Index

A

1100, 28, 40, 43
2024, 26, 28, 32, 37, 40, 43
2219, 40, 43
4043, 62
5052, 212–214
5086, 63
5356, 63
6061, 23, 26, 40, 43, 61–63, 96, 103–112, 189
7075, 22, 28, 32, 37, 38, 43, 96, 103–112
Compatibility with dissimilar materials, 42
Corrosion potentials, 23
Corrosion rates, 23
Galvanic corrosion, 20
Galvanic series, 26
Literature references on pitting, 276
Maximum pit depth, 212
Pipeline, 214
Pitting probability, 212
Power cables, 71
Area ratio, 15, 32, 36, 38, 50, 52, 54, 55, 66, 79, 139, 237, 238, 240, 241
ASTM exposure racks, 98
Atmospheric exposure, 94, 98, 106
Clean air, 132, 138
Galvanic, 94
Panama Canal Zone, 94
Polluted air, 141
Atmospheric pollutants
Effect on materials, 132
Effect on pitting, 136
Nitrogen dioxide, 133
Ozone, 133
Sulfur dioxide, 133
Autoclave tests, 148

B

Bimetallic couples (see also Galvanic couples and Dissimilar metals), 48
Brine solutions, 147
Pitting of titanium, 147
Buried structures (see also Soils), 69

C

Carbon
Effect on pitting of copper tubes, 162, 166, 177, 178
Residue in copper tubes, 156, 157, 163, 174, 175
Calcium, 253–255
Cadmium, 23, 25, 32, 40, 43
Carbon black (CB) test, 158, 176, 178
Case histories, 117
Catchment principle, 36, 38
Cathodic control, 78
Cathodic protection, 48, 54
Cathodic current, 90
Composite structures, 48
Current density distribution, 48
Galvanic couples, 33, 67, 105, 112, 150
Protection voltage, 48
Seawater, 48
Weld materials, 62
CB number, 158-171, 177
Round-robin testing, 177
Chemical analysis techniques
Atomic absorption, 244
Electron microprobe, 204
Emission spectrography, 247
Karl Fischer titration, 181
X-ray diffraction, 141, 246
X-ray fluorescence, 247
Cleaning procedures, 59
Abrasivc, 171-173
ASTM Recommended Practice, 101, 204
Chemical, 98, 101, 168, 178
Standard techniques, 22
Ultrasonic, 86
Coatings for corrosion protection, 117, 126
Inorganic conversion, 46
Metallic, 46
Copper and copper alloys, 11, 15, 17, 22-28, 32, 40, 43, 49-52, 71, 155-179, 192, 233, 237
122 alloy, 155
360 brass, 96, 103-112
70Cu-30Ni, 10, 233, 237
Corrosion products, 178
Literature references on pitting, 280
Pitting corrosion, 171
Potentials in water, 162
Copper tubes in cold water service, 155, 156
British standard specification, 157, 158, 172
Cleaning, 172
Effect of alloying, 169
Effect of carbon residues, 162, 166, 177
Effect of drawing lubricants, 156
Effect of temper, 167, 175
Effect of water composition, 164
Factors affecting corrosion, 156
Cobalt and cobalt alloys
Haynes 188, 25, 41
Concentration cell corrosion, 231, 237, 261
Area ratio effects, 238
Critical oxygen level, 138
Under-deposit corrosion, 119
Water-line attack, 119
Corrosion fatigue, 117, 125
Corrosion products
Analysis, 141, 246
Bridge over pit, 252
Carbon steel tubes, 122
Collection and identification, 204
Copper, 178
Galvanized steel-clean air, 142-144
Galvanized steel-polluted air, 144, 145
Iron, colloids, 259
Titanium, 150
Zinc, 139-141
Cost of corrosion, 129
Crevice corrosion (see also Concentration cell corrosion), 102, 103, 105
Area ratio effects, 237, 241
Electrode assembly, 262
Electrode-mount interface, 270
Evaluation, 261
Initiation and propagation, 16, 235, 239
In seawater, 231, 234
Morphology, 236, 238, 240
Probability, 236, 239
Potential regions, 268
Stainless steels in seawater, 234
Standard specimen, 232
Statistics, 231
Test method, 232
Types of crevices, 231
Current (see also Galvanic current)
Alternating, 69
Continuous monitoring, 12, 48
Diffusion current density, 39
Distribution, 52
Leakage, 69
Measurement, 11, 46, 58, 88
Protection, 50, 55
Current-time curves
Galvanic, 12, 14, 24–30

