

Table of Contents

	Page	Book
	Chapter	xv
Foreword		xv
Acknowledgments		xvii
Chapter 1 Generalities		
1.1 Units and Constants	1.1	1
1.2 Energy and Utility	1.2	2
1.3 Conservation of Energy	1.3	3
1.4 Planetary Energy Balance	1.4	4
1.5 The Energy Utilization Rate	1.5	5
1.6 The Population Explosion	1.8	8
1.7 The Market Penetration Function	1.9	9
1.8 Planetary Energy Resources	1.13	13
1.9 Energy Utilization	1.16	16
1.10 The Ecology Question	1.19	19
1.10.1 Biological	1.20	20
1.10.2 Mineral	1.20	20
1.10.3 Subterranean	1.21	21
1.10.4 Undersea	1.22	22
1.11 Nuclear Energy	1.22	22
1.11.1 Fission	1.25	25
1.11.2 Fusion	1.27	27
1.11.3 Cold Fusion	1.31	31
1.12 Financing	1.36	36
References	1.39	39
Problems	1.41	41

Part I Heat Engines

Chapter 2 A Minimum of Thermodynamics and of Kinetic Theory of Gases

	Page	Book
	Chapter	xv
2.1 The Motion of Molecules	2.1	53
2.2 Temperature	2.1	53
2.3 The Perfect-Gas Law	2.2	54
2.4 Internal Energy	2.3	55
2.5 Specific Heat at Constant Volume	2.3	55
2.6 The First Law of Thermodynamics	2.4	56
2.7 The Pressure-Volume Work	2.5	57

2.8	Specific Heat at Constant Pressure	2.5	57
2.9	Adiabatic Processes	2.6	58
2.9.1	Abrupt Compression	2.6	58
2.9.2	Gradual Compression	2.10	62
2.9.3	<i>p</i> - <i>V</i> diagrams	2.11	63
2.9.4	Polytropic Law	2.12	64
2.10	Isothermal Processes	2.13	65
2.11	Functions of State	2.15	67
2.12	Enthalpy	2.16	68
2.13	Degrees of Freedom	2.17	69
2.14	Entropy	2.19	71
2.14.1	Changes in Entropy	2.20	72
2.15	Reversibility	2.21	73
2.15.1	Causes of Irreversibility	2.23	75
2.15.1.1	Friction	2.23	75
2.15.1.2	Heat Transfer Across Temperature Differences	2.23	75
2.15.1.3	Unrestrained Compression or Expansion of a Gas	2.24	76
2.16	Negentropy	2.24	76
2.17	How to Plot Statistics	2.25	77
2.18	Maxwellian Distribution	2.26	78
2.19	Fermi-Dirac Distribution	2.29	81
2.20	Boltzmann's Law	2.31	83
	Appendix (Symbology)	2.33	85
	Problems	2.34	86

Chapter 3 Mechanical Heat Engines

3.1	Heats of Combustion	3.1	89
3.2	Carnot Efficiency	3.4	92
3.3	Engine Types	3.5	93
3.4	Efficiency of an Otto Engine	3.9	97
3.5	Gasoline	3.13	101
3.5.1	Heat of Combustion	3.13	101
3.5.2	Antiknock Characteristics	3.13	101
3.6	Knocking	3.13	101
3.7	Hybrid Engines for Automobiles	3.17	105
3.8	The Stirling Engine	3.18	106
3.9	The Implementation of the Stirling Engine	3.23	111
3.10	Cryogenic Engines	3.25	113
	References	3.28	116
	Problems	3.29	117

Table of Contents

Chapter 4 Ocean Thermal Energy Converters

4.1	Introduction	4.1	125
4.2	OTEC Configurations	4.2	126
4.3	Turbines	4.4	128
4.4	OTEC Efficiency	4.6	130
4.5	Example of OTEC Design	4.7	131
4.6	Heat Exchangers	4.9	133
4.7	Siting	4.10	134
	References	4.11	135
	Problems	4.12	136

