Contents

Preface XIV

1 Rules of Thumb 1
1.1 Rules of Thumb about Process Equipment 2
1.2 Rules of Thumb about the Context for a Chemical Process: Physical and Thermal Properties 4
1.3 Rules of Thumb about the Context for a Chemical Process: Corrosion 5
1.4 Rules of Thumb about the Context for a Chemical Process: Process Control (based on communication from T.E. Marlin, McMaster University, 2001) 6
1.5 Rules of Thumb about the Context for a Chemical Process: Batch versus Continuous 11
1.6 Rules of Thumb about the Context for a Chemical Process: Heterogenous Phase contacting 11
1.6.1 GL Systems 11
1.6.2 LL Systems 18
1.6.3 GLS Systems 18
1.6.4 Particulate Systems 20
1.7 Rules of Thumb about the Context for a Chemical Process: Economics 21
1.8 Rules of Thumb about the Thinking Process: Problem Solving and Creativity 22
1.9 Rules of Thumb about the Thinking Process: Goal Setting 25
1.10 Rules of Thumb about the Thinking Process: Decision Making 26
1.11 Rules of Thumb about the Thinking Process: Thermal Pinch 26
1.12 Rules of Thumb about the Thinking Process: “Systems” Thinking 27
1.13 Rules of Thumb about the Thinking Process: Design 30
1.14 Rules of Thumb about the Thinking Process: Process Improvement 31
1.15 Rules of Thumb about the Thinking Process: Trouble Shooting 31
1.16 Rules of Thumb about the Thinking Process: Environment, Waste Minimization, Safety 32
1.17 Rules of Thumb about the People Part of Engineering: Communication
1.18 Rules of Thumb about the People Part of Engineering: Listening
1.19 Rules of Thumb about the People Part of Engineering: People Skills
1.20 Rules of Thumb about the People Part of Engineering: Team and Group Skills
1.21 Rules of Thumb about the Context in Which We Function: Performance Review
1.22 Rules of Thumb about the Context in Which We Function: Leadership
1.23 Rules of Thumb about the Context in Which We Function: Entrepreneurship (based on Valikangas, 2003 and Cooper, 1987)
1.24 Rules of Thumb about the Context in Which We Function: Entrepreneurship
1.25 Rules of Thumb about the Context in Which We Function: e-Business
1.26 Rules of Thumb about Mentoring and Self-management
1.27 Summary

2 Transportation
2.1 Gas Moving: Pressure Service
2.2 Gas Moving: Vacuum Service
2.3 Liquid
2.4 Gas–Liquid (Two-phase Flow)
2.5 Pumping Slurries: Liquid–Solid Systems
2.6 Solids
2.7 Ducts and Pipes

3 Energy Exchange
3.1 Drives
3.2 Thermal Energy: Furnaces
3.3 Thermal Energy: Fluid Heat Exchangers, Condensers and Boilers
3.4 Thermal Energy: Fluidized Bed (Coils in Bed)
3.5 Thermal Energy: Static Mixers
3.6 Thermal Energy: Direct Contact L–L Immiscible Liquids
3.7 Thermal Energy: Direct Contact G–L Cooling Towers
3.8 Thermal Energy: Direct Contact G–L Quenchers
3.9 Thermal Energy: Direct Contact G–L Condensers
3.10 Thermal Energy: G–G Thermal Wheels and Pebble Regenerators and Regenerators
3.11 Thermal Energy: Heat Loss to the Atmosphere
3.12 Thermal Energy: Refrigeration
3.13 Thermal Energy: Steam Generation and Distribution
3.14 High Temperature Heat Transfer Fluids
3.15 Tempered Heat Exchange Systems
4 Homogeneous Separation 86
4.1 Evaporation 87
4.2 Distillation 90
4.3 Freeze Concentration 101
4.4 Melt Crystallization 101
4.5 Zone Refining 102
4.6 Solution Crystallization 102
4.7 Precipitation 107
4.8 Gas Absorption 107
4.9 Gas Desorption/Stripping 113
4.10 Solvent Extraction, SX 115
4.11 Adsorption: Gas 118
4.12 Adsorption: Liquid 119
4.13 Ion Exchange 120
4.14 Foam Fractionation 123
4.15 Membranes and Membrane Configurations 123
4.15.1 Membranes 124
4.15.2 Membrane Operation and Configuration 125
4.16 Membranes: Gas 128
4.17 Membranes: Dialysis 129
4.18 Membranes: Electrodialysis 129
4.19 Membranes: Pervaporation 130
4.20 Membranes: Reverse Osmosis, RO 131
4.21 Membranes: Nanofiltration 132
4.22 Membranes: Ultrafiltration, UF 132
4.23 Membranes: Microfiltration 134
4.24 Chromatography 135

