Contents

1. Introduction 1

1.1. Fuel Cell Technology: a Dream, Challenge or a Necessity? 1
1.2. The Historic Trends in Fuel Cell System Developments 1
1.3. Current Projects and Applications For Fuel Cells 2
1.3.1. Fuel Cell Technology Programs in the USA and Canada 2
1.3.2. Fuel Cell Activities in Japan 4
1.3.3. Fuel Cell Programs in Europe 4
1.4. Fuels for Fuel Cells: More Reformer Development 5
1.5. Fuel Cell Operated Electric Vehicles 6
1.6. Outlook for Fuel Cell Technology 7

2. General Aspects of Fuel Cell Systems 9

2.1. Introduction "Fuel Cells as Energy Converter" 9
2.2. Classification of Fuel Cell Systems 10
2.3. Characteristics of Fuel Cell Systems 11
2.3.1. High Efficiency and Reliability 11
2.3.2. Unparalleled Environmental Performance 12
2.3.3. Unique Operating Characteristics 13
2.3.4. Planning Flexibility 14
2.3.5. Future Potential 15
2.4. Economic Benefits of Fuel Cell Systems 15
2.5. The Potential Fuel Cell Market, Production Volume and Estimated Costs 18

3. Basic Principles 23

3.1. Thermodynamics of Chemical Reactions 23
3.1.1. Free-Energy Change of a Chemical Reaction 23
3.1.2. Standard Free-Energy Change of a Chemical Reaction 24
3.1.3. Relation between Free-Energy Change in a Cell Reaction and Cell Potential 24
3.1.4. Temperature and Pressure Coefficients of Thermodynamic Reversible Cell Potentials 26

3.2. Some Electrode Kinetic Aspects of Electrochemical Energy Conversion 27
3.2.1. Electrode Polarization (Overvoltage) – Nomenclature 27
3.2.2. Types of Overvoltage 27
3.2.3. Electrode Characteristics 30
3.3. The Electrode Mechanism of Fuel Cells 32
3.3.1. Anode Process 33
3.3.2. Cathode Process 36
3.4. Theory of the Gas Diffusion Electrode 38
3.5. Electrocatalysts 40
3.6. Fuel Cell Efficiency 42
3.6.1. General Theoretical Efficiency of the Conversion of Heat Liberated from a Chemical Reaction into other Forms of Energy (Mechanical, Electrical) 42
3.6.2. Thermodynamic Derivation of the Theoretical Efficiency of a Heat Engine 44
3.6.3. Thermodynamic Efficiency 45
3.6.4. Electrochemical Efficiency 47
3.6.5. Practical Efficiency 47
3.6.6. Faradaic Efficiency 48
3.6.7. Total Efficiency 48
3.7. Monopolar and Bipolar Electrode Constructions 49

4. Fuel Cell Systems 51

4.1. Introduction 51
4.2. Alkaline Fuell Cells (AFC) 54
4.2.1. General Principle 54
4.2.2. Early Developments of Alkaline Fuel Cell Systems 58
4.2.3. Further Developments 69
4.3. Polymer-Electrolyte Fuel Cells (PEFCs) 72
4.3.1. Introduction 72
4.3.2. History of Development 73
4.3.3. Operating Principles of PEFCs 75
4.3.3.1. General 75
4.3.3.2. Electrodes 76
4.3.3.3. Electrolytes-Membranes 78
4.3.3.4. Heat and Water Management 84
4.3.4. Performance of Polymer-Electrolyte Fuel Cells (PEFCs) 86
4.3.4.1. Influence of Temperature 87
4.3.4.2. Influence of Cathodic Reactant Composition and Pressure 87
4.3.4.3. Influence of CO in the Fuel Gas 89
4.3.5. Solid-Polymer Fuel Cell Stacks 90
4.3.6. Regenerative Fuel Cell Systems 92
4.4. Phosphoric Acid Fuel Cells (PAFC) 93
4.4.1. Introduction 93
4.4.2. Reaction Principle of the Phosphoric Acid Fuel Cell 94