D

Delamination
Aluminum alloys, 112
Depth gage, 208
Dew
Light cycle, 134
pH, 139–141
Dezincification, 103
Diffusion current density, 33, 39
Dissimilar metals, 22, 26, 42, 48, 56, 81, 102–112

Effect of potential difference (see also Galvanic couples), 39
Distilled water, 26, 28

E

Eddy-current testing, 157, 160, 206
Electrochemical instrumentation, 5, 43
Operational amplifier, 13, 45
Potentiostat, 12, 45, 182
Zero resistance ammeter, 11, 44, 58, 87
Electrochemical techniques
Applications and precautions, 7
Cathodic polarization, 186, 189
Cathodic protection, 48, 54
Critical pitting potential, 185
Current measurement, 11, 46, 58, 88
Evaluation of crevice corrosion, 261
Evaluation of pitting corrosion, 261
Examination of fused joints, 56
Galvanic currents, 11, 21, 43–45, 58
Galvanostatic polarization, 48, 71, 75, 77
Passive current density, 184
Polarization measurement, 15, 16, 39
Polarization resistance, 190
Potential measurement, 8, 15, 59, 87
Potentiodynamic polarization, 16, 261
Predicting galvanic corrosion, 5
Soil measurements, 86
Electromagnetic testing, 206
Electron microprobe analysis, 140, 204
Electroplated coatings
  Literature references on pitting, 280
Ellipsometry, 202
Environmental chamber, 133
Environmental effects
  Literature references on pitting, 280
Environmental Protection Agency (EPA), 132
Environments
  Concentrated brine, 147
  Distilled water, 26, 28
  Galvanic corrosion, 28, 39
  Marine, 95
  Seawater, 9, 48, 49, 57, 62, 63, 94
  Soils, 73, 77, 83, 85, 86, 100
  Tap water, 26, 28
  Tropical, 95
  Underground, 69
Exfoliation, 103

F
Failure analysis, 117
Faraday's law, 33, 79
Field failures (see Service failures)
Fused joints (see Welded joints)

G
Galvanic corrosion
  Air, soil, and sea environments, 94
  Aluminum alloys, 20
  Composite structures, 48
  Effect of area ratios, 32, 50, 52, 54, 55
  Effect of corrosive environment, 28, 39
  Effect of dissimilar metal, 22, 39
Electrochemical techniques, 5, 43
Laboratory studies, 20
Magnitude, 21
Panama Canal Zone, 94
Prediction, 5
Pitting, 14, 102–112, 152
Ranking of aluminum-metal couples, 25
Tests, 5
Theoretical considerations, 33
Underground, 81
Underground power cables, 69
Weld material, 66
Galvanic couples (see also Dissimilar metals)
  Aluminum alloys, 4130 steel, 14, 23, 31
  Aluminum 2024, copper, 35
  Aluminum 6061, metals and alloys, 26, 102–112
  Aluminum 7075, cadmium, 23, 32
  Aluminum 7075, copper, 22, 28
  Aluminum 7075, Ti-6Al-4V, 22, 102–112
  Aluminum 7075, zinc, 23, 32
  Aluminum 7075, Type 304 stainless steel, 22, 110
Atmospheric, 94
Cathodic protection, 33, 67, 105, 112, 150
Copper, carbon steel, 11, 48
Copper, iron, 15
Copper, Type 304 stainless steel, 16
Copper, Type 409 stainless steel, 11
Copper, Type 430 stainless steel, 11, 16
Combination of magnesium AZ31, Type 316 stainless steel, 4340 steel, 6061 and 7075 aluminum, 360 brass, 400
Monel, and Ti-6Al-4V, 102–112
Dissimilar metals, 22, 26, 42, 48, 56, 81, 102–112
SCPE, lead/tin alloy, 79, 80
SCPE, copper, 79, 80
Seawater, 94
Soil, 94
Stainless steel, magnesium, 87
Stainless steel, metals, 16, 89, 102–112
Welded joints, 56
Galvanic current, 5, 11, 12, 14, 22, 26, 28, 32, 33, 37, 40, 44–46, 59, 62, 66, 73, 78, 87, 89
Continuous monitoring, 12, 46
Current density, 33, 35, 40
Measured versus true, 14
Measurement, 11, 21, 43
Welded specimens, 60, 67
Galvanic series
Based on metal potentials, 10, 40
Factors affecting position, 10
For aluminum, 26
For seawater, 9
Ranking, 25, 26
Galvanized steel, 132, 135–142
Effect of dew, 141
Lead inclusions, 139
Moisture nucleation sites, 139
Pitting, 132
Potential, 142
Pourbaix diagram, 145
Graphite
Literature references on pitting, 282

