

Fuel Cells, Engines and Hydrogen

An Exergy Approach

Frederick J. Barclay

C.Eng., C.Phys.,

F.I.Mech.E., F.I.E.E., F.Inst.P.



John Wiley & Sons, Ltd

Contents

Foreword	xi
Introduction, and Commentary on Matters Affecting all Chapters	1
1 Altered Perspectives	29
1.1 Power Storage	30
1.2 Circulators	31
1.3 Incompleteness	31
1.4 The Hydrogen Mine	32
1.5 Coal Gasification	33
1.6 SOFCs	34
1.7 MCFCs	35
1.8 The PEFC	37
1.9 Engines	38
2 Regenerative Fuel Cells or Redox Flow Batteries	41
2.1 Introduction to the Regenesys System	41
2.2 History and Patents	43
2.3 Regenesys Technologies Ltd; Power Storage	44
2.4 Elementary Chemistry	44
2.5 Modus Operandi of Regenesys	46
2.6 Some Construction Details	48
2.7 Ion and Electron Transfer	48
2.8 Power Storage Applications	49
2.9 Initial Operating Experience	49
2.10 Electrical Equipment	50
2.11 Remarks	50
2.12 Conclusions	51

3	Irreversible Thermodynamics	53
3.1	Cells and Electrolysers with and without Circulators	53
3.2	Irreversibility – An Introduction via Joule’s Experiment	54
3.3	PEFC Irreversibility	56
3.4	Bacon’s Fuel Cell; Avoidance of Irreversibility	58
3.5	Fuel Cell Engineering	58
3.6	Irreversibility in Calculation Routes	58
3.7	Juggling with Irreversibilities	59
3.8	Air-Breathing Fuel Cells – Irreversibilities	60
3.9	Liquid Electrolytes at the Electrode, ‘Ice’ Films, Marangoni Forces and Diffusion Irreversibilities	62
3.10	Overtoltage – An Electrical Irreversibility	63
3.11	Biconductor Layers at the Electrode/Electrolyte Interface	64
3.12	IR Drop	65
3.13	Remarks	65
4	Solid Oxide Fuel Cells (SOFCs)	67
4.1	Introduction	67
4.1.1	The SOFC	67
4.1.2	Electrolytes	69
4.1.3	Electrolyte Thickness	69
4.1.4	Cell Performance	69
4.1.5	Competitive Cells	70
4.1.6	Oxygen Ion Concentration	70
4.1.7	Unused Fuel	71
4.1.8	SOFC Internal Process	71
4.1.9	SOFC Preheating for Start-Up	72
4.1.10	SOFC Manoeuvrability	72
4.1.11	Direct Hydrocarbon Oxidation	73
4.2	Siemens Westinghouse	74
4.2.1	Siemens – SOFC Integration with Gas Turbines	75
4.3	Rolls-Royce	76
4.4	NGK Insulators	78
4.5	Mitsubishi Materials Corporation (MMTL)	78
4.6	Imperial College London and Ceres Power Ltd	79
4.7	Ceramic Fuel Cells Ltd, Australia	80
4.8	Forschungs Zentrum Julich (FZJ)	81
4.9	Global Thermoelectric	82

4.10	Allied Signal	82
4.11	Acumentrics	83
4.12	Adelan	84
4.13	Sulzer Hexis	84
4.14	ECN/INDEC Petten, the Netherlands	84
4.15	Remarks	89
5	Molten Carbonate Fuel Cells (MCFCs)	91
5.1	Introduction to the MCFC	91
5.1.1	MCFCs of FCE and MTU	92
5.1.2	Detailed Fuel Cell Description	96
5.1.3	Matrix Initiation	96
5.1.4	Matrix and Cathode Deterioration	96
5.1.5	Performance of Complete Cells	97
5.1.6	Bipolar Plates	97
5.1.7	Stacks	97
5.1.8	Gas Turbine Integration with an MCFC	98
5.1.9	Nickel Oxide Deposition at the Cathode at High Pressure	100
5.1.10	Nickel Behaviour, Short-Circuiting	100
5.1.11	MCFC Integration with Coal Gasification	100
5.2	MCFC Status	101
5.3	Remarks	102
6	Polymer Electrolyte and Direct Methanol Fuel Cells	103
6.1	Introduction	103
6.1.1	Ballard Power Systems	103
6.1.2	Ballard History	104
6.1.3	Ballard Status	105
6.1.4	Ballard Stacks	105
6.1.5	Flexible Graphite and Ballard	105
6.1.6	Ballard MEAs	108
6.1.7	Nafion and Alternatives	109
6.1.8	Alternative Flow Plate Materials Used by Competitors	110
6.1.9	Ballard Operating Experience	111
6.2	Electrocatalysis in the SPFC	112
6.3	Cathode Voltage Losses in the PEFC	113
6.4	The PEFC Hydrogen Economy in Iceland	114
6.5	Fuel Supply	114
6.6	DMFCs	114

6.7	Tokyo Gas Company, Desulphuriser	117
6.8	Remarks	117
7	Fuel Cell Economics and Prognosis	119
7.1	Opening Remarks	119
7.2	Fuel Cell Economics – Selected Summaries	120
7.3	Non-Fuel-Cell Motor Vehicle Economics	121
7.4	Price Waterhouse Fuel Cell Industry Survey	122
7.5	Remarks	123
Appendix A Equilibrium Thermodynamics of Perfect Fuel Cells		125
A.1	Thermodynamic Preamble to the Fuel Cell Equilibrium Diagram	126
A.2	Utilisation of Equilibrium Diagram for Calculation of Chemical Exergy	136
A.3	Chemical Exergy of Methane and Related High-Efficiency Hydrogen Production	150
A.4	Elaboration of Figures A.4 and A.5, the Equilibrium Methane Oxidation Routes	165
A.5	Practical Power Production for the Future	166
Appendix B Patent Search Examples		171
Appendix C List of Web Sites		173
Bibliography		177
Index		185