5 Heterogeneous Separations 137
5.1 Gas–Liquid 137
5.2 Gas–Solid 141
5.3 Liquid–Liquid 144
5.3.1 Decanter 146
5.3.2 Hydrocyclone 148
5.3.3 Sedimentation Centrifuge 148
5.4 Gas–Liquid–Liquid Separators 149
5.5 Liquid–Solid: General Selection 150
5.6 Dryers 151
5.7 Screens for “Dewatering” or Liquid–Solid Separation 159
5.8 Settlers 160
5.9 Hydrocyclones 161
5.10 Thickener 162
5.11 CCD: Counter Current Decantation 163
5.12 Sedimentation Centrifuges 163
5.13 Filtering Centrifuge 165
5.14 Filter 168
5.15 Leacher 173
5.16 Liquid–Solid: Dissolved Air Flotation, DAF 174
5.17 Liquid–Solid: Expeller and Hydraulic Press 175
5.18 Solid–Solid: General Selection 175
5.19 Froth Flotation 176
5.20 Electrostatic 177
5.21 Magnetic 178
5.22 Hydrocyclones 180
5.23 Air Classifiers 180
5.24 Rake Classifiers 181
5.25 Spiral Classifiers 181
5.26 Jig Concentrators 182
5.27 Table Concentrators 182
5.28 Sluice Concentrators 182
5.29 Dense Media Concentrators, DMS 183
5.30 Screens 183

6 Reactors 185
6.1 Factors Affecting the Choice of Reactor 185
6.2 General Guidelines 194
6.2.1 General Rules of Thumb for the Type of Reactor 194
6.2.2 Specific Guidelines for Gas Phase, Liquid Phase and Gas–Liquid Reactions 197
6.2.3 Specific Guidelines for Reactions using Catalysts 199
6.2.4 Specific Guidelines for Gases Reacting with Solid 207
6.2.5 Bioreactors 207
6.2.6 Reactors for Supercritical Conditions 209
6.2.7 Reactors for Polymerization 209
6.2.8 Using the Phases to Guide in the Choice of Reactor Configuration 212
6.3 How the Type of Reaction Affects the Size of the Reactor 215
6.4 Burner 224
6.5 PFTR: Pipe/Tube, Empty Pipe for Fluid Systems 225
6.6 PFTR: Static Mixer in Tube 227
6.7 PFTR: Empty Pipe/Tube for Fluids and Solids 227
6.8 PFTR: Empty Multitube, Nonadiabatic 229
6.9 PFTR: Fixed Bed Catalyst in Tube or Vessel: Adiabatic 229
6.10 PFTR: Multi-bed Adiabatic with Inter-bed Quench or Heating 233
6.11 PFTR: Fixed Bed with Radial Flow 234
6.12 PFTR: Multitube Fixed Bed Catalyst or Bed of Solid Inerts: Nonadiabatic 234
6.13 PFTR: Bubble Reactor 236
6.14 PFTR: Spray Reactor and Jet Nozzle Reactor 239
6.15 PFTR: Trays 240
6.16 PFTR: Packing 241
6.17 PFTR: Trickle Bed 244
6.18 PFTR: Monolithic 246
6.19 PFTR: Thin Film 247
6.20 PFTR: Scraped Surface Reactor 248
6.21 PFTR: Multiple Hearth 248
6.22 PFTR: Traveling Grate 249
6.23 PFTR: Rotary Kiln 250
6.24 PFTR, Shaft Furnace 250
6.25 PFTR, Melting Cyclone Burner 253
6.26 PFTR via Multistage CSTR 253
6.27 STR: Batch (Backmix) 254
6.28 STR: Semibatch 260
6.29 CSTR: Mechanical Mixer (Backmix) 261
6.30 STR: Fluidized Bed (Backmix) 264
6.31 TR: Tank Reactor 273
6.32 Mix of CSTR, PFTR with Recycle 274
6.33 STR: PFTR with Large Recycle 276
6.34 Reaction Injection Molding and Reactive Extrusion 276
6.35 Reactive Distillation, Extraction, Crystallization 277
6.36 Membrane Reactors 278
6.37 Liquid Piston Reactor 279

