

ENERGY AND THE ENVIRONMENT

Abbas Ghassemi, Series Editor

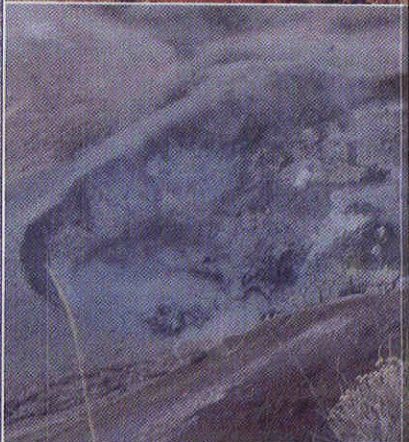
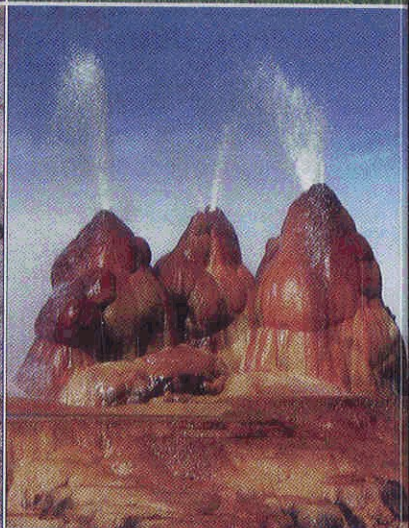
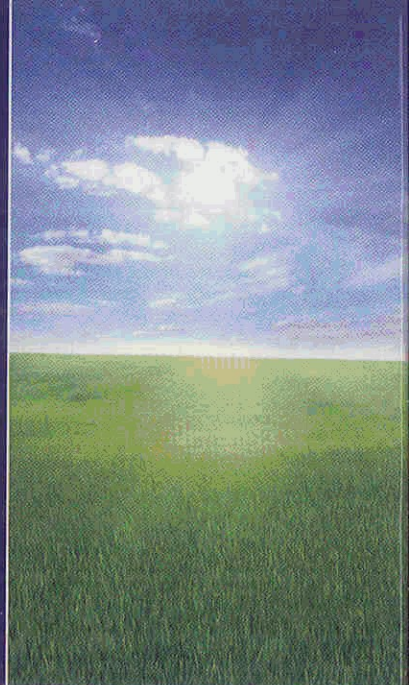
GEOHERMAL ENERGY

**Renewable Energy
and the
Environment**

William E. Glassley



CRC Press
Taylor & Francis Group



Contents

Series Editor's Preface	xi
Preface.....	xv
Acknowledgments.....	xvii
Series Editor.....	xix
Author	xxi
Chapter 1 Introduction	1
The Global Energy Landscape	1
The Historical Role of Fuel	1
The Impact of Population Growth and per Capita Energy Use.....	2
Fuel Emissions and Environmental Considerations	3
Geothermal Energy as a Renewable Energy Source.....	4
No Fuel, Few Emissions	4
Geothermal Energy Is a Flexible Energy Resource	5
Electrical Demand and the Characteristics of Geothermal Energy.....	7
Generating Electrical Power for the Grid.....	7
Generating Electrical Power for Local Use.....	8
How This Book Is Organized.....	8
Synopsis.....	8
References	9
Further Information Sources.....	9
Chapter 2 Sources of Geothermal Heat: Earth as a Heat Engine.....	11
Origin of Earth's Heat.....	11
Heat from Formation of the Core	11
Heat from Radioactive Decay of Long-Lived Isotopes	12
Transfer of Heat in the Earth.....	14
Radiation.....	14
Conduction.....	15
Convection	19
Plate Tectonics and the Distribution of Geothermal Resources	20
Availability and Utilization of Geothermal Energy	23
Synopsis.....	26
Case Studies	26
Spreading Centers	26
Subduction Zones	27
Hot Spots	27
References	28
Further Information.....	29
Chapter 3 Thermodynamics and Geothermal Systems	31
The First Law of Thermodynamics: The Equivalence of Heat and Work and the Conservation of Energy	31
Conservation of Energy	31

