

Subject Index

- absolute humidity (AH) 274, 275
ABTS (2,2'-azino-bis-(3-ethylbenzthiazoline-6-sulfonic acid) diammonium salt) 8, 9
ACC (anode current collecting)
layer 172
accelerated lifetime testing
need for viii–ix
PAFCs 249–61
background theory 249–53
corrosion current
monitoring 256–8, 259
corrosion potential
measurement 254–60
inter-cell effects 258–60
acetylene 162
acid leaching, HT-PEFCs 57, 60, 65
acid loading, HT-PEFCs 56, 57
acid migration, PAFCs 252–3, 260
added value 314, 315, 316, 323–30
adsorption effects 49–53, 164, 165
aeronautical applications
drag minimisation 105
large APUs
design objectives 77–80
fuel cell systems 91–3, 103–7
fuels 98–9
operating conditions 82–6
overview 76, 77, 141
system evaluation 113–36
AFCs (alkaline fuel cells) 88, 91
AH (absolute humidity) 274, 275
air compression, large APUs 126
air excess number, SOFC models 225
air ratios, large APUs 121, 127
alcohol dehydrogenase 14–15
alkali metals
lithium carbonate 194, 195
lithium hydroxide 196, 197
modified nickel cermet anodes
169
potassium carbonate 194, 195
potassium hydroxide 196, 197
sodium carbonate 194
sodium hydroxide 196, 197
alkaline fuel cells *see* AFCs
allowable cost 326–7
almond shells biomass 203, 204, 205
alumina 34
ambient air, large APUs 126
2-amino-1,4-naphthoquinone
(ANQ) 12
ammonia, SOFCs 156, 177–8
amorphous carbon 199, 200, 201
anode current collecting (ACC)
layer 172
anodes
see also bipolar plates
ink printed enzymatic biofuel
cells 22–3
liquid tin, SO electrolyte
combination 204–7
multilayer ceramics 37–8
SOFCs 153–78
activation 162, 231
basic requirements 171
conventional 159–68
improved/unconventional
SOFCs 168–76
nickel-free 171–5

- ANQ (2-amino-1,4-naphthoquinone) 12
 anti-icing, aircraft 84–5, 103
 antimony 166–7
 apparent activation energy 231
 APUs *see* auxiliary power units
 ARAL 314
 arsenic 166–7
Aspergillus niger glucose oxidase 8, 11
 ASR (area specific resistance)
 degradation integration into lifetime modelling 218–20, 222, 223, 227–45
 SOFCs in SOEC mode 273–4, 278, 279
 assembly costs 29
 Autonomy concept vehicle (General Motors) 328–9
 autothermal reforming (ATR) reaction
 ATR/HT-PEFC, large
 APUs 118–22, 124, 126–8, 131, 134
 carbonaceous fuels 157, 158
 fuel processors 100, 101
 auxiliary power units (APUs) vi, 70, 76–143
 aeronautical
 design objectives 77–80
 fuel cell systems 91–3, 103–7
 fuels 98–9
 operating conditions 82–6
 overview 76, 77, 141
 system evaluation 113–36
 maritime
 design objectives 81
 electric power requirements 81
 fuel cell systems 81, 93, 107–12
 fuels 99–100
 main engine emissions study 82
 operating conditions 86–7
 overview 140, 142–3
 system evaluation 136, 138–40
 2,2'-azino-bis-(3-ethylbenzthiazoline-6-sulfonic acid) diammonium salt (ABTS) 8, 9
Bacillus sp. 12
 balance-of-plant (BoP) issues 280, 282
 Bavarian Center for Applied Energy Research 198, 199
 benzothiophenes,
 desulfurisation 98–9
 bilirubin oxidase (BOD) 11, 13
 bioelectrocatalysis process 7
 biofuels
 biofuel cells 5–25
 biogases
 ammonia 156, 177–8
 resources 158
 carbonaceous fuels 156
 energy densities, large APUs 94, 95, 97
 biosensors 17–19
 bipolar plates (BiPs) 66–8, 249–61
 bisulfate anions 50
 BOD (bilirubin oxidase) 11, 13
 Boeing 787 aircraft 104
 boiling curves 95, 98
 BoP (balance-of-plant) issues 280, 282
 Boudouard reaction/equilibrium
 DCFCs 193, 194, 196, 203, 204, 302
 fuel processors 100
 boundary value problems (BVPs) 226, 227
 break-even point, large APUs 134
 break-in period, HT-PEFCs 62
 buffer concentration 13–14
 butanoic acid 162
 Butler–Volmer equation 221, 222, 250
 BVPs (boundary value problems) 226, 227

 C_{3v} symmetry 52
 cadmium 50, 167
 Canada 314
 carbohydrate-using biofuel cell 11, 12
 carbon
 see also DCFCs