7 Mixing 280
7.1 Liquids 280
7.2 Liquid–liquid (Immiscible) 284
7.3 Liquid–Solid 285
7.3.1 Solids Suspension 286
7.3.2 Solids Dispersion 288
7.3.3 Solids Dissolving 288
7.3.4 Solids Flocculating 289
7.3.5 Liquid Fluidized Bed 289
7.4 Dry Solids 289

8 Size Reduction 292
8.1 Gas in Liquid (Foams) 292
8.2 Liquid in Gas (Sprays) 293
8.3 Liquid–Liquid 293
8.4 Cell Disintegration 295
8.5 Solids: Crushing and Grinding 295

9 Size Enlargement 298
9.1 Size Enlargement: Liquid–Gas: Demisters 298
9.2 Size Enlargement: Liquid–Liquid: Coalescers 299
9.3 Size Enlargement: Solid in Liquid: Coagulation/Flocculation 301
9.4 Size Enlargement: Solids: Fluidization 302
9.5 Size Enlargement: Solids: Spherical agglomeration  
9.6 Size Enlargement: Solids: Disc Agglomeration  
9.7 Size Enlargement: Solids: Drum Granulator  
9.8 Size Enlargement: Solids: Briquetting  
9.9 Size Enlargement: Solids: Tabletting  
9.10 Size Enlargement: Solids: Pelletting  
9.11 Solids: Modify Size and Shape: Extruders, Food Extruders, 
Pug Mills and Molding Machines  
9.12 Solids: Solidify Liquid to Solid: Flakers, Belts and Prill Towers  
9.13 Coating

10 Process Vessels and Facilities  
10.1 Process Vessels  
10.2 Storage Vessels for Gases and Liquids  
10.3 Bins and Hoppers for Bulk Solids  
10.4 Bagging Machines

Appendix A: Units and Conversion of Units

Appendix B: Dimensionless Groups

Appendix C: Cox Charts – Vapor Pressures

Appendix D: Capital Cost Guidelines

D.1 Equipment Cost Correlations
D.2 Converting the FOB Cost into a Bare Module Cost
D.3 Converting FOB and L+M Costs into Total Fixed Capital Investment Costs
D.4 Detailed Equipment Cost Data Based on Equipment Type