H

Heat exchanger
Carbon steel tube failure, 118

Chromate inhibitor, 119
Cupro-nickel tubes, 119
Monel tube sheets, 147, 153
Titanium tubes, 147
Tube deposits, 119
Hydrogen embrittlement, 81, 90, 92

I

Inhibitors
Anions, 181
Chromate, 119
Organic, 156, 173

Ion concentrations
Calcium, 253–255, 258
Chloride, 39, 180, 249, 257
Hydroxyl, 247
Iron, 251, 258
Magnesium, 248–253, 258
Mass balance calculations, 255
Nitrate, 193
Perchlorate, 180, 193
Phosphate, 180, 193
Sodium, 255, 256
Sulfate, 180, 200, 258
Iron, 6, 8, 15, 83, 86, 87, 190, 199, 256–258
Colloids, 259
Corrosion products, 259
Ductile, 220–227
Gray cast iron pipe, 217, 229
In titanium scratches, 149
In aluminum pit, 204
Literature references on pitting, 282
Nodular, 217
Pitting in seawater, 243
Iron-chromium-nickel alloys (see also Stainless steels), 261
Literature references on pitting, 283
INDEX

L

Lead, 8
  Lead-tin alloy, 71, 78
Literature references on pitting corrosion
  Aluminum, 276
  Copper, 280
  Electroplated coatings, 280
  Environmental effects, 280
  Graphite, 282
  Iron and steel, 282
  Iron-chromium-nickel alloys, 283
  Nickel, 288
  Test methods, 289
  Theoretical, 290
  Titanium, 292
  Tungsten, 292
  Zinc, 292
  Zirconium, 292
Localized corrosion, 117

M

Magnesium and magnesium alloys, 83, 86, 87, 88, 248–253
  AZ-31, 96, 102, 104–112
Marine environments (see Seawater)
Metal-ion corrosion, 237
  Area ratio effects, 240
Methyl alcohol, 181, 182
  Acid additions, 181, 189, 193, 194
  Anhydrous, 181
  Aqueous, 181
  Decomposition potential, 202
  Water additions, 181, 182, 195, 197, 199
Microscopy
  Calibrated focus, 202
  Interference, 209

D

Optical, 88
  Scanning electron, 139, 141–143
Military equipment, 95
Mixed-potential theory, 5
Moisture nucleation sites, 146

N

National Bureau of Standards
  (NBS), 81, 218
National Committee on Materials Policy, 129
Nernst equation, 260
Nickel and nickel alloys, 10, 25, 43, 187, 199
  65Ni-35Cu, 233, 237
  Hastelloy C, 233, 241
  Incoloy 825, 233, 237
  Inconel 625, 233, 241
  Inconel 718, 25, 40
Literature references on pitting, 288
  Monel, 147, 152
  Monel 400, 96, 103–112
  Pitting morphology, 192
Nondestructive testing, 203, 206
  Acoustic emissions, 207
  Eddy current, 157, 160, 164, 165, 206
  Electromagnetic, 206
  Hydrostatic, 120, 129
  Magnetic field, 206
  Penetrants, 207
  Radiographic, 119, 124, 206
  Sonics, 206
  Ultrasonics, 206