Internal Energy	31
PV Work	33
Enthalpy	33
The Second Law of Thermodynamics: The Inevitable Increase of Entropy	34
Efficiency	34
Carnot Cycle	34
Heat Capacity	35
Entropy	37
Gibbs Function and Gibbs Energy (ΔG)	38
The Standard State	39
Thermodynamic Efficiency	40
Case Study: The Thermodynamic Properties of Water and Rock–Water Interaction	41
Synopsis	47
References	47
Further Information	48
Chapter 4 Subsurface Fluid Flow: The Hydrology of Geothermal Systems	51
A General Model for Subsurface Fluid Flow	51
Matrix Porosity and Permeability	51
Definition of Matrix Permeability	54
The Kozeny–Carman Equation	55
Hydraulic Conductivity	55
Fracture Porosity and Permeability	55
Fracture Permeability	56
Fracture Transmissivity	57
Effect of Depth on Porosity and Permeability	58
Hydrologic Properties of Real Geothermal Systems	60
Case Study: Long Valley Caldera	61
Synopsis	65
References	65
Further Information	66
Chapter 5 Chemistry of Geothermal Fluids	69
Why the Geochemistry of Geothermal Fluids Matters	69
Water as a Chemical Agent	70
Components and Chemical Systems	72
Chemical Potentials, μ , and Gibbs Energy	72
Activity, a	74
Saturation and The Law of Mass Action	74
Equilibrium Constants	74
Activity Coefficients, γ	75
Affinity	76
Ion Exchange	77
Kinetics of Geothermal Reactions	78
Gases in Geothermal Fluids	80
Gas Partitioning between Liquid and Vapor	81
Fluid Flow and Mixing in Natural Systems	83
Simulating Reactive Transport	84

Case Study: The Silica System.....	85
Synopsis.....	86
References	87
Chapter 6 Exploring for Geothermal Systems.....	91
Field Geology and Surface Manifestations	91
Volcanoes: Active and Dormant.....	91
Faulting and Associated Rock Alteration.....	92
Surface Deposits.....	93
Geochemistry as an Exploration Tool.....	95
Fluid Composition and Geothermometry.....	95
Isotopes.....	100
Geophysics as an Exploration Tool	104
Aeromagnetic Surveys.....	104
Resistivity and Magnetotelluric Surveys.....	105
Gravity Surveys	107
Seismicity and Reflection Seismology	108
Temperature Measurements	110
Remote Sensing as an Exploration Tool: A Promising New Technique	111
Multispectral Studies.....	111
Case Study: Fallon, Nevada	113
Synopsis.....	115
References	116
Further Information.....	118
Chapter 7 Resource Assessments.....	119
Assessing a Geothermal Resource.....	119
Resource Base and Reserves	120
Uncertainty	120
Establishing the Reservoir Volume	122
Establishing the Reservoir Heat Content	123
The Significance of Heat Capacity.....	125
Efficiency of Heat Extraction.....	126
Case Study: Establishing the United States Geothermal Resource	129
Synopsis.....	132
References	133
Further Information.....	134
Chapter 8 Drilling.....	135
Background	135
Drilling for Ground Source Heat Pump and Direct Use Applications	135
Drilling Equipment and Technology	136
Drilling Fluid and Circulation.....	137
Properties of Drilling Fluids	139
Well Completion.....	140
Environmental Issues	140
Drilling for Geothermal Fluids for Power Generation.....	141
Drilling Rigs.....	141