4.4.3. Electrodes and Manufacturing 96
4.4.4. The Electrode Materials 100
4.4.5. Carbon Corrosion and Cathode-Catalyst Stability in the PAFC 105
4.4.6. Performance 106
4.4.7. Stacks and Systems 108
4.5. Molten Carbonate Fuel Cells (MCFC) 111
4.5.1. Introduction 111
4.5.2. Operating Principle 114
4.5.3. Cell Components 117
4.5.3.1. Matrix Support Material 117
4.5.3.2. Cathode 118
4.5.3.3. Anode 121
4.5.4. Internal Reforming Concept 122
4.5.5. Performance of MCFCs 125
4.5.6. MCFC R & D Programs 129
4.6. Solid Oxide Fuel Cells (SOFC) 133
4.6.1. Introduction 133
4.6.2. Reactions, Electrolyte and Cell Materials of SOFCs 134
4.6.3. Variations of SOFC Developments 138
4.6.4. Performance of SOFCs 140
4.6.5. SOFC Programs 141
4.6.6. Processing Techniques of SOFC Components 143
4.7. Direct Methanol Fuel Cells (DMFC) 151
4.8. Hybrid Cells 157
4.8.1. Metal-Air Batteries 158
4.8.2. Zinc-Air Batteries 159
4.8.3. Iron-Air Batteries 162
4.8.4. Metaloxide-Hydrogen Batteries 165
4.8.5. Metaloxide-Metalhydride Batteries 166

5. Fuel Cells and Their Applications in Dispersed Energy Systems (Utility Use) 181

5.1. Utility Interest in Fuel Cells 181
5.2. Integrated Resource Planning (IRP) 182
5.2.1. Least Cost Planning (LCP) 183
5.2.2. Demand-Side Management (DSM) 183
5.3. Utility Phosphoric Acid Fuel Cell Plants 185
5.3.1. History 185
5.3.2. 11 MW PAFC Demonstration (TEPCO) 186
5.3.2.1. Introduction 186
5.3.2.2. Plant Construction and Operation 188
5.3.2.3. Plant Performance 188

5.3.3. 5 MW PAFC Demonstration (FE) 191
5.3.3.1. General 191
5.3.3.2. Basic Specifications and Configuration of Plant 191
5.3.3.3. Main Components 194
5.4. Utility Molten Carbonate Fuel Cell (MCFC) 196
5.4.1. Introduction 196
5.4.2. System Description of Energy Research Corporation's 2 MW MCFC 197
5.4.2.1. Introduction 197
5.4.2.2. General Plant Overview 197
5.4.2.3. Main Components 198
5.4.3. Demonstration of MCFC Stacks and Plant System at Akagi Stack and System Square (3S) 201
5.4.4. Development Status of MCFC at the Central Research Institute of Electric Power Industry (CRIEPI) 202
5.5. Further Concepts Including SOFC 205

6. Fuel Cells and Their Applications in On-Site Integrated Energy Systems and Industrial Co-generation 207

6.1. Introduction 207
6.2. Phosphoric Acid Fuel Cells for On-Site Use 207
6.2.1. Historical Review of Developments 207
6.2.2. International Fuel Cells Corp. (IFC) 211
6.2.3. Westinghouse/ERC 217
6.2.4. Engelhard On-Site Fuel Cell Program 218
6.2.5. Developments in Japan 218
6.2.6. Work and Developments at Toshiba 220
6.2.7. Fuji Electric 224
6.2.7.1. PAFC Plants Using Natural Gas (Town Gas 14A) 225
6.2.7.2. PAFC Plants Using Various Fuels 230
6.2.8. Mitsubishi Electric Corporation 232
6.2.9. Technological, Ecological and Economic Comparison Between PAFC and Conventional On-Site Power Plants 236
6.2.10. Troubles and Their Eradications Referring to PAFC 241
6.3. Molten Carbonate Fuel Cells (MCFC) for On-Site Use 242
6.4. Other Projects for On-Site Use 246

7. Fuel Cell Powered Electric Vehicles 251

7.1. Introduction 251
7.2. The Environmental Benefits of Fuel Cell Vehicles 252
7.3. Present Day Electric Vehicle Technology 253
7.3.1. The Performance of Rechargeable Batteries 253
7.3.2. Electric Motors 255