- amorphous 199, 200, 201
corrosion 65, 250
deposition 100, 155, 160–3, 168–75
electrochemical oxidation 190–3
nanotubes 8, 22
whiskers/filaments 161, 162
- carbon dioxide
DCFCs 190–209, 301, 303
emissions reduction 190, 192, 318, 320–1
IR-SOFC co-production of hydrogen 292, 297
large APUs 129
aeronautical 135
fuels 94, 95, 96–7, 98
maritime 139, 140
- carbon fibre (CF) 11, 13, 59–60
- carbon monoxide
DCFCs hydrogen production 301, 303
IR-SOFC co-production of hydrogen 292, 297
PEMs 154
tolerance
HT-PEFCs vi, 45, 63, 64
stacks design 67
- carbon-supported catalysts 58
- carbon-supported electrodes 9, 10
- carbon-supported platinum transition metal alloy catalysts 53–4
- carbonaceous fuels viii, 156, 157–76, 207–9
- carbonates 194–6
- carbon-graphite separator plates 249–61
- carbon–polymer composites 66
- Carnot efficiency 190, 192, 301, 302
- catalysts
see also enzymatic biofuel cells; nickel-based catalyst anode
conventional SOFC anodes 159
enzymatic biofuel cells 5–25
HT-PEFC catalyst layer
development 58–61
- PEM electrolyzers 270
- platinum alloy catalysts 53–4
- catalytic partial oxidation (CPO) 158
- cathodes
see also bipolar plates
carbohydrate-using biofuel cell 14
inks 22–3
multilayer ceramics 38
- CCE (Clean Coal Energy, USA) 203
- cell testing, PAFC separator plates 253
- cell-and-one-half configuration 254, 259
- CellTech Power, USA 204–6
- ceramic multilayers *see* multilayer ceramics
- ceramic systems 173
- ceria 169–70, 175–6
- cermet electrodes 169–71, 273, 277
- charge transfer coefficient (β) 221
- chemical equilibrium 102
- chemical stability 22, 23, 66, 159, 179
- chitosan 8, 14
- chloride anions 50
- chlorine 167–8
- CHP (combined heat and power) 77, 78
- chromium 171–2, 174–5, 176
- Clean Coal Energy (CCE, USA) 203
- closed porosity 259
- closed water balance 117–18, 122, 124, 127
- CNC (computerised numerically controlled) machinery 31, 33
- co-production of hydrogen and power 287–304
- coal
DCFCs 196, 203, 205
SOFCs fuel 155, 156, 158
syngas, SOFCs fuel 163, 165, 166, 167, 168
- coated electrodes 8–11, 19–21
- cobalt 53, 170–1
- coefficient of thermal expansion (CTE) 174
- coking 155, 171
- cold-start vi, 62, 70

- combined heat and power generation (CHP) 77, 78
- combined heat/power/hydrogen production 287–304
- combined (hybrid) systems 29, 79, 83–4, 111
- commercial systems ix, 270, 311–31
see also large-scale production
- complex hydrocarbons, SOFCs 155, 156, 158, 171
- component failures, micro-systems 29
- compressed hydrogen 93, 128, 130, 131, 132, 136, 137
- compression of membrane electrode assemblies 63–4
- computerised numerically controlled (CNC) machinery 31, 33
- condensation-related degradation 280
- conditioning process 62
- conductivity behaviour 60, 159, 172
n-type 173, 174, 178
Nafion® 56, 57
p-type 172–3
- constant-current mode 294–5
- constant-(low)voltage mode 295–8
- consumer incentives 119–20, 312, 331
 added value 314, 315, 316, 323–30
- contact bridges 239
- conversion technologies 157–8
- copper 170–1, 175
- Coriolus* spp. 8, 11
- corrosion
 carbon corrosion 65, 250
 current 256–8
 HT-PEFCs electrode degradation 65
 molten carbonates 195
 corrosion potential (E_C) 250, 251, 254–6
- costs
 enzymatic biofuel cells 6
 large-scale production 29
 liquid chamber biofuel cells 8
 market introduction 323–30
- PEM electrolyzers 271
- CPOX (catalytic partial oxidation) 119, 120, 121, 158
- cracking, methane 155
- crystallised carbon fuels 207, 208
- C_s symmetry 52
- CS-25 Approval Directive 92
- CTE (coefficient of thermal expansion) 174
- cubic perovskites 173
- current density
 DCFCs 203
 HT-PEFC cell performance 61–2
- IR-SOFC co-production of hydrogen 292, 293, 295
- SOFCs lifetime modelling 223
 change over time 244–5
 constant 240, 241–2
 loss of contact bridges 239
 varying 242–4
- current–voltage (I–V) curves
- DCFCs
 molten hydroxide electrolyte 197–8
 SO electrolyte 199, 200
- IR-SOFC co-production of hydrogen 296, 298
- SOFC lifetime modelling
 theory 222, 227–34, 235
- SOFC in SOEC mode 273–4, 275, 276
- Cyclo Tempo flow-sheet program 291–5
- DCFCs (direct carbon fuel cells) 190–209
 Boudouard reaction 193, 194, 196, 203, 204
 different carbon fuels comparison 207–9
 electrochemical oxidation of carbon 190–3
 hydrogen production 300–3
 reaction mechanism 192–3
 solid oxide electrolyte 198–207
 thermodynamics 191–2

- types 193–207
molten carbonate electrolyte 194–6
molten hydroxide electrolyte 196–8
solid oxide electrolyte 198–207
carbon conversion with preceding chemical reaction step 202–7
SOFC combined with liquid carbonate-based anode 200–2, 203
- degradation
see also lifetime testing
HT-PEFC electrodes 65
HTE stacks 279, 280
PAFC carbon-graphite separator plates 249–61
SOFCS
ASR simulation 234–6
models 217–45
elaborated linear with internal methane reforming 236–41
one-dimensional isothermal 217–36
extensions 236–7
simple lifetime prediction model 237–41
in SOEC mode 276, 277, 278
- delamination 276, 277
- DESIRE project 109
- desulfurisation 98–9, 108, 111, 156
- DET (direct electron transfer) 7
- diaphorase (DI) 12
- diesel 94–6, 99, 100, 101, 108, 109, 111, 120, 139
- diffusion layers design 58–61
- dihydrogen phosphate ion 52
- p*-diphenol dioxygen oxido-reductases (EC 1.10.3.2) 21, 22
- direct carbon fuel cells *see* DCFCs
- direct electron transfer (DET) 7
- direct methanol biocatalytic fuel cells (DMBFCs) 10–11
- direct methanol fuel cells (DMFCs) vii, 36, 81, 89, 91
- disruptive development of fuel cell products 312–17
- DMBFCs (direct methanol biocatalytic fuel cells) 10–11
- DMFCs (direct methanol fuel cells) vii, 36, 81, 89, 91
- double perovskite-based structures 174
- drag minimisation 105
- driver interfaces 329–30
- durability *see* lifetime prediction
- efficiency
DCFCs 191, 192, 202
IR-SOFC co-production of hydrogen 293–8
large APUs 79, 112–40
leaps in development 317
PEM electrolyzers 271
- EHS (electrochemical hydrogen separator) 290
- electric circuit equivalent 222
- electric current
see also current density; current–voltage curves
ASR 218–20, 222, 223, 224, 227–45, 273–4, 278, 279
- conductivity 159, 172
- load, SOFCs 164
- multilayer ceramics 35–6
- power density, large APUs 134
- power production, enzymatic microsystems 8–15
- requirements
aeronautical APUs 84, 85
maritime applications 81
- SOFC lifetime modelling theory 223–34
transport, multilayers 35–6
- electrical-to-chemical energy conversion 268, 272, 282–3
- electrochemical carbon oxidation 190–3