Section 1.4 Rules of Thumb about the Context for a Chemical Process: Process Control Sensors
Section 2.1 Gas Moving: Pressure Service
Section 2.2 Gas Moving: Vacuum Service
Section 2.3 Liquid
Section 2.4 Gas-Liquid (Two-phase Flow)
Section 2.5 Pumping Slurries: Liquid–Solid Systems
Section 2.6 Solids
Section 2.7 Ducts and Pipes
Section 3.1 Drives
Section 3.2 Thermal Energy: Furnaces
Section 3.3 Thermal Energy: Fluid Heat Exchangers, Condensers and Boilers
Section 3.4 Thermal Energy: Fluidized Bed (Coils in Bed)
Section 3.5 Thermal Energy: Static Mixers
Section 3.6 Thermal Energy: Direct Contact L–L Immiscible Liquids
Section 3.7 Thermal Energy: Direct Contact G–L Cooling Towers 390
Section 3.8 Thermal Energy: Direct Contact G–L Quenchers 391
Section 3.9 Thermal Energy: Direct Contact G–L Condensers 391
Section 3.10 Thermal Energy: G–G Thermal Wheels and Pebble Regenerators and Regenerators 391
Section 3.11 Thermal Energy: Refrigeration 391
Section 3.12 Thermal Energy: Steam Generation and Distribution 392
Section 3.13 High Temperature Heat Transfer Fluids 392
Section 3.14 Tempered Heat Exchange Systems 392
Section 4.1 Evaporation 392
Section 4.2 Distillation 393
Section 4.3 Freeze Concentration 395
Section 4.4 Melt Crystallization 396
Section 4.5 Zone Refining 396
Section 4.6 Solution Crystallization 396
Section 4.7 Precipitation 397
Section 4.8 Gas Absorption 397
Section 4.9 Gas Desorption/Stripping 397
Section 4.10 Solvent Extraction, SX 397
Section 4.11 Adsorption: Gas 399
Section 4.12 Adsorption: Liquid 399
Section 4.13 Ion Exchange 399
Section 4.14 Foam Fractionation 400
Section 4.15 Membranes and Membrane Configurations 400
Section 4.16 Membranes: Gas 400
Section 4.17 Membranes: Dialysis 400
Section 4.18 Membranes: Electrodialysis 400
Section 4.19 Membranes: Pervaporation 401
Section 4.20 Membranes: Reverse Osmosis, RO 401
Section 4.21 Membranes: Nanofiltration 401
Section 4.22 Membranes: Ultrafiltration, UF 401
Section 4.23 Microfiltration 401
Section 4.24 Chromatography 402
Section 5.1 Gas–Liquid 402
Section 5.2 Gas–Solid 402
Section 5.3 Liquid–Liquid 404
Section 5.3.1 Decanter 404
Section 5.3.2 Hydrocyclone 404
Section 5.3.3 Sedimentation Centrifuge 405
Section 5.4 Gas–Liquid–Liquid Separators 405
Section 5.5 Liquid–Solid: General Selection 405
Section 5.6 Dryers 405
Section 5.7 Screens for “Dewatering” 408
Section 5.8 Settlers 408
Section 5.9 Hydrocyclones 409
Section 5.10 Thickener 409
Section 5.11 CCD: Counter Current Decantation 410
Section 5.12 Sedimentation Centrifuges 410
Section 5.13 Filtering Centrifuge 410
Section 5.14 Filter 411
Section 5.15 Leacher 414
Section 5.16 Liquid–Solid: Dissolved Air Flotation, DAF 414
Section 5.17 Liquid–Solid: Expeller and Hydraulic Press 415
Section 5.18 Solid–Solid: General Selection 415
Section 5.19 Froth Flotation 415
Section 5.20 Electrostatic 415
Section 5.21 Magnetic 415
Section 5.22 Hydrocyclones 417
Section 5.23 Air Classifiers 417
Section 5.24 Rake Classifiers 417
Section 5.25 Spiral Classifiers 417
Section 5.26 Jig Concentrators 418
Section 5.27 Table Concentrators 418
Section 5.28 Sluice Concentrators 418
Section 5.29 Dense Media concentrators, DMS 418
Section 5.30 Screens 418
Sections 6.1 to 6.3 Consider Principles of Selecting Reactors 419
Section 6.4 Burner 418
Section 6.5 PFTR: Pipe/Tube, Empty Pipe for Fluid Systems 419
Section 6.6 PFTR: Static Mixer in Tube 420
Section 6.7 PFTR: Empty Pipe/Tube for Fluids and Solids 420
Section 6.8 PFTR: Empty Multitube, Nonadiabatic 420
Section 6.9 PFTR: Fixed Bed Catalyst in Tube or Vessel: Adiabatic 420
Section 6.10 PFTR: Multibed Adiabatic with Inter-bed Quench or Heating 420
Section 6.11 PFTR: Fixed Bed with Radial Flow 421
Section 6.12 PFTR: Multitube Fixed Bed Catalyst or Bed of Solid Inerts: Nonadiabatic 421