	Confining Pressure and Rock Strength	141
	Temperature and Drilling Fluid Stability	143
	Casing and Grouting	145
	Packers	146
	Lost Circulation	147
	Directional Drilling	147
	Case Study: Kakkonda, Japan	149
	Synopsis	151
	References	151
	Further Information	152
Chapter 9	Generating Power Using Geothermal Resources	153
	The History of Geothermal Power Production	153
	General Features of Geothermal Power Generation Facilities	154
	Dry Steam Resources	155
	Hydrothermal Systems	161
	Flashing	163
	Steam Quality	165
	Dual-Flash Systems	166
	The End State: Condensers and Cooling Towers	167
	Binary Generation Facilities: The Organic Rankine Cycle	168
	Case Study: The Geysers	170
	Geology	170
	Power Generation History	172
	Emissions	172
	Sustainability and Reinjection	173
	Synopsis	176
	References	177
	Further Information	178
Chapter 10	Low Temperature Geothermal Resources: Ground Source Heat Pumps	183
	Basic Heat Pump Principles	183
	Thermodynamics of Heat Pumps	186
	Coefficient of Performance (COP) and Energy Efficiency Ratio (EER)	187
	Near-Surface Thermal Reservoir	187
	Solar Insolation	188
	Soil Characteristics	188
	Thermal Conductivity and Heat Capacity of Soils	190
	Design Considerations for Closed-Loop Systems	191
	Heating and Cooling Loads	191
	Calculating Loop Length	191
	Case Study: Weaverville	193
	Synopsis	198
	References	199
	Further Information	199
Chapter 11	Direct Use of Geothermal Resources	201
	Assessing the Magnitude of the Direct Use Reservoir	201
	The Nature of Thermal Energy Transfer	203

Heat Transfer by Conduction.....	204
Heat Transfer by Convection.....	207
Heat Transfer by Radiation.....	208
Heat Transfer by Evaporation.....	209
Establishing the Feasibility of a Direct Use Application.....	210
District Heating.....	210
Evaluation and Operation.....	210
Managing Return Temperature.....	212
Piping and Heat Loss.....	213
Materials Compatibility and Fluid Chemistry.....	213
Aquaculture.....	214
Drying.....	216
Case Study: Canby Cascaded System.....	217
Synopsis.....	222
References.....	223
Further Information.....	223
Chapter 12 Use of Geothermal Resources: Environmental Considerations.....	225
Emissions.....	225
Carbon Dioxide.....	225
Hydrogen Sulfide.....	228
Mercury.....	229
Solute Load and Resource Recovery.....	229
Seismicity.....	231
Mechanics of Seismic Events.....	231
Shear Stress, Normal Stress, and Frictional Strength.....	231
Pore Water.....	232
Seismic Activity Associated with Geothermal Projects.....	233
Seismicity Associated with Injection of Cool Water.....	233
Rupture Area and Magnitude.....	235
Seismicity Associated with Fluid Extraction.....	236
Seismicity Associated with High-Pressure Injection of Fluid to Enhance Reservoir Permeability.....	237
Ground Subsidence.....	238
Water Use.....	241
Land Use.....	242
Synopsis.....	244
References.....	245
Additional Information.....	247
Chapter 13 Use of Geothermal Resources: Economic Considerations.....	251
Economics of Geothermal Power.....	251
Capacity Factors.....	251
Levelized Costs.....	253
Economics of R&D Investment in Geothermal Energy.....	255
Technology Evolution and S-Curves.....	255
Projected Energy Costs.....	255
Developing a Geothermal Project.....	257
Rights to Develop a Resource and Permitting.....	257
Initial Resource Assessments.....	258

Refining the Resource Assessment through Exploration Drilling	259
Production Wells and Feasibility Study	259
Synopsis.....	260
References	261
Chapter 14 The Geothermal Energy Future: Possibilities and Issues	263
Geopressured Resources	263
Magnitude of the Resource.....	263
Why Geopressured Reservoirs Form	263
Challenges to Development	264
Fluid Chemistry.....	264
Reinjection	266
Enhanced Geothermal Systems (EGS)	266
Magnitude of the Resource.....	266
Technological Requirements	269
EGS Efforts to Date.....	270
Drilling and Downhole Equipment	271
Drilling Fluids	271
High-Temperature Downhole Equipment.....	271
Reservoir Engineering	271
Reservoir Management for Sustainability	272
Synopsis.....	274
References	275
Further Information.....	276
Index.....	277
Index of Locations.....	289