Solution Mining

Leaching and Fluid Recovery of Materials

Second Edition

Robert W. Bartlett

GORDON AND BREACH SCIENCE PUBLISHERS
Australia Canada China France Germany India
Japan Luxembourg Malaysia The Netherlands
Russia Singapore Switzerland

CONTENTS

mbols	XV
	xxiii
Introduction	1
Scope of Solution Mining	1
Importance of Solution Mining	5
Sharpening Our Intuitive Understanding	
of Leaching	6
-	
by Chemical Diffusion	11
Heap Leaching Gold (Silver) Ore—Theory	17
Disseminated Gold Ore Deposits	17
Gold Leaching Chemistry	18
Modeling Disseminated Gold Ore Heap	
Leaching Extractions	20
Estimating Fractional Extraction of Dissolved Solute	
from a Distribution of Ore Rock Particle Sizes	
Using a Dimensionless Extraction Curve	25
Valuable Mineral Accessibility to the Lixiviant	
and Extraction	30
_	31
Measuring Internal Rock Microporosity, ε	33
Heap Leaching Practice	
(With Applications to Gold and Silver Ores)	37
Overview	37
	Scope of Solution Mining Importance of Solution Mining Sharpening Our Intuitive Understanding of Leaching Modeling Extraction Rates Controlled by Chemical Diffusion Heap Leaching Gold (Silver) Ore—Theory Disseminated Gold Ore Deposits Gold Leaching Chemistry Modeling Disseminated Gold Ore Heap Leaching Extractions Estimating Fractional Extraction of Dissolved Solute from a Distribution of Ore Rock Particle Sizes Using a Dimensionless Extraction Curve Valuable Mineral Accessibility to the Lixiviant and Extraction Rock Particle Leaching Size Versus Sieve Passing Size Measuring Internal Rock Microporosity, ε Heap Leaching Practice (With Applications to Gold and Silver Ores)

	Heap Construction	39
	Ore Preparation	.42
	Choosing Between Reusable Pad and Valley-Fill	
	Heap Leaching	49
	Solution Distribution	52
	Solution Ponds	58
	Solution Chemical Control for Gold/Silver	
	Leaching	60
	Gold (Silver) Recovery from Dilute	
	Leaching Solutions	62
	Testing Gold (Silver) Ores for Heap Leaching	65
	Alternate Processes for Gold (Silver) Leaching	71
	Refractory Ore	72
	Examples of Gold Ore Heap Leaching Operations	74
FOUR	Environmental Control in Percolation Leaching	79
	Environmental Concerns	79
	Percolation Leach Pad Design	80
	Leach Pad Site Selection	85
	Solution Collection and Pond Design	86
	Seepage and French Drain Pipe Spacing	87
	Evidence of Seepage from Solution Chemistry	91
	Heap Geotechnical Failures	92
	Water Balance	93
	Cyanide Detoxification	96
	Permitting	103
FIVE	Percolation Leaching Oxidized and Secondary	
	Sulfide Copper Minerals	107
	Introduction	107
	Copper Ore Deposit Geology	108
	Consequences of Different Copper Ore Types	111
	Mineralogy and Leaching Chemistry of Oxide	
	Copper Ore	112
	Bluebird Mine Oxide Copper Ore Heap	
	Leaching Practice	113
	Copper Solvent Extraction/Electrowinning	114
	Underground Copper Leaching Practice	117
	Leach Extraction from Oxide Copper Ore	
	Rock Fragments	119

Contents ix

	The Shrinking Core Model of Monosize Oxide	
	Copper Ore Rock Leaching	123
	Example of the Shrinking Core Model for Monosize	
	Oxide Copper Ore Leaching	126
	Estimating Metal Extraction Versus Leaching	
	Time for Multisize Ore Using Dimensionless	
	Design Curves Based on the Shrinking Core Model	130
	Vertical Solution Variations in Heap Leaching	
	Oxide Copper Ores	134
	Shallow Lift (Thin Layer) Leaching and	
	Acid Cure Leaching	141
	Acid Cure Leaching Practice at the El Abra	
	Copper Mine in Chile	142
	Advances in Mechanical Ore Stacking Systems	
	at Large Copper Mines	143
	Leaching Secondary Sulfide Copper Minerals	145
	Ferric Sulfate Generation	146
	Measuring the Ferric Ion Concentration	
	in Leaching Solutions	148
	Required Secondary Copper Sulfide Leaching Time	
	When Governed by Ferric Ion Availability	150
	Ferric Cure Leaching Process	152
	Ore Testing	153
SIX	Percolation Leaching Copper Mine Waste	
DIZI	(Primary Sulfides)	159
	Introduction	159
	Overview of Copper Mine Dump Leaching	
	Practice	161
	Copper Sulfide Minerals and Ferric Sulfate	
	Leaching Kinetics	164
	Biologically Enhanced Oxidative Leaching	
	of Sulfide Minerals	167
	Limiting Copper Oxidation Rates in Copper	
	Dump Leaching	173
	Iron Removal from Copper Leach Solution	175
	Copper Separation	176
	Acid Weathering of Gangue Minerals	177
	Characteristics of As-Mined Rock Fragments	179
	Rock Leaching Mechanism and Implications	
	for Forecasting Production	180