Chapter 5 Thermoelectricity

5.1	Experimental Observations	5.1	139
5.2	Thermoelectric Thermometers	5.6	144
5.3	The Thermoelectric Generator	5.8	146
5.4	Figure of Merit of a Material	5.11	149
5.5	The Wiedemann-Franz-Lorenz Law	5.12	150
5.6	Thermal Conductivity in Solids	5.16	154
5.7	Seebeck Coefficient of Semiconductors	5.17	155
5.8	Performance of Thermoelectric Materials	5.18	156
5.9	Some Applications of Thermoelectric Generators	5.20	158
5.10	Design of a Thermoelectric Generator	5.22	160
5.11	Thermoelectric Refrigerators and Heat Pumps	5.25	163
5.11.1	Design Using an Existing Thermocouple	5.25	163
5.11.2	Design Based on Given Semiconductors	5.29	167
5.12	Temperature Dependence	5.32	170
5.13	Battery Architecture	5.33	171
5.14	The Physics of Thermoelectricity	5.33	171
5.14.1	The Seebeck Effect	5.34	172
5.14.2	The Peltier Effect	5.37	175
5.14.3	The Thomson Effect	5.38	176
5.14.4	Kelvin's Relations	5.39	177
5.15	Direction and Signs	5.43	181
	Appendix	5.45	183
	References	5.46	184
	Problems	5.47	185

Chapter 6 Thermionics

6.1	Introduction	6.1	199
6.2	Thermionic Emission	6.3	201
6.3	Electron Transport	6.6	204
6.3.1	The Child-Langmuir Law	6.8	206

6.4	Lossless Diodes with Space Charge Neutralization	6.12	210
6.4.1	Interelectrode Potentials	6.12	210
6.4.2	<i>V-J</i> Characteristics	6.14	212
6.4.3	The Open-Circuit Voltage	6.14	212
6.4.4	Maximum Power Output	6.15	213
6.5	Losses in Vacuum Diodes with No Space Charge	6.16	214
6.5.1	Efficiency	6.16	214
6.5.2	Radiation Losses	6.17	215
6.5.2.1	Radiation of Heat	6.17	215
6.5.2.2	Efficiency with Radiation Losses Only	6.19	217
6.5.3	Excess Electron Energy	6.21	219
6.5.4	Heat Conduction	6.22	220
6.5.5	Lead Resistance	6.22	220
6.6	Real Vacuum Diodes	6.22	220
6.7	Vapor Diodes	6.23	221
6.7.1	Cesium Adsorption	6.24	222
6.7.2	Contact Ionization	6.27	225
6.7.3	Thermionic Ion Emission	6.28	226
6.7.4	Space Charge Neutralization Conditions	6.29	237
6.7.5	<i>V-J</i> Characteristics	6.30	228
6.8	High-Pressure Diodes	6.34	232
	References	6.37	235
	Problems	6.38	236

Chapter 7 AMTEC

7.1	Operating Principle	7.1	241
7.2	Vapor Pressure	7.3	243
7.3	Pressure Drop in the Sodium Vapor Column	7.4	244
7.4	Mean Free Path of Sodium Ions	7.6	246
7.5	<i>V-I</i> Characteristics of an AMTEC	7.7	247
7.6	Efficiency	7.9	249
7.7	Thermodynamics of an AMTEC	7.12	252
	References	7.14	254