O

Operational amplifier, 13, 45
INDEX 305

P

Panama Canal Zone, 95, 98
Galvanic corrosion, 94
Passivation
Titanium, 195, 197
Passivity, 184, 197, 199
Passive films, 10, 196, 202
pH
Effect on potential, 142
Measurement in pits, 246
Microelectrode, 246
Profile in simulated pit, 256
Variations, 75, 259
Phosphorus-deoxidized copper, 168
Pipeline
Service life, 213, 227
Pits
Acidic conditions, 153
Active, 173
Density, 205
Detection by nondestructive methods, 206
Examination, 204
Identification, 204
Macropit, 244
Morphology, 120, 122, 148–153, 190–197, 205, 208, 211, 267
pH within, 246
Size and distribution, 205
Solution chemistry, 246–257
Pit depth measurements, 207–210, 217, 218, 220, 229
Average, 210
Depth gage, 208
Machining, 208
Maximum, 210–214
Metallographic, 207
Micrometer, 208
Microscopic, 209
Spherometer, 209
Pitting corrosion
Artificial pit, 243
Autocatalytic, 141
Copper tubes in water, 155, 156, 160, 171
Effect of alloying, 169
Effect of carbon residues, 155, 156, 162, 177, 178
Effect of pH, 156
Effect of temper, 167
In England, 175
Data interpretation, 217
Definition, 203
Density, 205
Effect of chloride, 180, 196
Effect of pH, 146, 153
Effect of scratches, 149–153
Effect of sulfates, 180, 200
Effect of water, 164, 194
Effect of pollutants, 136
Effect on mechanical properties, 214
Evaluation, 203, 261
Galvanic couples, 102–112, 152
Galvanized steel, 132
Heat exchanger tube, 120
Initiation and propagation, 16, 139, 150
Literature references, 276
Loss in mechanical properties, 214
Macropit, 244
Measurement, 203, 218
Methods to determine extent, 207
Morphology, 120, 122, 148–153, 190–197, 205, 208, 211, 267
Organic media, 180, 186
Protection, 16
Rate of attack, 137
Solution chemistry, 243–257
Statistical calculations, 217
Steam condensate line, 120
Steam generator line, 129
Test cell, 244
Theoretical (literature references), 290
Titanium tubes, 147
Zinc, 138, 140
Pitting evaluation, 209
Burst pressure, 215
Metal penetration, 210
Standard charts, 209
Statistical, 211
Pitting factor, 211
Pitting potential, 185
Aluminum alloys, 23, 39
Copper, 160, 167
Effect of chloride, 196
Effect of crevices, 262
Effect of hydrochloric acid, 188
Effect of water, 187
Regions, 266, 273
Titanium, 195
Pitting probability, 211, 212
Platinum, 192
Platinum group metals, 16
Polaristat, 48
Polarization
Activation, 6
Anodic, 9, 10, 16, 183–201, 261
Cathodic, 49, 62, 186, 263
Cathodic control, 55
Concentration, 63, 66
Galvanic couple, 12, 50
Galvanostatic, 48, 71, 75, 77
Measurement, 5, 15, 39, 77
Prediction of localized corrosion, 15
Potentiodynamic, 9, 10, 16, 261
Potentiostatic, 39, 183–201
Resistance, 58, 190
Test cell, 263
Weld zones, 61
Polarization curves
Aluminum and stainless steel in seawater, 52–54
Aluminum 6061 in CH$_3$OH plus H$_2$SO$_4$, 196, 197
Carbon steel 1006 in 5 percent sodium chloride, 15
Copper in CH$_3$OH plus H$_2$SO$_4$, 198
Copper in 5 percent sodium chloride, 15
Copper and steel in seawater, 50–52
Effect of scan rate, 264
Effect of surface finish, 269
Galvanic couple regions, 17
Hysteresis loop, 265, 268
Iron in 5 percent sodium chloride, 9
Iron in CH$_3$OH plus H$_2$SO$_4$, 198
Iron in 1.0 N sodium sulfate, 6
Lead in 5 percent sodium chloride, 9
Nickel in CH$_3$OH plus H$_2$SO$_4$, 191
Pitting regions, 266, 273
Platinum in CH$_3$OH plus H$_2$SO$_4$, 199
Stainless steel
Type 304 in CH$_3$OH plus H$_2$SO$_4$, 193
Type 304 in sodium chloride, 264–274
Type 310 in 5 percent sodium chloride, 10
Type 434 in 5 percent sodium chloride, 10
Titanium in CH$_3$OH plus H$_2$SO$_4$, 189
Titanium 75A in CH₃OH plus HCl, 182-184, 200
Titanium 75A in organic media plus H₂SO₄, 201
Zinc in 5 percent sodium chloride, 9
Polyethylene
  Semiconducting (SCPE), 71
Potential
  Critical, 15, 16
  Critical breakdown, 16, 173, 184
  Constant, 186, 266, 270, 273
  Copper tubes, 163
  Corrosion, 8, 21, 23, 28, 162
  Equilibrium, 6
  Galvanic, 28
  Measurement, 8, 46, 59, 87, 160
  Mixed, 6, 8, 15, 17
  Open circuit, 57, 63, 75, 92
  pH influence, 142
  Protection, 50
  Repassivation, 265, 270
  Solution, 260
  Variation with time, 11, 162-168
  Welded specimens, 60, 67
Potential, pH behavior
  Zinc, 142
Potential, time curves
  Copper tubes in water, 162-168
  Copper-nickel in seawater, 11
  Nickel in seawater, 11
  Stainless steel in seawater, 11
Potentiostat, 12, 45, 182
Pourbaix diagram
  Galvanized steel, 145
  Zinc, 145
Power lines, 69
Pressure tests, 215