- electrochemical hydrogen separator (EHS) 290
- electrodes *see* anodes; cathodes; membrane electrode assemblies
- electrolysis 267–83
- electrolytes
- alternatives, HT-PEFCs, enhanced activity 54, 55
 - DCFCs
 - molten hydroxide 196–8
 - solid oxide electrolyte 198–207
 - water content 196
 - migration, separator plate in PAFC 252–3, 260
 - molten carbonate, DCFCs 194–6
- electron transfer,
- bioelectrocatalysis 7
- embossing, multilayer ceramics 31–2
- emissions
- carbon dioxide 190, 192, 318, 320–1, 329–30
 - large APUs 80, 81, 82, 129
 - aeronautical 135
 - fuels 94, 95, 96–7, 98
 - maritime 139, 140
 - main engines, container ships 82
 - encapsulating carbon formation 161
 - endothermic reactions 202–7, 272, 304
 - endurance testing 217–45
 - energy carriers 101, 102, 114
 - see also* fuels
 - energy consumption, large APUs 129
 - energy conversion 177, 191–2, 268, 294, 298, 301–2
 - energy conversion efficiency (η) 191, 192, 301
 - energy densities 94–7
 - energy-consumer analyses, aircraft APUs 83–6
 - enthalpy (ΔH) 191, 268, 272, 301, 302
 - entropy 302
 - environmental benefits 312, 315, 318, 319–20, 331
 - enzymatic biofuel cells 5–25
 - applications 6
- biosensors 17–19
- enzyme catalysts used in 6–7
- history 6
- large-scale production 11–15
- liquid chamber biofuel cell construction 8–11
- microsystems for power production 8–15
- miniature membraneless 11
- performance 10
- printed 21–4
 - generic structure 24
 - inkjet printing 20–1
 - printing processes 15–17
 - screen printing 15, 16, 17, 19–20
- structures 8, 9, 10
- weaknesses to be overcome 24
- enzymes
- see also* enzymatic biofuel cells; individual enzymes
 - immobilisation v, 9, 11, 14
 - printing and coating 19–21
 - substrate specificity 6–7
 - equilibrium gas compositions 101, 102, 114
 - equivalent input current density 292
 - ethane 162
 - ethanoic acid 162
 - ethanol 96, 101, 102, 162
 - ethanol/O₂ biofuel cells 9, 14–15
 - Europe 314, 315
 - European Institute for Energy Research 279
 - exchange current density 46
 - exothermic operation 272
 - exponential degradation 238, 239, 240, 241
- F-76 NATO fuel 108, 109
- FAD electron acceptor 8, 9
- FAME (fatty acid methyl esters) 95, 96
- Faraday's constant 292
- Faraday's law 225
- FeMCA (ferrocene monocarboxylic acid) 8

- first law of thermodynamics 294, 298, 301
first-order ODEs 226
Fischer-Tropsch diesel production 94, 95, 96
flexography 15, 16
flowfield current pickup 35, 36
fluctuating power sources 298–300
fluid distribution channels 34, 35
fluidised-bed technologies 203–4, 205
fluorinated acids 54, 55
food labels 18
Forschungszentrum Jülich 218, 222, 228
Fourier transform infrared (FT-IR) spectra 51–2
free energy (ΔG) 191, 268, 272, 273, 301, 302
free enthalpy (ΔH) 191, 268, 272, 301, 302
free-radical gas-phase condensation reactions 160
Freundlich-type isotherms 50
fructose sensor 19
FT-IR (Fourier transform infrared spectra) 51–2
Fuel Cell Energy 290
fuel utilisation (U_F)
 DCFCs 192
 IR-SOFC co-production of hydrogen 292, 294, 295, 296, 297
 SOFC lifetime modelling theory 233–4, 242–4
 Superwind Concept 297
fuels
 DCFC fuels 190, 207–9
 delivery, multilayer ceramics, hidden channels 34, 35
 humidity 223, 224, 228–34, 235, 274, 275
 hydrogen production, large APUs 81, 93–100
 mobile applications 76
 non-standard, pure carbon viii
oil/petrol, mobile applications 96, 99, 313
processors 100–1, 117, 118
SOFCs ammonia 156, 177–8
carbonaceous resources 157–8
hydrogen sulfide 178–9
 novel 153–78, 190–209
fungal laccase 21, 22
future outlook 311–31
gas channels 218–20, 223–4, 227–31, 236, 238–41, 244–5
gas compositions, chemical equilibrium 102
gas hourly space velocity (GHSV) 108
gas oil, large maritime APUs 96, 99
gas shift reaction 100, 108, 154, 300–1
gasification, SOFCs fuels 155
gasoline, characteristics 96
GDC composites 172
General Motors Autonomy concept vehicle 328–9
geological carbonaceous fuel sources 156
geometrical shaping 30–6
Germany 314, 315
GFG 50M graphitic carbon 200, 201
GH2 (compressed hydrogen) 93, 128, 130, 131, 132, 136, 137
GHSV (gas hourly space velocity) 108
Gibbs free energy (ΔG) 191, 268, 272, 273, 301, 302
glucose dehydrogenase (GDH) 9, 12
glucose oxidase (GOx) 5, 8, 9, 11
glycerol, inkjet inks 21
gold 35, 36, 51–2, 170–1
government regulation 315
grape 11, 12
graphitic carbon
 carbon-graphite PAFC separator plates 249–61
 formation mechanisms 161
HT-PEFC stacks design 67

