

# CONTENTS

<b>PREFACE</b>	<b>xi</b>
<b>PREFACE TO THE FIRST EDITION</b>	<b>xiii</b>
<b>SYMBOLS</b>	<b>xv</b>
<b>ABBREVIATIONS AND ACRONYMS</b>	<b>xvii</b>
 <b>PART I INTRODUCTION</b>	 <b>1</b>
<b>Introduction</b>	<b>3</b>
What Is a Fuel Cell? Definition of the Term, 3	
Significance of Fuel Cells for the Economy, 3	
 <b>1 The Working Principles of a Fuel Cell</b>	 <b>5</b>
1.1 Thermodynamic Aspects, 5	
1.2 Schematic Layout of Fuel Cell Units, 9	
1.3 Types of Fuel Cells, 13	
1.4 Layout of a Real Fuel Cell: The Hydrogen–Oxygen Fuel Cell with Liquid Electrolyte, 13	
1.5 Basic Parameters of Fuel Cells, 18	
Reference, 24	

<b>2</b>	<b>The Long History of Fuel Cells</b>	<b>25</b>
2.1	The Period Prior to 1894,	25
2.2	The Period from 1894 to 1960,	28
2.3	The Period from 1960 to the 1990s,	31
2.4	The Period After the 1990s,	37
	References,	38
<b>PART II</b>	<b>MAJOR TYPES OF FUEL CELLS</b>	<b>41</b>
<b>3</b>	<b>Proton-Exchange Membrane Fuel Cells</b>	<b>43</b>
3.1	History of the PEMFC,	44
3.2	Standard PEMFC Version from the 1990s,	47
3.3	Special Features of PEMFC Operation,	51
3.4	Platinum Catalyst Poisoning by Traces of CO in the Hydrogen,	54
3.5	Commercial Activities in Relation to PEMFCs,	56
3.6	Future Development of PEMFCs,	57
3.7	Elevated-Temperature PEMFCs,	64
	References,	67
<b>4</b>	<b>Direct Liquid Fuel Cells</b>	<b>71</b>
	Part A: Direct Methanol Fuel Cells,	71
4.1	Methanol as a Fuel for Fuel Cells,	71
4.2	Current-Producing Reactions and Thermodynamic Parameters,	72
4.3	Anodic Oxidation of Methanol,	72
4.4	Milestones in DMFC Development,	74
4.5	Membrane Penetration by Methanol (Methanol Crossover),	74
4.6	Varieties of DMFCs,	77
4.7	Special Operating Features of DMFCs,	79
4.8	Practical Models of DMFCs and Their Features,	81
4.9	Problems to Be Solved in Future DMFCs,	83
	Part B: Direct Liquid Fuel Cells,	85
4.10	The Problem of Replacing Methanol,	85
4.11	Fuel Cells Using Organic Liquids as Fuels,	86
4.12	Fuel Cells Using Inorganic Liquids as Fuels,	91
	References,	94
<b>5</b>	<b>Phosphoric Acid Fuel Cells</b>	<b>99</b>
5.1	Early Work on Phosphoric Acid Fuel Cells,	99
5.2	Special Features of Aqueous Phosphoric Acid Solutions,	100
5.3	Construction of PAFCs,	101

5.4	Commercial Production of PAFCs, 102	
5.5	Development of Large Stationary Power Plants, 103	
5.6	The Future of PAFCs, 103	
5.7	Importance of PAFCs for Fuel Cell Development, 104	
	References, 105	
<b>6</b>	<b>Alkaline Fuel Cells</b>	<b>107</b>
6.1	Hydrogen–Oxygen AFCs, 108	
6.2	Alkaline Hydrazine Fuel Cells, 115	
6.3	Anion-Exchange (Hydroxyl Ion–Conducting) Membranes, 118	
6.4	Methanol Fuel Cells with Anion-Exchange Membranes, 119	
6.5	Methanol Fuel Cell with an Invariant Alkaline Electrolyte, 120	
6.6	Direct Ammonia Fuel Cell with an Anion-Exchange Membrane, 121	
	References, 121	
<b>7</b>	<b>Molten Carbonate Fuel Cells</b>	<b>123</b>
7.1	Special Features of High-Temperature Fuel Cells, 123	
7.2	Structure of Hydrogen–Oxygen MCFCs, 124	
7.3	MCFCs with Internal Fuel Reforming, 126	
7.4	Development of MCFC Work, 128	
7.5	The Lifetime of MCFCs, 129	
	References, 131	
<b>8</b>	<b>Solid-Oxide Fuel Cells</b>	<b>133</b>
8.1	Schematic Design of Conventional SOFCs, 134	
8.2	Tubular SOFCs, 136	
8.3	Planar SOFCs, 140	
8.4	Monolithic SOFCs, 143	
8.5	Varieties of SOFCs, 144	
8.6	Utilization of Natural Fuels in SOFCs, 146	
8.7	Interim-Temperature SOFCs, 148	
8.8	Low-Temperature SOFCs, 152	
8.9	Factors Influencing the Lifetime of SOFCs, 154	
	References, 156	
<b>9</b>	<b>Other Types of Fuel Cells</b>	<b>159</b>
9.1	Redox Flow Cells, 159	
9.2	Biological Fuel Cells, 162	
9.3	Semi-Fuel Cells, 167	
9.4	Direct Carbon Fuel Cells, 169	
	References, 174	

