Contents

Preface		xv
Acknowledgement		xvii
Chapter 1	**Introduction**	**1**
1.1	Acid Gas	2
1.1.1	Hydrogen Sulfide	3
1.1.2	Carbon Dioxide	4
1.2	Anthropogenic CO_2	5
1.3	Flue Gas	5
1.3.1	Sulfur Oxides	7
1.3.2	Nitrogen Oxides	8
1.4	Standard Volumes	8
1.4.1	Gas Volumes	8
1.4.2	Liquid Volumes	9
1.5	Sulfur Equivalent	9
1.6	Sweetening Natural Gas	11
1.6.1	Combustion Process Gas	12
1.6.1.1	Post-Combustion	13
1.6.1.2	Pre-Combustion	14
1.7	Acid Gas Injection	14
1.8	Who Uses Acid Gas Injection?	16
1.8.1	Western Canada	16
1.8.2	United States	17
1.8.3	Other Locations	17
1.8.4	CO_2 Flooding	18
1.9	In Summary	18
References		18
Appendix 1A	Oxides of Nitrogen	20
Appendix 1B	Oxides of Sulfur	22

Chapter 2 Hydrogen Sulfide and Carbon Dioxide 23
2.1 Properties of Carbon Dioxide 25
2.2 Properties of Hydrogen Sulfide 27
2.3 Estimation Techniques for Physical Properties 31
2.3.1 Thermodynamic Properties 31
2.3.1.1 Ideal Gas 31
2.3.1.2 Real Gas 33
2.3.2 Saturated Liquid and Vapor Densities 36
2.3.2.1 Liquids 36
2.3.2.2 Corresponding States 37
2.3.3 Thermodynamic Properties 39
2.3.4 Transport Properties 40
2.3.4.1 Low Pressure Gas 40
2.3.4.2 Gases Under Pressure 41
2.3.4.3 Liquids 42
2.3.5 Viscosity Charts 43
2.4 Properties of Acid Gas Mixtures 44
2.4.1 Thermodynamic Properties 44
2.4.1.1 Corresponding States 45
2.4.2 Transport Properties 47
2.4.3 Word of Caution 48
2.5 Effect of Hydrocarbons 50
2.5.1 Density 50
2.5.2 Viscosity 51
2.6 In Summary 51
References 51
Appendix 2A Transport Properties of Pure Hydrogen Sulfide 53
2A.1 Viscosity 53
2A.1.1 Liquid 53
2.A.1.2 Vapor 54
2A.2 Thermal Conductivity 55
References 57
Appendix 2B Viscosity of Acid Gas Mixtures 59
2B.1.1 Correcting for High Pressure 59
2B.1.2 Carbon Dioxide 59
2B.1.3 Generalization 61

2B.1.4 Mixtures 62
2B.1.5 Final Comments 63
References 63
Appendix 2C Equations of State 64
2C.1.1 Soave-Redlich-Kwong Equation of State 64
2C.1.2 Peng-Robinson Equation of State 64
2C.1.3 The Patel-Teja Equation of State 65

Chapter 3 Non-Aqueous Phase Equilibrium 69
3.1 Overview 69
3.2 Pressure-Temperature Diagrams 70
3.2.1 Pure Components 70
3.2.2 Mixtures 73
3.2.3 Binary Critical Points 76
3.2.4 Effect of Hydrocarbons 77
3.2.4.1 Methane 78
3.2.4.2 Ethane and Propane 79
3.2.4.3 Butane and Heavier 80
3.2.4.4 In Summary 81
3.3 Calculation of Phase Equilibrium 82
3.3.1 Equations of State 82
3.3.2 K-Factor Charts 83
3.4 In Summary 85
References 85
Appendix 3A Some Additional Phase Equilibrium Calculations 86
3A.1.1 Hydrogen Sulfide + Hydrocarbons 86
3A.1.2 Carbon Dioxide + Hydrocarbons 87
3A.1.3 Multicomponent Mixtures 88
References 92
Appendix 3B Accuracy of Equations of State for VLE in Acid Gas Mixtures 96
References 98

Chapter 4 Fluid Phase Equilibria Involving Water 99
4.1 Water Content of Hydrocarbon Gas 100
4.2 Water Content of Acid Gas 101
4.2.1 Carbon Dioxide 102
4.2.2 Hydrogen Sulfide 103

4.2.3 Practical Representation 106
4.2.3.1 In Summary 108
4.3 Estimation Techniques 108
4.3.1 Simple Methods 109
4.3.1.1 Ideal Model 109
4.3.1.2 McKetta-Wehe Chart 109
4.3.1.3 Maddox Correction 110
4.3.1.4 Wichert Correction 110
4.3.1.5 Alami et al. 111
4.3.2 Advanced Methods 111
4.3.2.1 AQUAlibrium 111
4.3.2.2 Other Software 112
4.4 Acid Gas Solubility 113
4.4.1 Henry's Law 113
4.4.2 Solubility in Brine 115
4.4.2.1 Carbon Dioxide in NaCl 116
4.4.2.2 Hydrogen Sulfide in NaCl 116
4.4.2.3 Mixtures of Gases 119
4.4.2.4 Effect of pH 119
4.5 In Summary 119
References 120
Appendix 4A Compilation of the Experimental Data for the Water Content of Acid Gas 122
References 124
Appendix 4B Comments on the Work of Selleck et al. 127
Appendix 4C Density of Brine (NaCl) Solutions 129