Chapter 8 Radio-Noise Generators

	References	8.5	259
--	------------	-----	-----

Part II The World of Hydrogen

Chapter 9 Fuel Cells

9.1	Introduction	9.1	263
9.2	Electrochemical Cells	9.2	264

Table of Contents

9.3	Fuel Cell Classification	9.6	268
9.3.1	Temperature of Operation	9.6	268
9.3.2	State of the Electrolyte	9.7	269
9.3.3	Type of Fuel	9.7	269
9.3.4	Chemical Nature of the Electrolyte	9.8	270
9.4	Fuel Cell Reactions	9.8	270
9.4.1	Alkaline Electrolytes	9.9	271
9.4.2	Acid Electrolytes	9.9	271
9.4.3	Molten Carbonate Electrolytes	9.10	272
9.4.4	Ceramic Electrolytes	9.10	272
9.4.5	Methanol Fuel Cells	9.10	272
9.5	Typical Fuel Cell Configurations	9.12	274
9.5.1	Demonstration Fuel Cell (KOH)	9.12	274
9.5.2	Phosphoric Acid Fuel Cells (PAFC)	9.13	275
9.5.2.1	A Fuel Cell Battery (Engelhard)	9.13	275
9.5.2.2	First-Generation Fuel Cell Power Plant	9.14	276
9.5.3	Molten Carbonate Fuel Cells (MCFC)	9.15	277
9.5.4	Ceramic Fuel Cells (SOFC)	9.16	278
9.5.4.1	High Temperature Ceramic Fuel Cells	9.21	283
9.5.4.2	Low Temperature Ceramic Fuel Cells	9.23	285
9.5.5	Solid-Polymer Electrolyte Fuel Cells	9.25	287
9.5.5.1	Cell Construction	9.26	288
9.5.5.2	Membrane	9.28	290
9.5.5.3	Catalysts	9.29	291
9.5.5.4	Water Management	9.30	292
9.5.6	Direct Methanol Fuel Cells	9.31	293
9.5.7	Solid Acid Fuel Cells	9.33	295
9.5.8	Rechargeable Fuel Cells (NiMH)	9.34	296
9.5.9	Metallic Fuel Cells—Zinc-Air Fuel Cells	9.36	298
9.6	Fuel Cell Applications	9.37	299
9.6.1	Stationary Power Plants	9.38	300
9.6.2	Automotive Power Plants	9.38	301
9.6.3	Other Applications	9.40	302
9.7	The Thermodynamics of Fuel Cells	9.41	303
9.7.1	Heat of Combustion	9.41	303
9.7.2	Free Energy	9.43	305
9.7.3	Efficiency of Reversible Fuel Cells	9.46	308
9.7.4	Effects of Pressure and Temperature on the Enthalpy and Free Energy Changes of a Reaction	9.47	309
9.7.4.1	Enthalpy Dependence on Temperature	9.47	309
9.7.4.2	Enthalpy Dependence on Pressure	9.49	311
9.7.4.3	Free Energy Dependence on Temperature	9.50	312
9.7.4.4	Free Energy Dependence on Pressure	9.54	316
9.7.4.5	Voltage Dependence on Temperature	9.56	318
9.8	Performance of Real Fuel Cells	9.57	319

9.8.1	Current Delivered by a Fuel Cell	9.57	319
9.8.2	Efficiency of Practical Fuel Cells	9.58	320
9.8.3	Characteristics of Fuel Cells	9.59	321
9.8.3.1	Scaling Fuel Cells	9.62	324
9.8.4	More Complete <i>V-I</i> Characteristics of Fuel Cells	9.63	325
9.8.5	Heat Dissipation by Fuel Cells	9.71	333
9.8.5.1	Heat Removal from Fuel Cells	9.73	335
	References	9.74	336
	Problems	9.76	338

Chapter 10 Hydrogen Production

10.1	Generalities	10.1	353
10.2	Chemical Production of Hydrogen	10.3	355
10.2.1	Historical	10.3	355
10.2.2	Modern Production	10.4	356
10.2.2.1	Partial Oxidation	10.4	356
10.2.2.2	Steam Reforming	10.5	357
10.2.2.3	Thermal Decomposition	10.5	357
10.2.2.4	Syngas	10.6	358
10.2.2.5	Shift Reaction	10.6	358
10.2.2.6	Methanation	10.7	359
10.2.2.7	Methanol	10.7	359
10.2.2.8	Syncrude	10.8	360
10.2.3	Hydrogen Purification	10.8	360
10.2.3.1	Desulfurization	10.8	360
10.2.3.2	CO ₂ Removal	10.8	360
10.2.2.3	CO Removal and Hydrogen Extraction	10.9	361
10.2.4	Hydrogen Production Plants	10.11	363
10.2.4.1	Compact Fuel Processors	10.11	363
10.3	Electrolytic Hydrogen	10.16	368
10.3.1	Introduction	10.16	368
10.3.2	Electrolyzer Configurations	10.17	369
10.3.2.1	Liquid Electrolyte Electrolyzers	10.17	369
10.3.2.2	Solid Polymer Electrolyte Electrolyzers	10.18	370
10.3.2.3	Ceramic Electrolyte Electrolyzers	10.19	371
10.3.3	Efficiency of Electrolyzers	10.19	371
10.3.4	Concentration-Differential Electrolyzers	10.22	374
10.3.5	Electrolytic Hydrogen Compressors	10.24	376
10.4	Thermolytic Hydrogen	10.25	377
10.4.1	Direct Dissociation of Water	10.25	377
10.4.2	Chemical Dissociation of Water	10.31	383
10.5	Photolytic Hydrogen	10.33	385