- graphitic carbon (*continued*)
 solid oxide electrolyte
 DCFCs 200, 201
 weight loss in hot phosphoric acid,
 accelerated lifetime testing 254,
 255
- gravure printing 15, 16, 17
- green (unfired) ceramic layers 29–30,
 31–2, 33, 34
- Grothus transport mechanism 56, 57
- ground operation, aircraft
 APUs 83–4, 120, 125
- Haber–Bosch process 177
- half-cell DCFC reactions 195, 196,
 197, 198, 199
- halogens, chlorine 167–8
- HD-CCD (high density charge-coupled device) 32
- head-head polybenzimidazoles 55
- head-tail polybenzimidazoles 55, 56
- heat exchange areas, large APUs 122,
 124, 127
- heterogeneous microreactors 34–5
- HFO (heavy fuel oil) 99
- hidden channels 34, 35
- high density charge-coupled device
 (HD-CCD) 32
- high-efficiency mode 293–4, 295
- high-power mode 295–8
- high-temperature electrolysis
 (HTE) 267–9
 high-temperature steam
 electrolysis 271–83
 stacks 279–82
- high-temperature fuel cells *see* AFCs;
 DCFCs; HT-PEFCs; HT-PEMs;
 MCFCs; SOFCs
- high-temperature polymer electrolyte
 fuel cells *see* HT-PEFCs
- history
 DCFCs 193
 enzymatic biofuel cells 6
 mobile telephones 313, 316
 natural gas vehicles 313, 314–15
 technological change 313–17
- HOR (hydrogen oxidation reaction) 46
- horseradish peroxidase (HRP) 20–1
- hot-pressing, HT-PEFCs 60–1
- HOTELLY (High Operating Temperature ElectrolYsis) 271
- HotModule MCFC system 110, 111
- HRP (horseradish peroxidase) 20–1
- HSR (heated-steam reforming) 118,
 119
- HT-PEFCs (high-temperature polymer electrolyte fuel cells)
 advantages 45–6, 69–70
 aeronautical large APUs 92–3,
 106, 117, 119, 121, 122, 124, 126,
 127, 128, 130
 mass requirements 132, 135,
 137
- applications viii
- catalyst/diffusion layer
 development 58–61
- characteristics 89, 90
- development trends vi, 45–70
- large auxiliary power units
 76–143
- maritime large APUs 107, 108,
 110, 138
- membrane electrode assembly
 manufacture 58–61
- membrane polymers 54–7
- ORR activity 46–54, 55
- PBI-doped with phosphoric acid,
 large APUs 91
- performance/durability 61–6
- phosphoric acid/phosphate ions
 adsorption on platinum 49–53
 stacks 66–9
- HT-PEM fuel cell generator 104, 105
- HTceramix cell 276, 277–8
- HTE (high-temperature electrolysis) 267–9, 271–83
- humidity, SOFCs fuels 223, 224,
 228–34, 235, 274, 275
- HVO (hydrotreated vegetable oil) 95
- Hy-Light car 91
- hybrid systems 29, 79, 83–4, 111

- hydrocarbonaceous energy
carriers 101, 103
- hydrogen
aeronautical large APUs 113–16,
131
anode tail gas 103
consumption, large APUs 115, 116
fuel processor reactions 100–1
GH₂ (compressed) 93, 128, 130,
131, 132, 136, 137
LH₂ (liquefied) 93, 96, 115, 116,
128, 130, 131, 135, 136, 137
MCFC/SOFC anode/cathode
reversible cell voltage 288
mobile applications, fuels 76
PAFC separator plates 259
PEFCs 153–4
production
high/low-temperature
electrolysis 267–83
large APUs, fuels 93–100
tri-generation systems 287–304
short-lived, large APUs 94
SOFC lifetime modelling
theory 223, 224, 225
storage, large APUs 115, 116, 131,
134–5
- hydrogen oxidation reaction
(HOR) 46
- hydrogen sulfide (H₂S) 156, 157, 164,
175–6
- hydrolysis, hydrogen
generation 267–83
- hydroxides 196–8
- HyWire concept (General
Motors) 329–30
- Idaho National Laboratory
(INL) 279, 280, 281
- ILS (Integrated Laboratory
Scale) 280, 281
- impedance spectroscopy (IS) 277, 278
- impurities
carbonaceous fuels 156
DCFCs, intermediate product
formation method 203
- HT-PEFCs
electrode degradation 65
Tafel slope effects 48
- inorganic, SOFCs anode
effects 163–8
- in-cell testing 253
- incumbent technology 317–18, 324–6
- industrial production *see* large-scale
production
- infrastructures, existing 313–18,
324–6
- initial value problem (IVP)
software 226, 227
- inkjet printing 15, 16, 17, 20–1
- INL (Idaho National
Laboratory) 279, 280, 281
- inorganic species 156, 163–8, 177–8
- integral separator plate (ISP) 252,
253
- integrated fluid channels 34
- Integrated Laboratory Scale
(ILS) 280, 281
- intelligent food labels 18
- inter-cell effects 258–60
- intermediate product
formation 202–7
- internal reforming fuel cells
carbonaceous fuels 157, 158, 165
hydrogen production 287–304
IR-SOFC system 290–8
literature reports 289–90
methane in SOFCs 154, 155,
236–41
- iridium 270
- irreversible anode degradation
164–5
- IS (impedance spectroscopy)
277, 278
- isosteric heat of adsorption 164
- isothermal one-dimensional lifetime
prediction models 217–36
- ISP (integral separator plate) 252,
253
- Italy 314
- IVP (initial value problem)
software 226, 227