Chapter 5 Hydrates 131
5.1 Introduction to Hydrates 131
5.2 Hydrates of Acid Gases 132
5.3 Estimation of Hydrate Forming Conditions 135
5.3.1 Shortcut Methods 135
5.3.2 Rigorous Methods 136
5.4 Mitigation of Hydrate Formation 136
5.4.1 Inhibition with Methanol 136
5.4.2 Water-Reduced Cases 138
5.4.2.1 Carbon Dioxide 139
5.4.2.2 Dehydration 140

5.4.2.3 To Dehydrate or Not to Dehydrate? – That is the Question! 141
5.4.3 Application of Heat 142
5.4.3.1 Line Heaters 142
5.4.3.2 Heat Tracing 142
5.4.3.3 Final Comment 142
5.5 Excess Water 142
5.6 Hydrates and AGI 143
5.7 In Summary 143
References 143

Chapter 6 Compression 145
6.1 Overview 145
6.2 Theoretical Considerations 148
6.3 Compressor Design and Operation 148
6.4 Design Calculations 149
6.4.1 Compression Ratio 150
6.4.2 Ideal Gas 151
6.4.3 Efficiency 157
6.4.4 Ratio of the Heat Capacities 158
6.5 Interstage Coolers 159
6.5.1 Design 160
6.5.2 Pressure Drop 164
6.5.3 Phase Equilibrium 164
6.6 Compression and Water Knockout 167
6.6.1 Additional Cooling 171
6.7 Materials of construction 172
6.8 Advanced design 172
6.8.1 Cascade 172
6.8.2 CO_2 Slip 173
6.9 Case studies 174
6.9.1 Wayne-Rosedale 174
6.9.2 Acheson 175
6.9.3 West Pembina 175
6.10 In Summary 175
References 176
Appendix 6A Additional Calculations 177

Chapter 7 Dehydration of Acid Gas **183**
7.1 Glycol Dehydration 184
7.1.1 Acid Gas Solubility 185
7.1.2 Desiccant 187
7.2 Molecular Sieves 189
7.2.1 Acid Gas Adsorption 191
7.3 Refrigeration 192
7.3.1 Selection of Inhibitor 193
7.4 Case Studies 194
7.4.1 CO_2 Dehydration 194
7.4.2 Acid Gas Dehydration 195
7.4.2.1 Wayne-Rosedale 195
7.4.2.2 Acheson 195
7.5 In Summary 196
References 196

Chapter 8 Pipeline **199**
8.1 Pressure Drop 199
8.1.1 Single Phase Flow 199
8.1.1.1 Friction Factor 202
8.1.1.2 Additional Comments 204
8.1.2 Two-Phase Flow 205
8.1.3 Transitional Flow 205
8.2 Temperature Loss 206
8.2.1 Carroll's Method 206
8.3 Guidelines 207
8.4 Metering 208
8.5 Other Considerations 209
8.6 In Summary 210
References 210
Appendix 8A Sample Pipeline Temperature Loss Calculation 211
8A.1 AQUAlibrium 3.0 212
8A.1.1 Acid Gas Properties 212
8A.1.1.1 Conditions 212
8A.1.1.2 Component Fractions 212
8A.1.1.3 Phase properties 212
8A.1.1.4 Warnings 212

Chapter 9 Injection Profiles **215**
9.1 Calculation of Injection Profiles 215
9.1.1 Gases 216
9.1.1.1 Ideal Gas 216
9.1.1.2 Real Gas 217
9.1.2 Liquids 220
9.1.3 Supercritical Fluids 221
9.1.4 Friction 221
9.1.5 AGIProfile 221
9.2 Effect of Hydrocarbons 224
9.3 Case Studies 228
9.3.1 Chevron Injection Wells 228
9.3.1.1 West Pembina 229
9.3.1.2 Acheson 230
9.3.2 Anderson Puskwaskau 232
9.4 Other Software 232
9.5 In Summary 232
References 232
Appendix 9A Additional Examples 234

Chapter 10 Selection of Disposal Zone **239**
10.1 Containment 239
10.1.1 Reservoir Capacity 240
10.1.2 Caprock 240
10.1.3 Other Wells 241
10.2 Injectivity 241
10.2.1 Liquid Phase 241
10.2.2 Gas Injection 244
10.2.3 Fracturing 245
10.2.4 Horizontal Wells 245
10.3 Interactions With Acid Gas 245
10.4 In Summary 246
References 246

Chapter 11 Health, Safety and The Environment **247**
11.1 Hydrogen Sulfide 247
11.1.1 Physiological Properties 248
11.1.2 Regulations 248
11.1.3 Other Considerations 249

11.2 Carbon Dioxide 249
11.2.1 Physiological Properties 249
11.2.2 Climate Change 250
11.2.3 Other Considerations 250
11.3 Emergency Planning 250
11.3.1 Accidental Releases 250
11.3.2 Planning Zones 251
11.3.3 Other Considerations 255
11.3.3.1 Sour vs. Acid Gas 255
11.3.3.2 Wind 256
11.3.3.3 Carbon Dioxide 256
11.3.3.4 Sensitive Areas 256
References 256

Chapter 12 Capital Costs 257
12.1 Compression 257
12.1.1 Reciprocating Compressor 258
12.1.2 Centrifugal 259
12.2 Pipeline 259
12.3 Wells 260
12.4 In Summary 261
References 261

Chapter 13 Additional Topics 263
13.1 Rules of Thumb 263
13.1.1 Physical Properties 263
13.1.2 Water Content 264
13.1.3 Hydrates 264
13.1.4 Compression 264
13.1.5 Pipelines 265
13.1.6 Reservoir 266
13.2 Graphical Summary 266
13.2.1 Pressure-Temperature 266
13.2.2 Water Content 268
13.2.3 Operation 269
13.2.4 Summary 270
13.3 The Three Types of Gas 270
13.3.1 Example Gases 270

Index 275