Probability
Crevice corrosion, 236, 239
Protective coatings, 46, 117, 126
R
  Radiographic inspection, 119, 124, 206
Reference electrodes
  Copper-copper sulfate, 86
  Saturated calomel, 182
  Silver-silver chloride, 160
S
  Salt evaporators, 147
  Salt plugs, 152
  Seawater, 9, 49, 57, 62, 63, 94
    Artificial, 244
    Barnacle growth, 112
    Cathodic protection, 48
    Composite structures, 48
    Crevice corrosion, 231, 234
    Exposure, 100, 105, 233
    Flume, 233
    Galvanic corrosion, 94
    Immersion racks, 100, 104, 110
    Oxygen concentration corrosion, 238
    Panama Canal Zone, 94
    Pitting of iron, 243
Service failures
  Carbon steel high-pressure steam condensate line, 119
  Carbon steel steam generator blow-down line, 129
  Carbon steel tube heat exchanger, 118
  Carbon steel waste line, 124
  Case histories, 118-129
  Cause of equipment failures, 118
  Copper tubes in cold water service, 155, 172
Copper tubes in United Kingdom, 177
Ductile iron pipe underground, 227
Estimated life, 228
Salt evaporator, 147
Steel pipe underground, 227
Power cables in soil, 69
Welds in seawater, 64
Shepard cane, 86
Silver, 25, 40, 43
Sodium, 255, 256
Sodium chloride, 9, 10, 12-15, 21 24-26, 28, 31, 32, 37, 73, 263-274
Sodium sulfate, 6, 73
Soil
Aggressive, 227
Burial, 69, 94, 102, 108
Chemical analysis, 73
Polarization measurements, 77
Properties, 83
Resistivity, 86, 91, 221
Specimen exposure and removal, 86
Test site variations, 83-85, 94, 100, 221, 228
Types, 83, 220
Soil resistivity, 91, 221
Measurement, 86
Solution chemistry, 243-259
Solution potential, 260
Sonic testing, 206
Specimens
Atmospheric, 96, 98
Coupled, 21, 96
Crevice, 232
Galvanic, 76
Seawater immersion, 49, 97
Soil burial, 86, 97, 102
Welded, 57
Specimen preparation, 21, 49, 59, 75, 85, 95, 135, 233, 263
ASTM Recommended Practice G 1, 204
Neutral wire electrode, 71
Stainless steels, 15, 16, 25, 50, 52-54, 81, 82, 83, 87, 88
6X, 233, 241
26CR-1Mo, 82, 90, 92
26Cr-6.5Ni, 83, 90, 92
CA-15, 235
CA-8M, 235
Mechanical properties, 82
PH13-8Mo, 21
Pitting morphology, 194
Stressed, 85
Type 301, 82, 88, 90, 92
Type 304, 10, 16, 17, 22, 28, 82, 90, 92, 189, 199, 232, 237, 262, 264
Type 304 L, 26, 28, 32
Type 310, 10
Type 316, 10, 96, 102, 104-112, 231, 237, 262, 271
Type 409, 11
Type 430, 11, 16
Type 434, 10
Standards
ASTM Method E 3, 205
ASTM Recommended Practice G 1, 101, 204
ASTM Recommended Practice G 16, 235
ASTM Specification D 1141, 245
NACE RP-01-73, 204
Statistical analysis, 203, 217
Statistics, crevice corrosion, 231
ASTM Recommended Practice G 16, 235
Probability plot, 235
Statistics, pitting
Confidence limits, 219
Extreme valve probability, 213, 219
Log-normal distribution, 219
Maximum pit depth, 210–214
Prediction intervals, 217, 219, 221–230
Probability test, 211, 212
Regression calculations, 219, 221
Statistical analysis, 132
Steam condensate line
Corrosion fatigue of carbon steel, 119
Low-frequency cyclic loading, 124
Steam generator
Carbon steel blow-down lines, 129
Steel
4130, 14, 23, 25, 28, 31, 32, 40, 43
4340, 96, 102, 104–112
Bessemer pipe, 229, 230
Carbon, 11, 15, 17, 50–52, 220–227
Carbon steel service failures, 117
Galvanized, 132, 135–142
Literature references on pitting, 282
Localized corrosion, 117
Stress corrosion, 81
Strain gages, 85
U-bend specimens, 85
Test cell
Polarization, 263
Simulated pit, 245
Test methods (see also Electrochemical Techniques)
Autoclave, 148
Carbon black (CB), 158, 176, 178
Crevice corrosion, 232
Eddy current, 157, 160, 206
Environmental, 133
Galvanic, 5, 21
Literature references on pitting, 289
Seawater immersion, 105
Test racks
ASTM exposure racks, 98
Chill, 135
Laboratory tube testing, 159
Monel, 98
Seawater, 100, 104
Site tube testing, 159
Test sites
Atmospheric, 98
Panama Canal Zone, 95, 98
Seawater, 100, 233
Soil, 83, 100, 221, 228
Thallium in seawater, 260
Time of wetness, 134
Dew-light cycle, 134
Tin, 25, 41
Titanium and titanium alloys, 147, 152, 181, 193–195
Corrosion products
Titanium chloride, 150
Titanium dioxide, 150
Titanium hydride, 153
Effect of methyl alcohol plus acids, 181, 193
Effect of organic solvents, 194
Heat exchangers, 147
Literature references on pitting, 292
Mechanism of pitting, 149, 150
Passivation, 195, 197
Pitting in hot brine, 147
Ti-6Al-4V, 22, 25, 26, 28, 32, 40, 96, 103–112, 181, 186
Ti-75A, 181, 186
Tropical environments, 95
Tungsten
Literature references on pitting, 292