Table of Contents

10.5.1	Generalities	10.33	385
10.5.2	Solar Photolysis	10.34	386
10.6	Photobiologic Hydrogen Production	10.35	387
	References	10.37	389
	Problems	10.38	390

Chapter 11 Hydrogen Storage

11.1	Compressed Gas	11.3	399
11.2	Cryogenic Hydrogen	11.5	401
11.3	Storage of Hydrogen by Adsorption	11.7	403
11.4	Storage of Hydrogen in Chemical Compounds	11.8	404
11.4.1	Generalities	11.8	404
11.4.2	Hydrogen Carriers	11.10	406
11.4.3	Water Plus a Reducing Substance	11.11	407
11.4.4	Metal Hydrides	11.11	407
11.4.4.1	Characteristics of Hydride Materials	11.17	413
11.4.4.2	Thermodynamics of Hydride Systems	11.21	417
11.5	Hydride Hydrogen Compressors	11.25	421
11.6	Hydride Heat Pumps	11.29	425
	References	11.32	428
	Problems	11.33	429

Part III Energy from the Sun

Chapter 12 Solar Radiation

12.1	The Nature of the Solar Radiation	12.1	445
12.2	Insolation	12.4	448
12.2.1	Generalities	12.4	448
12.2.2	Insolation on a Sun-Tracking Surface	12.7	451
12.2.3	Insolation on a Stationary Surface	12.7	451
12.2.4	Horizontal Surfaces	12.10	454
12.3	Solar Collectors	12.11	455
12.3.1	Solar Architechture	12.11	455
12.3.1.1	Exposure Control	12.11	455
12.3.1.2	Heat Storage	12.11	455
12.3.1.3	Circulation	12.12	456
12.3.1.4	Insulation	12.13	457
12.3.2	Flat Collectors	12.14	458
12.3.3	Evacuated Tubes	12.15	459
12.3.4	Concentrators	12.15	459
12.3.4.1	Holographuc Plates	12.16	460
12.3.4.2	Nonimaging Concentrators	12.17	461
12.4	Some Solar Plant Configurations	12.18	462

12.4.1	High Temperature Solar Heat Engine	12.18	462
12.4.2	Solar Chimney	12.20	464
12.4.3	Solar Ponds	12.20	464
Appendix A (The Measurement of Time)		12.22	466
The Duration of an Hour		12.22	466
Time Zones		12.22	466
Time Offset		12.23	467
The Calendar		12.23	467
The Julian Day Number		12.25	469
Appendix B (Orbital Mechanics)		12.26	470
Sidereal versus Solar		12.26	470
Orbital Equation		12.28	472
Relationship Between			
Ecliptic and Equatorial Coordinates		12.32	476
The Equation of Time		12.33	477
Orbital Eccentricity		12.36	480
Orbital Obliquity		12.37	481
References		12.39	483
Problems		12.40	484

Chapter 13 Biomass

13.1	Introduction	13.1	493
13.2	The Composition of Biomass	13.1	493
13.2.1	A Little Bit of Organic Chemistry	13.2	494
13.2.1.1	Hydrocarbons	13.2	494
13.2.1.2	Oxidation Stages of Hydrocarbons	13.3	495
13.2.1.3	Esters	13.4	496
13.2.1.4	Carbohydrates	13.4	496
13.3	Biomass as Fuel	13.6	498
13.3.1	Wood Gasifiers	13.7	499
13.3.2	Ethanol	13.8	500
13.3.2.1	Ethanol Production	13.8	500
13.3.2.2	Fermentation	13.11	503
13.3.3	Dissociated Alcohols	13.13	505
13.3.4	Anaerobic Digestion	13.14	506
13.4	Photosynthesis	13.21	513
References		13.28	520
Problems		13.29	521