<b>10 Fuel Cells and Electrolysis Processes</b>	<b>177</b>
10.1 Water Electrolysis, 177	
10.2 Chlor-Alkali Electrolysis, 182	
10.3 Electrochemical Synthesis Reactions, 185	
References, 187	
 <b>PART III INHERENT SCIENTIFIC AND ENGINEERING PROBLEMS</b>	 <b>189</b>
<b>11 Fuel Management</b>	<b>191</b>
11.1 Reforming of Natural Fuels, 192	
11.2 Production of Hydrogen for Autonomous Power Plants, 196	
11.3 Purification of Technical Hydrogen, 199	
11.4 Hydrogen Transport and Storage, 202	
References, 205	
 <b>12 Electrocatalysis</b>	 <b>207</b>
12.1 Fundamentals of Electrocatalysis, 207	
12.2 Putting Platinum Catalysts on the Electrodes, 211	
12.3 Supports for Platinum Catalysts, 214	
12.4 Platinum Alloys and Composites as Catalysts for Anodes, 217	
12.5 Nonplatinum Catalysts for Fuel Cell Anodes, 220	
12.6 Electrocatalysis of the Oxygen Reduction Reaction, 221	
12.7 Stability of Electrocatalysts, 227	
References, 228	
 <b>13 Membranes</b>	 <b>233</b>
13.1 Fuel Cell–Related Membrane Problems, 234	
13.2 Work to Overcome Degradation of Nafion Membranes, 235	
13.3 Modification of Nafion Membranes, 235	
13.4 Membranes Made from Polymers Without Fluorine, 237	
13.5 Membranes Made from Other Materials, 239	
13.6 Matrix-Type Membranes, 239	
13.7 Membranes with Hydroxyl Ion Conduction, 240	
References, 241	
 <b>14 Structural and Wetting Properties of Fuel Cell Components</b>	 <b>243</b>
<i>Coauthor: Yuriy M. Volfkovich</i>	
14.1 Methods for Investigating Porous Materials, 244	

14.2	A New Method: The Method of Standard Contact Porosimetry, 245	
14.3	Catalysts Used in Fuel Cells, 248	
14.4	The Catalytic Layer, 252	
14.5	The Gas-Diffusion Layer, 254	
14.6	Membranes, 257	
14.7	Influence of Structural and Wetting Properties on Fuel Cell Performance, 262	
	References, 264	
<b>15</b>	<b>Mathematical Modeling of Fuel Cells</b>	<b>267</b>
	<i>Felix N. Büchi</i>	
15.1	Zero-Dimensional Models, 270	
15.2	One-Dimensional Models, 270	
15.3	Two-Dimensional Models, 271	
15.4	Three-Dimensional Models, 272	
15.5	Time Domain, 273	
15.6	Concluding Remarks, 273	
	References, 274	
<b>16</b>	<b>Experimental Methods for Investigating Fuel Cell Stacks</b>	<b>275</b>
16.1	Methods Developed Before 2007, 277	
16.2	Optical, X-Ray, and EM Methods, 278	
16.3	Neutron Beam-Based Methods, 281	
16.4	Electrochemical Methods, 283	
16.5	Miscellaneous Methods, 286	
	References, 288	
<b>17</b>	<b>Small Fuel Cells for Portable Devices</b>	<b>291</b>
17.1	Special Operating Features of Mini-Fuel Cells, 292	
17.2	Flat Mini-Fuel Batteries, 293	
17.3	Silicon-Based Mini-Fuel Cells, 296	
17.4	PCB-Based Mini-Fuel Cells, 298	
17.5	Mini-Solid-Oxide Fuel Cells, 299	
17.6	The Problem of Air-Breathing Cathodes, 300	
17.7	Prototypes of Power Units with Mini-Fuel Cells, 301	
17.8	Concluding Remarks, 304	
	References, 305	
<b>18</b>	<b>Nonconventional Design Principles for Fuel Cells</b>	<b>307</b>
18.1	Conventional Design Principles and Their Drawbacks, 307	
18.2	The Principle of Mixed-Reactant Supply: Mixed-Reactant Fuel Cells, 308	

18.3	Coplanar Fuel Cell Design: Strip Cells, 310	
18.4	The Flow-Through Electrode Principle, 312	
18.5	Single-Chamber SOFCs, 313	
18.6	Microfluidic Fuel Cells, 319	
	References, 321	
<b>PART IV</b>	<b>COMMERCIALIZATION OF FUEL CELLS</b>	<b>325</b>
<b>19</b>	<b>Applications</b>	<b>327</b>
19.1	Large Stationary Power Plants, 327	
19.2	Small Stationary Power Units, 332	
19.3	Fuel Cells for Transport Applications, 335	
19.4	Portables, 341	
19.5	Military Applications, 345	
19.6	Handicaps Preventing a Broader Commercialization of Fuel Cells, 347	
	References, 348	
<b>20</b>	<b>Fuel Cell Work in Various Countries</b>	<b>351</b>
20.1	Driving Forces for Fuel Cell Work, 351	
20.2	Fuel Cells and the Hydrogen Economy, 353	
20.3	Activities in North America, 355	
20.4	Activities in Europe, 356	
20.5	Activities in other Countries, 357	
20.6	The Volume of Published Fuel Cell Work, 359	
20.7	Legislation and Standardization in the Field of Fuel Cells, 361	
	References, 362	
<b>21</b>	<b>Outlook</b>	<b>363</b>
21.1	Periods of Alternating Hope and Disappointment, 363	
21.2	Some Misconceptions, 364 <i>Klaus Müller</i>	
21.3	Ideal Fuel Cells, 366	
21.4	Projected Future of Fuel Cells, 368	
	References, 369	
<b>GENERAL BIBLIOGRAPHY</b>		<b>371</b>
<b>AUTHOR INDEX</b>		<b>373</b>
<b>SUBJECT INDEX</b>		<b>379</b>