- I–V (current–voltage) curves
 MCFCs/SOFCs internal reforming 296, 298
 SOFC lifetime modelling theory 222, 227–34, 235
 SOFC in SOEC mode 273–4, 275, 276
 solid oxide electrolyte DCFCs 199, 200
- JET A-1 jet fuel 98, 115–17, 122, 126–30, 132, 137, 140
- katal (kat), definition 7
 kerosene 96, 106, 107, 115, 116–36
 kilowatt power range 67
- labelling, intelligent 18
 laccases applications 21
Coriolus spp. 8, 11
 printed layers, storage stability 22, 23
Trametes hirsuta 21, 22
- lamination 16, 19, 24, 253
 land transport large APUs 77, 80, 81, 82, 91 vehicles 313, 314–15, 321, 328–9
- Langmuir isotherm 47
- lanthanum-doped strontium titanate (LST) 174–5, 176
- large auxiliary power units mobile applications 76–143 design objectives 77, 79–82 operating conditions 82–7 overview 76, 77, 140–3 system evaluation 112–40 technologies 87–112
- large-scale production enzymatic biofuel cells 11–15 printed 15–17 sensors 17–19
- HT-PEFC membrane electrode assemblies 58–61
- micro-systems assembly costs 29
- component failures 29
 low-temperature co-fired ceramic 30–9
- PEM electrolyzers 270
- product creation 320–3
- product marketing ix, 271, 311–31
 laser ablation 32, 33, 34
 Lawrence Livermore National Laboratory (LLNL, USA) 194–6, 207
- LCSF (strontium-doped lanthanum ferrite) 273
- lead pollution 315
- least square minimisation 227
- LH₂ (liquefied hydrogen) 93, 96, 115, 116, 128, 130, 131, 135, 136, 137
- lifetime prediction enzymatic biofuel cells 10
 HT-PEFCs 58, 61–6
 HTE stacks 279, 280
 PAFCs accelerated testing 249–61
 PEM electrolyzers 270
 SOFCs basic theory 35, 220–7 degradation inclusion 217–45 experimental validation 228–31 simple model 237–45 in SOEC mode 276, 277, 278
- linear degradation 238, 239, 241
 linear isothermal lifetime models 217–45
 liquefied hydrogen (LH₂) 93, 96, 115, 116, 128, 130, 131, 135, 136, 137
- liquid carbonate-based anode 200–2, 203
- liquid chamber biofuel cell construction 8–11
- liquid tin-based anode/SOFC combination 204–7
- lithium carbonate 194, 195
 lithium hydroxide 196, 197
- LLNL (Lawrence Livermore National Laboratory, USA) 194–6, 207
- logarithmic behaviour 287–8
 long-haul heavy-duty trucks 80

- long-range aircraft missions 84–6, 113–14, 127, 132–3
low-temperature co-fired ceramic (LTCC) 30–9
low-temperature electrolysis 269–71
low-temperature fuel cells
see also AFCs; DMFCs; PAFCs; PEMFCs
characteristics 88–9
LSCM ($\text{La}_{1-x}\text{Sr}_x\text{Cr}_y\text{Mn}_{1-y}\text{O}_3$) 171–3, 174–5, 176
LSM (strontium-doped lanthanum manganite) 273
LST (lanthanum-doped strontium titanates) 174–5, 176
LTCC (low-temperature co-fired ceramic) 30–9

manganese 171–2, 174–5, 176
manufacturing *see* large-scale production
maritime applications
large APUs
design objectives 81
electric power requirements 81
fuel cell systems 81, 93, 107–12
fuels 99–100
main engine emissions study 82
operating conditions 86–7
overview 140, 142–3
system evaluation 136, 138–40
marketing ix, 271, 311–31
Mars–van Krevelen mechanism 169
mass
large APUs 129
HT-PEFC-based 135, 137
process water 114
mass transport 198
matrix punch tools 32, 33, 34
MCFCs (molten carbonate fuel cells)
characteristics 90
development vi, vii
HotModule MCFC system 110, 111
internal reforming 287, 298–300
I–V curve 296, 298

maritime large APUs 81, 86–7, 93, 107, 111, 112
MDH (methanol dehydrogenase) 10
MDO (marine diesel oil) 96, 99
MEA (membrane electrode assembly) 58–61, 63–4
MEA (more electric aircraft) 83, 114, 140
mechanical stress, membrane degradation 63, 64–5
mediated electron transfer (MET) 7, 8
megayachts 87, 108, 110
methane, SOFCs fuel 154
membrane electrode assembly (MEA) 58–61, 63–4
membrane polymers 54–7
see also individual membrane polymers
membraneless biofuel cells 11
mercury 167
MET (mediated electron transfer) 7, 8
meta-PBI (poly(2,2'-*m*-phenylene-5,5'-bibenzimidazole)) 54, 55, 56
metal sulfides 179
metalloids 166–7
meteorological information 122, 123, 124
methane
large APUs 94, 95, 97, 132, 137
stationary system targets 77, 78
steam reforming
SOFCs
fuel 154, 155
kinetics, lifetime modelling 236–41
Ni-YSZ anode 161–2
synthesis reaction 100
vehicle fuel 313, 314–15, 321
methanol
DMBFCs 10–11
DMFCs vii, 36, 81, 89, 91
HT-PEFC/methanol large APUs 139, 140

