistance .....	690	Current Technologies .....	756
Surface Treatment to Improve Corrosion Resistance .....	690	Corrosion Resistance .....	757
Processing to Improve Corrosion Resistance .....	691	CVD and PVD Coatings .....	759
Selection of Fabrication Operations .....	691	Deposition Processes .....	759
Corrosion Resistance of Magnesium Alloys .....	692	Coating Materials and Applications .....	761
Metallurgical Factors .....	693	Pack Cementation Coatings .....	763
Causes of Corrosion Failures in Magnesium Alloys .....	695	Halide-Activated Pack Cementation .....	763
Corrosion Resistance of Stainless Steels and Nickel Alloys .....	697	Types of Pack Cementation Processes .....	763
Stainless Steels .....	697	<b>Metal Coatings</b>	
Nickel-Base Alloys .....	700	Electroplated Coatings .....	772
Corrosion Resistance of Titanium Alloys .....	703	Idealized Coating .....	772
Corrosion Resistance of Titanium and Titanium-Base Alloys in Aqueous Environments .....	703	Substrates .....	773
Passivating Titanium Oxides .....	703	Design for Plating .....	775
Corrosion Vulnerability of Titanium and Titanium Oxides .....	703	Advantages and Disadvantages of Electroplated Coatings .....	777
		Effects of Deposition Parameters .....	778
		Mechanisms of Corrosion Prevention of Plated Coatings .....	778
		Applications for Electrodeposited Coatings .....	780
		Selection of Coatings .....	781
		Plating of Mill Products .....	782
		Electrochemical Predictions of Corrosion Performance .....	783
		Future Trends .....	784

Continuous Hot Dip Coatings .....	786	Background and Theory .....	851
Basic Principles .....	786	Equipment Required for Anodic Protection .....	852
Hot-Dip Coatings .....	788	Design Concerns .....	853
Batch Process Hot Dip Galvanizing .....	794	Applications .....	853
Surface Preparation .....	794	Economics .....	853
Galvanizing .....	794	Cathodic Protection .....	855
Coating Weight and Thickness .....	795	Fundamentals of Cathodic Protection .....	855
Factors Affecting Coating Thickness and Structure .....	795	Types of Cathodic Protection .....	857
Mechanical Properties of the Coating and Steel .....		Cathodic Protection Criteria .....	858
Substrate .....	796	Anode Materials .....	859
Fabrication Details for Galvanizing .....	796	Power Sources .....	861
Galvanized Coatings in Corrosion Service .....	797	Design .....	861
Joining of Galvanized Structural Members .....	799	Case Histories .....	861
Painting Galvanized Steel .....	800	<b>Corrosion Inhibitors</b>	
Economics of Hot-Dip Galvanizing .....	801	Vapor Phase Corrosion Inhibitors .....	871
Selected Applications of Hot Dip Galvanized Steel .....	801	Definition and Classification .....	871
Galvanizing Specifications .....	801	VCI Action Mechanism .....	871
Thermal Spray Coatings .....	803	Structure of VCIs .....	872
Thermal Spray Processes .....	803	Vapor Pressure of VCIs .....	873
Controlling the Structure, Properties, and Performance .....		VCI Evaluation Methods .....	873
of Coatings .....	804	VCI Applications .....	874
Criteria for Coating Selection .....	804	Protection of Aluminum .....	874
Costs of Thermal Spray Coatings .....	807	Protection of Ferrous and Nonferrous Metals .....	874
Case Studies .....	808	Corrosion Inhibitors for Oil and Gas Production .....	878
Specification and Quality Control for Coatings .....	809	Inhibitor Formulations .....	878
Summary .....	811	Varying Characteristics of Oil and Gas Wells .....	879
Further Literature Sources for Thermal Spray .....	811	Influence of Well Depth and Completion Method .....	879
<b>Coatings and Linings</b>		Factors Influencing Corrosivity of Produced Fluids .....	880
Introduction to Coatings and Linings .....	814	Methods of Inhibitor Application .....	880
The Effect of Legislation on the Coatings Industry .....	814	Corrosion Problems and Inhibition in Waterfloods .....	882
Coating Industry Response to Legislative Pressure .....	814	Bacteria-Induced Corrosion .....	883
Organic Coatings and Linings .....	817	Laboratory Testing of Corrosion Inhibitors .....	883
Autooxidative Cross-Linked Resins .....	817	Monitoring Results of Inhibition in the Field .....	884
Thermoplastic Resins .....	820	Quality Control of Inhibitors .....	884
Cross-Linked Thermosetting Coatings .....	825	Computerization of Inhibitor Treatment Programs .....	884