Chapter 14 Photovoltaic Converters

14.1	Introduction	14.1	525
14.2	Theoretical Efficiency	14.6	530
14.3	Carrier Multiplication	14.13	537

Table of Contents

14.4	Spectrally Selective Beam Splitting	14.14	538
14.4.1	Cascaded Cells	14.15	539
14.4.2	Filterd Cells	14.16	540
14.4.3	Holographic Concentrators	14.17	541
14.5	Thermo-photovoltaic Cells	14.17	541
14.6	The Ideal and the Practical	14.19	543
14.7	The Photodiode	14.20	544
14.8	The Reverse Saturation Current	14.40	564
14.9	Practical Efficiency	14.42	566
14.10	Solar-Power Satellite	14.44	568
14.10.1	Beam from Space	14.46	570
14.10.2	Solar Energy to DC Conversion	14.46	570
14.10.3	Microwave Generation	14.47	571
14.10.4	Radiation System	14.48	572
14.10.5	Receiving Array	14.49	573
14.10.6	Attitude and Orbital Control	14.50	574
14.10.7	Space Transportation and Space Construction	14.50	574
14.10.8	Future of Space Solar Power Projects	14.51	575
Appendix A		14.52	576
Appendix B		14.53	577
References		14.60	584
Problems		14.61	585

Part IV Wind and Water

Chapter 15 Wind Energy

15.1	History	15.1	597
15.2	Wind Turbine Configurations	15.4	600
15.2.1	Drag-Type Wind Turbines	15.4	600
15.2.2	Lift-Type Wind Turbines	15.6	602
15.2.3	Magnus Effect Wind Machines	15.7	603
15.2.4	Vortex Wind Machines	15.8	604
15.3	Eolergometry	15.8	604
15.4	Availability of Wind Energy	15.9	605
15.5	Wind Turbine Characteristics	15.10	606
15.6	Principles of Aerodynamics	15.12	608
15.6.1	Flux	15.12	608
15.6.2	Power in the Wind	15.13	609
15.6.3	Dynamic Pressure	15.13	609
15.6.4	Wind Pressure	15.13	609
15.6.5	Available Power	15.14	610
15.6.6	Efficiency of a Wind Turbine	15.15	611
15.7	Airfoils	15.16	612

15.8	Reynolds Number	15.19	615
15.9	Aspect Ratio	15.21	617
15.10	Wind Turbine Analysis	15.23	619
15.11	Aspect Ratio (of a wind turbine)	15.30	626
15.12	Centrifugal Force	15.31	627
15.13	Performance Calculation	15.33	629
15.14	Magnus Effect	15.35	631
	References	15.36	632
	Problems	15.37	633

Chapter 16 Ocean Engines

16.1	Introduction	16.1	651
16.2	Wave Energy	16.1	651
16.2.1	About Ocean Waves	16.1	651
16.2.1.1	The Velocity of Ocean Waves	16.2	652
16.2.1.2	Wave Height	16.3	653
16.2.1.3	Energy and Power	16.4	654
16.2.2	Wave Energy Converters	16.4	654
16.2.2.1	Offshore Wave-Energy Converters	16.5	655
16.2.2.1.1	Heaving Buoy Converters	16.5	655
16.2.2.1.2	Hinged Contour converters	16.6	656
16.2.2.1.3	Overtopping Converters	16.7	657
16.2.2.2	Shoreline Wave Energy Converters	16.8	658
16.2.2.2.1	Tapered Channel System	16.8	658
16.2.2.2.2	Wavegen System (OWC)	16.9	659
16.3	Tidal Energy	16.11	661
16.4	Energy from Currents	16.11	661
16.4.1	Marine Current Turbine System	16.13	663
16.4.1.1	Horizontal Forces	16.13	663
16.4.1.2	Anchoring Systems	16.14	664
16.4.1.3	Corrosion and Biological Fouling	16.14	664
16.4.1.4	Cavitation	16.14	664
16.4.1.5	Large Torque	16.15	665
16.4.1.6	Maintenance	16.15	665
16.4.1.7	Power Transmission	16.16	666
16.4.1.8	Turbine Farms	16.16	666
16.4.1.9	Ecology	16.16	666
16.4.1.10	Modularity	16.16	666
16.5	Salination Energy	16.16	666
16.6	The Osmotic Engine	16.19	669
	References	16.22	672
	Problems	16.24	674
	Subject Index		677