- methanol (*continued*)
 steam reforming, large APUs 101, 108, 110
 methanol dehydrogenase (MDH) 10
 methyl-1,4-naphthoquinone 12
Methylobacterium extorquens 10
 MGO (marine gas oil) 96, 99
 micro-applications 5–25, 28–39
 microbial fuel cells 5
 microreactors 34–5
 microstructures 174–5, 176
 middle distillates *see* diesel; kerosene
 milling 31, 33
 miniaturisation of fuel cells viii, 11
 mission range, aircraft 84–6, 113–14, 127, 128, 130, 132–3
 mixing of fuels, large APUs 95
 mobile applications
 fuels 313
 large APUs 76–143
 design objectives 77, 79–82
 operating conditions 82–7
 overview 76, 77, 140–3
 system evaluation 112–40
 technologies 87–112
 mobile telephones 313, 316
 modelling, SOFC lifetimes 217–45
 modified hydrorefining process 99
 modified nickel cermet
 anodes 168–70
 molten carbonate electrolyte 194–6
 molten carbonate fuel cells *see*
 MCFCs
 molten hydroxide electrolyte 196–8
 more electric aircraft (MEA) 83, 114, 140
 MP3 player 11–14
 multi-source multi-product systems 299, 302
 multilayer ceramics 28–39
 examples 36–8
 flowfield current pickup 35, 36
 fluid distribution channels 34, 35
 fuel cell relevant features 32–6
 heterogeneous microreactors 34–5
 hidden channels 34, 35
 overview 29–30
 structuring technologies 31–4
 sub-systems 30–6
 laser ablation 32, 33, 34
 matrix punch tools 32, 33, 34
 milling 31, 33
Myrothecium verucaria 13
 n-type conductivity 173, 174, 178
 Nafion®
 conductivity behaviour 56, 57
 enzyme immobilisation v, 9, 14
 PEM electrolyzers 269
 natural gas *see* methane
 Nernst equation 160, 191, 192
 Nernst loss 289, 292, 293, 297
 Nernst voltage (V_{Nernst}) 220, 222–6, 229, 233, 235
 Netherlands 291–5
 nickel-based catalyst anode
 carbon formation on 160–1
 Ni-YSZ anode 159–62, 164–6, 177, 273
 SOFCs 154–7, 159–63
 characteristics 159–60
 modified nickel cermet
 anodes 168–70
 sulfur effects 163–5
 nickel-free cermet anodes 170–1
 nickel-free oxide anodes 171–5
 nickel/copper alloy 169
 β-nicotinamide adenine dinucleotide disodium salt (NADH) 9, 12–13
 nitrogen 225
 noble metals *see* precious metals
 non-hydrogen fuels 153–78
 non-linear area specific resistance over time behaviour 238–41
 nonlinear first order ODEs 226
 novel fuels 153–78, 190–209
 n-octane 162
 OCV (open cell voltage) 287–8, 296, 302, 303
 OCV (operating cell voltage) 220, 221, 222, 223, 224

- ODEs (ordinary differential equations) 223, 226, 227
offset printing, enzymatic biofuel cells 15, 16
ohmic resistance 218–20, 222, 223, 224, 227–45, 279
oil, mobile applications 96, 99, 313
on-board electricity generation, HT-PEFCs 70
one-dimensional isothermal lifetime models 217–45
open cell voltage (OCV) 287–8, 296, 302, 303
operating cell voltage (OCV) 220, 221, 222, 223, 224
ordinary differential equations (ODEs) 223, 226, 227
organic species 160–3
ORR (oxygen reduction reaction) vi, 46–54, 55, 59
Ostwald ripening 65
out-of-cell testing 253
outlook for the future 311–31
over-voltages 272
oxidation, electrochemical, carbon 190–3
oxidation potential (ϵ) 250, 251, 256
oxide formation 47–8
oxide-based anodes 171–5
oxygen absorption, carbohydrate-using biofuel cell 14
concentrations, aeronautical application 104, 105
electrode delamination 276, 277
HTE stacks sweep gas 282
IR-SOFC co-production of hydrogen 297
SOFC lifetime modelling theory 223, 224, 225
storage, aeronautical APUs 113
oxygen reduction reaction (ORR) vi, 46–54, 55, 59
p-type conductivity 172–3
packaging 18
PAFCs (phosphoric acid fuel cells) vi, 88, 249–61
paradigm shifts 318–20
partial oxidation (POX) 100, 157–8
particle size, carbon 207, 208
passive-type carbohydrate-using biofuel cells 11, 12
PBI *see* polybenzimidazoles
PCECs (proton ceramic electrolyser cells) 272–3
PEFCs (polymer electrolyte fuel cells) 249, 250, 251
aeronautical large APUs 88, 89, 91–3, 106, 119, 126, 127, 128, 130, 132, 134
characteristics 88
development vi
hydrogen 153–4
maritime large APUs 81, 107–9, 111
PEGDGE (poly(ethylene glycol) diglycidyl ether) 11
pelleted carbon 199
PEMs (polymer electrolyte membranes) 36, 153–4, 267, 269–71, 289
perovskites 171–3
phasing-in of fuel cell products 312–17
phosphate anions 49–53
phosphoric acid 49–53, 60
phosphoric acid fuel cells *see* PAFCs
phosphorus, SOFCs anode effects 165–6
planar cell technology SOECs 273, 282
SOFCs 271
large APUs 93
plants, membraneless biofuel cell implants 11, 12
plasma reforming 157
platinum alloy catalysts 53–4
platinum electrodes 49–53
platinum rotating disk 47–9, 50
POA (Power-Optimized Aircraft) 104
poisoning *see* impurities