Zinc-Rich Coatings .....	834	Corrosion Inhibitors for Crude Oil Refineries .....	887
Characteristics of Zinc-Rich Coatings .....	834	Areas of Corrosion in the Refinery .....	887
Zinc-Rich Coatings with Organic Binders .....	835	Types of Inhibitors .....	888
Zinc-Rich Coatings with Inorganic Binders .....	835	Application of Inhibitors .....	889
Comparisons of Inorganic and Organic Zinc-Rich .....		Corrosion Monitoring .....	889
Coatings .....	836	Corrosion Inhibitors in the Water Treatment Industry .....	891
Paint Systems .....	837	Boiler Systems .....	891
Coating System Selection .....	837	Cooling Systems .....	893
Surface Preparation .....	837	Corrosion Processes in Water-Recirculating Systems .....	894
Coating Application .....	840	Influence of Water Quality .....	895
Quality Assurance .....	842	Corrosion Control in Municipal Water Systems .....	904
Rubber Coatings and Linings .....	845	<b>Designing for Corrosion Control and Prevention</b> .....	<b>907</b>
Rubber as a Protective Lining .....	845	Materials Selection for Corrosion Control .....	909
Commercial Lining Products .....	845	The Materials Selection Process .....	909
Types of Rubbers .....	845	Selecting Materials to Prevent or Control Corrosion .....	911
Vulcanization .....	848	Economics .....	925
Rubber Lining Application .....	848	Designing to Minimize Corrosion .....	929
Inspecting Rubber Lining Work .....	849	Design Considerations .....	929
Material and Installation Costs .....	850	Corrosion Awareness .....	929
<b>Electrochemical and Corrosion Control Methods</b>		Why Failures Occur .....	930
Anodic Protection .....	851	Design and Materials Selection .....	930
History .....	851	Design Factors That Influence Corrosion .....	932
Anodic Protection Uses .....	851	Corrosion Economic Calculations .....	940
Comparison of Anodic and Cathodic Protection .....	851	Money and Time .....	940
		Notation and Terminology .....	940



Methods of Economic Analysis .....	941	Confidence Limits .....	975
Annual versus Continuous Compounding .....	941	Sampling Issues .....	976
Depreciation .....	942	Analysis of Variance .....	976
Generalized Equations .....	943	Correlation and Regression .....	977
Examples and Applications .....	944	<b>Materials Science for the Corrosionist .....</b>	<b>980</b>
<b>Predictive Modeling of Structure Service Life .....</b>	<b>946</b>	Classification of Materials .....	980
Design Philosophies .....	946	Properties .....	982
Conceptual Framework .....	947	Processing .....	987
Corrosion Fatigue Model Applications .....	949	<b>Applications of Modern Analytical Instruments in Corrosion .....</b>	<b>992</b>
Application of Models during Their Development .....	954	Strategy for Selecting Analytical Approaches .....	992
Conclusions .....	957	Surface Structure Analysis .....	992
<b>Direct Costs of Corrosion in the United States .....</b>	<b>959</b>	Determination of Chemical Composition .....	992
Methodology .....	959	Analytical Methods .....	993
Definitions .....	960	<b>Information Sources and Databases for the Corrosionist .....</b>	<b>999</b>
Costs of Corrosion Control Methods and Services .....	960	Societies and Associations .....	999
Costs of Corrosion Estimated by Industry Sector .....		Corrosion Standards, Specifications, Recommended .....	
Analysis .....	962	Practices, and Related Topics .....	999
Conclusions Based on 1998 U.S. Study .....	967	Sources of Corrosion Information .....	1000
Corrosion Prevention Strategies .....	967	Corrosion Databases and Data Compilations .....	1000
<b>Tools for the Corrosionist .....</b>	<b>969</b>	Other Web Resources .....	1000
Introduction to Tools for the Corrosionist .....	971	<b>Conventions and Definitions in Corrosion and Oxidation .....</b>	<b>1002</b>
Statistics .....	971	Corrosion and Electrochemical Cells .....	1002
Materials .....	971	Cathodic Protection .....	1004
Instruments .....	971	Electricity .....	1006
Additional Help .....	971	Oxidation .....	1007
Terminology and Presentation of Data .....	971	<b>Reference Information .....</b>	<b>1009</b>
<b>Statistics for the Corrosionist .....</b>	<b>972</b>	Glossary of Terms .....	1011
Definitions and Expressions .....	972	Corrosion Rate Conversion .....	1028
Measurement .....	973	Metric Conversion Guide .....	1029
Statistical Hypothesis Testing .....	973	Abbreviations and Symbols .....	1032
Simple Statistical Tests .....	975	Index .....	1034