U
Underground corrosion (see also Soil)
Galvanic, 81
NBS tests, 218
Stressed stainless steel, 81
Underground power distribution cable, 69
Concentric neutral wires, 69
Galvanic corrosion, 69
Laboratory tests, 73, 74
U. S. Army Tropical Testing Station, 95

W
Waste line, 124, 126
Coatings, 126
Water
Aggressive, 176
Compositional analysis, 161
Distilled, 26, 28
Distribution systems, 155
Domestic, 155
Effect of composition on pitting, 166, 176
Hard, untreated, 157
Passivating effect, 195
Softened, public supply, 157
Tap, 26, 28, 159, 160
Treatment, 176, 177
Water line attack, 121
Welded joints, 56, 274
Cathodic protection, 62
Field failures, 63
Filler metal (FM), 56, 63
Galvanic corrosion, 66
Galvanic couples, 62
Galvanic susceptibility, 67
Heat affected zone (HAZ), 56, 60–64
Parent metal (PM), 56, 60, 63
Seawater corrosion, 56
Specimen, 57
Weld metal, 61
Wenner bridge, 86

Z
Zero resistance ammeter, 11, 44, 58, 87
Zinc, 8, 22, 25, 26, 28, 32, 35, 40, 43, 83, 86, 87, 136
Corrosion products, 139–141
Carbonate, 139
Hydroxide, 140
Oxide, 140
Sulfate, 141
Lead inclusions, 139
Literature references on pitting, 292
Pit initiation sites, 139
Potential, pH behavior, 142
Zirconium
Literature references on pitting, 292