- polarisation curves
 HT-PEFCs 62, 63, 68–9
 alternative electrolytes 54, 55
- poly(2,2'-*m*-phenylene-5,5'-bibenzimidazole) (*meta*-PBI) 54, 55, 56
- polybenzimidazole-type membranes
 HT-PEFCs 54–7
 large auxiliary power units 76–143
 trends 45–70
- PBI-HT-PEFC 91
- structures 55, 56
- poly(ethylene glycol) diglycidyl ether (PEGDGE) 11
- polymer electrolyte fuel cells *see* PEFCs
- polymer electrolyte membranes (PEMs) 36, 153–4, 189, 267, 269–71
- poly(methylene green)-modified electrodes 14
- polyphosphoric acid (PPA) 60, 61
- poly(tetrafluoroethylene) (PTFE) 58, 59
- porosity, SOFC anodes 159
- pot tests 254–6
- potassium carbonate 194, 195
- potassium hydroxide 196, 197
- Power-Optimized Aircraft (POA) 104
- POX (partial oxidation) 157–8
- PPA (polyphosphoric acid) 60, 61
- PQQ electron acceptor 8, 9
- pre-reforming, methane in
 SOFCs 155
- precious metals
 gold 35, 36, 51–2, 170–1
 iridium 270
 modified nickel cermet anodes 169
 platinum 47–54
 ruthenium 270
- printed circuit board technology 29
- printed enzymatic biofuel cells 5–25
 applications 21–4
 coating/printing 19–21
 large-scale production 15–17
- thin printable 17
- process water 103–4, 106, 114, 128
- processing options, carbonaceous fuels 157–8
- products *see* large-scale production
 progressive degradation, SOFCs 238, 239
- propane 162
- proton ceramic electrolyser cells (PCECs) 272–3
- proton exchange membrane *see* PEFCs
- proton transfer, HT-PEFCs 48–9, 56, 57, 60
- PTFE (poly(tetrafluoroethylene)) 58, 59
- punch tools 32, 33, 34
- pyrolysis reaction 100
- pyrolytic carbon 160
- P–O stretch vibration 52
- P–(OH)₂ stretch vibration 52
- quality, process water 106, 128
- radio-frequency identification (RFID)
 tags 21
- radiotracer techniques 50–1
- RAT (ram air turbine) 92
- re-chargers, multilayer ceramics 38
- reaction enthalpy ($\Delta_r H$) 191
- reaction mechanism, DCFCs 192–3
- reaction pathways, HT-PEFCs
 oxidation/reduction 46–9, 50
- recycling, IR-SOFC co-production of hydrogen 291–2
- reference technology 112–13
- reformed gas, HT-PEFCs 45, 63, 64
- reformers, large APUs 100–1
- reforming process 100, 101, 108–12
- resistance, ASR 218–20, 222, 223, 224, 227–45, 273–4, 278, 279
- reversible fuel cells ix, 267–83, 287–304
- RFID (radio-frequency identification)
 tags 21
- Ro-Ro/Ro-Pax vessels 86

- road vehicles 313, 314–15, 321, 328–9
Rosenberg and Howell's sailing ship effect 317
rotating disk electrode technique 46–9, 50
rotogravure printing 15, 16, 17
ruthenium 270
- SAE (Society of Automotive Engineers) 82
safety standards, aeronautical 82
sailing ship effect 317
SARA (Scientific Application) 197–8
scandia stabilised zirconia (ScSZ) 159
screen printing 15, 16, 17, 19–20, 35, 36
ScSZ (scandia stabilised zirconia) 159
second law of thermodynamics 302
selenium 166
sensors 17–19
separator plates 249–61
shift reaction 100, 108, 154, 300–1
ship service generators (SSGs) *see* maritime applications, large APUs
shooting method 227
short-lived hydrogen 94
short-ranged aircraft missions 113–14, 127, 128, 130, 135, 137
shunt current 252
silicon 166–7
simple lifetime prediction models 237–45
sintered materials 29, 30
Smart Fuel Cells 322, 323, 326
Society of Automotive Engineers (SAE) 82
SOCs (solid-oxide ion (O^{2-}) conductors) 267–8
sodium carbonate 194
sodium hydroxide 196, 197
SOECs (solid oxide electrolyser cells) 268–9, 273–9
SOFCs (solid oxide fuel cells) anodes conventional 159–68
inorganic impurities 163–8
organic species effects 160–3
hydrogen sulfide as fuel 157
as impurity 156–7
improved/ unconventional 168–76
non-hydrogen fuels 153–78 carbon deposition 155
carbonaceous 157–76
complex hydrocarbons 155
gasification 155
methane 154
applications viii
characteristics 90
development vii
fluidised-bed technologies combination 203–4, 205
internal reforming combined heat/power/hydrogen production 287–304
heat distribution at different fuel utilisations 289
Superwind Concept 298–300
I–V curve 296
lifetime modelling 222, 227–34, 235
in SOEC mode 273–4, 275, 276
large APUs 119, 120
mobile 91, 92, 93 aeronautical 106, 118, 119
hybrid aeronautical 79, 83–4
maritime 107, 108, 110, 111, 138, 139
lifetime prediction including degradation 217–45
liquid carbonate-based anode combination, DCFCs 200–2, 203
liquid tin-based anode combination 204–7
SOEC mode 268–9, 273–4, 275, 276
YSZ electrolyte 159–60, 161–2, 198, 201, 273, 275, 277
solar power 298–300, 303