Section 6.13 PFTR: Bubble Reactor 421
Section 6.14 PFTR: Spray Reactor and Jet Nozzle Reactor 422
Section 6.15 PFTR: Trays 422
Section 6.16 PFTR: Packing 422
Section 6.17 PFTR: Trickle Bed 422
Section 6.18 PFTR: Monolithic 422
Section 6.19 PFTR: Thin Film 422
Section 6.20 PFTR: Scraped Surface Reactor 423
Section 6.21 PFTR: Multiple Hearth 423
Section 6.22 PFTR: Traveling Grate 423
Section 6.23 PFTR: Rotary Kiln 423
Section 6.24 PFTR, Shaft Furnace 423
Section 6.25 PFTR, Melting Cyclone Burner 424
Section 6.26 PFTR via Multistage CSTR 424
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.27</td>
<td>STR: Batch (Backmix)</td>
<td>424</td>
</tr>
<tr>
<td>6.28</td>
<td>STR: Semibatch</td>
<td>425</td>
</tr>
<tr>
<td>6.29</td>
<td>CSTR: Mechanical Mixer (Backmix)</td>
<td>425</td>
</tr>
<tr>
<td>6.30</td>
<td>STR: Fluidized Bed (Backmix)</td>
<td>425</td>
</tr>
<tr>
<td>6.31</td>
<td>TR: Tank Reactor</td>
<td>425</td>
</tr>
<tr>
<td>6.32</td>
<td>Mix of CSTR, PFTR with Recycle</td>
<td>426</td>
</tr>
<tr>
<td>6.33</td>
<td>STR: PFTR with Large Recycle</td>
<td>426</td>
</tr>
<tr>
<td>6.34</td>
<td>Reaction Injection Molding and Reactive Extrusion</td>
<td>426</td>
</tr>
<tr>
<td>6.35</td>
<td>Reactive Distillation, Extraction, Crystallization</td>
<td>427</td>
</tr>
<tr>
<td>6.36</td>
<td>Membrane Reactors</td>
<td>427</td>
</tr>
<tr>
<td>6.37</td>
<td>Liquid Piston Reactor</td>
<td>427</td>
</tr>
<tr>
<td>7.1</td>
<td>Liquids</td>
<td>427</td>
</tr>
<tr>
<td>7.2</td>
<td>Liquid–Liquid</td>
<td>428</td>
</tr>
<tr>
<td>7.3</td>
<td>Liquid–Solid</td>
<td>428</td>
</tr>
<tr>
<td>7.3.1</td>
<td>Solids Suspension</td>
<td>428</td>
</tr>
<tr>
<td>7.3.2</td>
<td>Solids Dispersion</td>
<td>428</td>
</tr>
<tr>
<td>7.3.3</td>
<td>Solids Dissolving</td>
<td>428</td>
</tr>
<tr>
<td>7.3.4</td>
<td>Solids Flocculating</td>
<td>429</td>
</tr>
<tr>
<td>7.4</td>
<td>Dry Solids</td>
<td>429</td>
</tr>
<tr>
<td>8.1</td>
<td>Gas in Liquid (Foams)</td>
<td>429</td>
</tr>
<tr>
<td>8.2</td>
<td>Liquid in Gas (Sprays)</td>
<td>430</td>
</tr>
<tr>
<td>8.3</td>
<td>Liquid–Liquid</td>
<td>430</td>
</tr>
<tr>
<td>8.4</td>
<td>Cell Disintegration</td>
<td>430</td>
</tr>
<tr>
<td>8.5</td>
<td>Solids: Crushing and Grinding</td>
<td>430</td>
</tr>
<tr>
<td>9.1</td>
<td>Size Enlargement: Liquid–Gas: Demisters</td>
<td>432</td>
</tr>
<tr>
<td>9.2</td>
<td>Size Enlargement: Liquid–Liquid: Coalescers</td>
<td>432</td>
</tr>
<tr>
<td>9.3</td>
<td>Size Enlargement: Solid in Liquid: Coagulation/Flocculation</td>
<td>432</td>
</tr>
<tr>
<td>9.4</td>
<td>Size Enlargement: Solids: Fluidization</td>
<td>432</td>
</tr>
<tr>
<td>9.5</td>
<td>Size Enlargement: Solids: Spherical Agglomeration</td>
<td>432</td>
</tr>
<tr>
<td>9.6</td>
<td>Size Enlargement: Solids: Disc Agglomeration</td>
<td>433</td>
</tr>
<tr>
<td>9.7</td>
<td>Size Enlargement: Solids: Drum Granulator</td>
<td>433</td>
</tr>
<tr>
<td>9.8</td>
<td>Size Enlargement: Solids: Briquetting</td>
<td>433</td>
</tr>
<tr>
<td>9.9</td>
<td>Size Enlargement: Solids: Tabletting</td>
<td>433</td>
</tr>
<tr>
<td>9.10</td>
<td>Size Enlargement: Solids: Pelleting</td>
<td>433</td>
</tr>
<tr>
<td>9.11</td>
<td>Solids: Modify Size and Shape: Extruders, Food Extruders, Pug Mills and Molding Machines</td>
<td>433</td>
</tr>
<tr>
<td>9.12</td>
<td>Solids: Solidify Liquid to Solid: Flakers, Belts and Prill towers</td>
<td>434</td>
</tr>
<tr>
<td>9.13</td>
<td>Coating</td>
<td>434</td>
</tr>
<tr>
<td>10.1</td>
<td>Process Vessels</td>
<td>434</td>
</tr>
<tr>
<td>10.2</td>
<td>Storage Vessels for Gases and Liquids</td>
<td>435</td>
</tr>
<tr>
<td>10.3</td>
<td>Bins and Hoppers for Bulk Solids</td>
<td>436</td>
</tr>
<tr>
<td>10.4</td>
<td>Bagging Machines</td>
<td>436</td>
</tr>
</tbody>
</table>