7.4. Historical Review of Fuel Cell Vehicles 255
7.4.1. The Early Developments 255
7.4.2. The General Motors Corp. "Electrovan" 256
7.4.3. The Kordesch Fuel Cell-Battery Hybrid Passenger Car 257
7.4.3.1. Description of the Vehicle 257
7.4.3.2. The Fuel Cell System 261
7.4.3.3. The Hybrid System: Fuel Cell and Rechargeable Battery 262
7.4.4. Improved Fuel Cell/Secondary Battery Hybrid Systems 265
7.4.5. Other Fuels for Fuel Cell Systems 266
7.4.5.1. Ammonia as Fuel 266
7.4.5.2. Hydrazine as Fuel 267
7.4.6. Overview – The Changes in Fuel Cell Technology 269
7.5. Fuel Cell Vehicle Technology in the 1980s and 90s 272
7.5.1. Alkaline Fuel Cells for Electric Vehicles 272
7.5.1.1. The Elenco Fuel Cell System 272
7.5.1.2. The EUREKA Bus Project 273
7.5.1.3. Fuel Cells for Underwater Propulsion 275
7.5.2. Phosphoric Acid Fuel Cells for Electric Vehicles 275
7.5.2.1. The DOE-Program for Fuel Cells in Transportation 275
7.5.2.2. The PAFC City Bus Program 276
7.5.2.3. The Engelhard Industries "Liquid Cooled System" 278
7.5.3. The Proton Exchange Membrane FC for Electric Vehicles 279
7.5.3.1. The DOE-PEM Fuel Cell Program 279
7.5.3.2. The Ballard Power System PEFC Activities 280
7.5.4. International Fuel Cells Corporation (IFC) 287
7.5.5. Other PEM-Fuel Cell Programs 287
7.5.5.1. Energy Partners 287
7.5.5.2. United Technologies – Hamilton Standard Div. 289
7.5.5.3. Ergenics Power Systems, Inc. (EPSI) 289
7.5.5.4. Siemens AG 289
7.6. Technological Outlook and Conclusion 290

8. Fuels for the Fuel Cell Technology 297

8.1. Hydrogen 297
8.1.1. Hydrogen Production 297
8.1.2. Safety Aspects of Hydrogen 298
8.2. The Industrial Production of Hydrogen 300
8.3. Hydrogen by Catalytic Steam Reforming of Natural Gas 302
8.3.1. The Reforming Process for Phosphoric Acid Fuel Cells 309
8.3.2. Problem Areas in the Reforming Process 309
8.3.3. Substitution of Gaseous Fuels in PAFC Systems 311
8.4. Hydrogen by Methane Decomposition 313
8.5. Partial Oxidation of Heavy Hydrocarbons 315

8.6. Hydrogen from Coal 317
8.6.1. Hydrogen from Coal Gasification 317
8.6.2. Coal-Assisted Electrolysis 323
8.7. Internal Hydrocarbon Processing 324
8.8. Hydrogen as a By-Product from Other Conventional Processes 324
8.9. Methanol Steam Reforming 325
8.10. The Production of Hydrogen and Methanol from Solid Biomass 326
8.11. Hydrogen from Electrolysis of Water 329
8.12. Hydrogen from the Steam-Iron Process 332
8.13. Carbon-Free Energy Carriers 333
8.13.1. Ammonia 333
8.13.2. Hydrazine, N_2H_4 335

9. Fuel Cells: Summary and Outlook beyond 2000 339

9.1. Fuel Cell Systems as Energy Converters, Applications 340
9.1.1. Dispersed Systems Partly Replacing Central Systems 340
9.1.2. Environmental Performance 340
9.1.3. Economic Aspects 341
9.2. The Worldwide State of the Art and Readiness of the Different Fuel Cell Systems 344
9.2.1. Programs in USA and Canada 344
9.2.2. Japan 349
9.2.3. Europe 352
9.3. The Hydrogen Technology (Gaseous-, Liquid- or Solid Fuels?) 354
9.4. The Fuel Cell Strategies until and beyond 2000 (Support and Opposition) 355
9.5. My Outlook on Fuel Cells (A personal post scriptum by the senior author) 357

Index 363