- solid oxide electrolyser cells
 (SOECs) 268–9, 273–9
 solid oxide electrolyte,
 DCFCs 198–207
 solid oxide fuel cells *see* SOFCs
 solid-oxide ion (O^{2-}) conductors
 (SOCs) 267–8
 solid-oxide proton conductors,
 electrolysis 268
 Sony Corporation 11–14
 space requirements, large APUs 129,
 130
 specific surface area 207, 208
 SRI (Stanford Research Institute,
 USA) 201, 202, 203, 209
 SSGs (ship service generators) *see*
 maritime applications, large APUs
 stability, chemical 22, 23, 66, 159, 179
 stacks 66–9, 249–61, 279–82
 Stanford Research Institute (SRI,
 USA) 201, 202, 203, 209
 start-up 62
 stationary systems vi, 77, 78
 steam
 see also humidity; water vapour
 distribution, HTE stacks
 degradation 279
 high-temperature steam
 electrolysis 271–83
 load, SOFC lifetime modelling
 theory 225
 reforming
 carbonaceous fuels 157, 158,
 165
 equation, fuel processors 100
 hydrogen production 287–304
 methane 154–5, 236–41
 stepped potential method 47
 storage 22, 23, 115, 116, 131, 134–5
 strontium-doped lanthanum ferrite
 (LCSF) 273
 strontium-doped lanthanum
 manganite (LSM) 273
 structuring technologies 31–4
 sub-systems 28, 30–6
 substrate specificity, enzymes 6–7
- sulfonated-acid groups 269
 sulfur
 content
 JET A-1 jet fuel 98
 marine fuels 99, 108, 111
 HT-PEFCs electrode
 degradation 65
 SOFCs
 anode effects 163–5
 improved tolerance 175–6
 carbonaceous fuels 156
 Superwind Concept 298–300
 surface area, carbon fuels 207, 208
 surface area normalised corrosion
 rate 257, 258
 sweep gas, HTE stacks 282
 synergetic effects 168
 syngas 292
- Tafel equations 250, 251
 Tafel slope 46–9, 50
 tail-tail polybenzimidazoles 55
 tank inerting 123
 tank storage values 128
 tantalum 270
 Taylor expansion 238, 239
 TD (time domain) 238–42
 technological change
 added value 324, 326, 327–30
 battling incumbent
 technology 317–18
 history 313–17
 paradigm shifts 318–20
 phasing-in vs. disruptive
 development 312–17
 product creation 320–3
 succession of generations 318–20
 Teflon®-carbon bond 251, 253
 Temkin isotherm 47
 temperature
 see also HT-PEFCs
 DCFCs hydrogen production 302
 fuel cell operation 268, 282
 HT-PEFC performance 62
 SOFCs
 carbon formation on anode 162

- lifetime prediction
modelling 228–34, 242–5
operational temperature 154,
156, 159, 161, 162
- thermal compatibility 159
- thermal power 116
- thermal-neutral operation 272
- thermodynamic efficiency (η_{th}) 191,
192, 301
- thermodynamics 177, 191–2, 268,
301–2
first law 294, 298, 301
second law 302
- thin power sources, printable 17
- time domains (de Haart) 238–42
- tin 169, 204–7
- titanate systems 173
- toluene 162, 163
- Trachyderma tsunodae* 11
- Trametes hirsuta* 21, 22
- trehalose 21
- tri-generation systems 287–304
- tubular concepts 93
- turbines, large APUs 79, 80, 111, 112,
121
- turbo engines 115
- U_F (fuel utilisation)
DCFCs 192
IR-SOFC co-production of
hydrogen 292, 294, 295, 296,
297
- SOFC lifetime modelling
theory 233–4, 242–4
Superwind Concept 297
- unleaded petrol 313, 315
- US Coast Guard 81
- US Department of Energy (DoE) 77,
78, 79
- UTC Power 249–61
- $U-j$ (voltage-current) data 273–4,
275, 276
- validation 228–31
- vanadium-based perovskites
178–9
- V_{cell} (operating cell voltage,
OCV) 220, 221, 222, 223, 224
- vias, multilayer ceramics 35–6
- vibrational symmetries 52
- viscosity, inkjet inks 20
- V_{Nernst} (Nernst Voltage) 220, 222–6,
229, 233, 235
- volatile metals 167
- voltage efficiency, DCFCs 192
- voltage-based degradation
behaviour 234–6
- volume requirements 130, 132
- Vulcan XC72 amorphous
carbon 199, 200, 201
- water
see also process water; steam
balance, aeronautical large
APUs 122, 124, 125, 126, 127
content in DCFCs electrolyte
196
electrolysis, high/low-
temperature 267–83
- humidity, SOFCs fuels 223, 224,
228–34, 235, 274, 275
- hydrolysis, hydrogen
generation 267–83
- IR-SOFC co-production of
hydrogen 297
- process water 103–4, 106,
114, 128
- production, HT-PEFC/methanol
large APUs 139, 140
- vapour
acid leaching, HT-PEFCs 56–7,
69
- SOFC lifetime modelling
theory 223, 224, 225, 228–34,
235
- water-gas shift (WGS) reaction 100,
108, 154, 300–1
- weight differences, fuels 115
- weight loss, graphite samples 254,
255
- WGS (water-gas shift) reaction 100,
108, 154, 300–1

wind power 132–3, 137, 298–300
wood-derived BtL fuels 95, 128, 129,
 130, 132, 134, 137
young people's attitudes 319–20
YSZ (yttria-stabilised zirconia)
 conventional SOFC
 anodes 159–60, 161–2
 DCFCs 198, 199, 301

nickel-based catalyst
 anode 159–62, 164–6, 177
SOECs 273, 275, 277
SOFCs 159–60, 161–2, 198, 201,
 273, 275, 277
ZAE Bayern 198, 199
zinc 167