x Contents

	Leaching Production Forecasting	183
	Acid Usage in Copper Dump Leaching	190
•	Managing Primary Copper Sulfide Mineral	
	Leaching Operations	190
SEVEN	Solution Flow During Percolation Leaching	
	of Ore Heaps	195
	Introduction	195
	Solution and Air Flow Regions	
	in Fragmented Rock	196
	Solution Retention and Capillarity	198
	Hydraulic Conductivity Versus Intrinsic	
	Permeability	200
	Percolation Flow Rates and Flooding	204
	Solution Percolation Flow Rates and	
	Washing Efficiency	206
	Estimating Intrinsic Permeability from Rock Sizes	210
	Measuring Heap Hydraulic Conductivity	216
	Agglomeration to Improve Intrinsic Permeability	218
	Optimum Solution Application and Irrigation Rates	218
	Rubblization with Chemical Explosives	219
EIGHT	Oxygen Diffusion and Air Flow During	
	Heap Leaching	223
	Gaseous Diffusion of Oxygen in Ore Heaps	223
	Vertical Air Flow by Natural Advection	228
	Air Flow by Natural Advection from the Sloping	
	Sides of Ore Heaps	231
	Finger Dumps	234
	Horizontal Flow by Natural Air Advection	
	Underneath a Heap	237
	Forced Air Ventilation of Ore Heaps	239
	Forced Air Ventilation with Non-Uniform Heap	
	Permeability	245
	Estimating Intrinsic Permeability	246
	Measuring Intrinsic Permeability	247
	Rejuvenating Depleted Copper Mine Waste	
	Dumps with Forced Air Ventilation	249

NINE	Biooxidation Heap Pretreatment of Sulfide	
	Refractory Gold Ore and High-Sulfur Coal	253
	Introduction	253
	Refractory Gold Ore Sulfide Mineralogy	254
	Development of Heap Biooxidation of Refractory	
	Gold Ore	255
	Ore Crushing Requirements	257
	Bioheap Acidity, Bacteria Culture and Ore	
	Agglomeration	259
	Bioheap Energy Balance and Temperature Control	260
	Intrinsic Sulfide Mineral Oxidation Kinetics	263
	Economic Considerations	271
	Heap Biooxidation Processing of Other	
	Metal Sulfide Ores	274
	Desulfurization of Coal	274
	Heap Biooxidation of Pyrite in Coal	275
TEN	In Situ Flooded Leaching	281
	Ore Deposit Types	281
	Modified In Situ (Flooded) Leaching of Fragmented	
	Copper Deposits	285
	True In Situ (Flooded) Leaching of Copper	
	Ore Deposits	287
	Uranium Ore Deposit Geology	289
	Uranium Leaching Chemistry	291
	Flooded Leaching with Wells	293
	Pregnant Liquor Recovery Using Wells	293
	Leaching Kinetics	294
	Injectivity Response	296
	Displacement Studies (Dilution)	296
	Stream Tube Leaching Experiments	298
	Logarithmic Decline of Well Production during	
	In Situ Leaching	300
	Evaluating Ore Deposit Host Formations	
	for <i>In Situ</i> (Flooded) Leaching	302
	Well Patterns	305
	Vertical Wells	306
	Deviated and Horizontal Wells	307
	Well Completion	307

	Well Stimulation	310
	Hydraulic Fracturing	311
	Explosive Fracturing	311
	Economics of <i>In Situ</i> Leaching Ore Deposits	312
	Waste Water Treatment and Aquifer Restoration	317
	Uranium Solution Mining Environmental	51,
	Restoration	318
ELEVEN	In Situ Leaching Hydrology	323
	Steady State Flow Assumptions and Definitions	324
	Flow from a Single Well in a Horizontal Aquifer	324
	Confined Ore-Bearing Aquifer	324
	Unconfined Ore-Bearing Aquifer	326
	Steady Flow from an Injection Well to a Production	
	Well in a Confined Aquifer	327
	Well Radius and Skin Effects in	
	Horizontally Confined Aquifers	329
	Steady Flow for Wellfield Configurations	332
	Flow in a Five Spot Extended Pattern	
	of Vertical Wells	333
	Flow Between Two Levels of Horizontal	
	Fractures	333
	Flow Between Fan Well Patterns	335
	Environmental Containment	337
TWELVE	Numerical Simulation of Fragmented	
	Rock Leaching	341
	_	241
	Introduction	341
	A Review of Diffusion Controlled Rock	2.42
	(Ore Fragment) Leaching	343
	Extraction (Washing) Governed by Diffusion	
	in Solution-Filled Pores	343
	Pseudo-Steady State Diffusion Coupled with	
	Fast Mineral Dissolution	344
	Rock (Ore Fragment) Leaching with	2.1-
	Mixed Kinetics	345
	Nonsteady State Mixed Kinetics Model	347
	Reaction Zone Model: Pseudo-Steady State	
	Mixed Kinetics	351

Contents	xiii

	In Situ Leaching of Primary Copper Ore	
	with Sparged Oxygen	354
	Mixed Kinetics Models Compared with Livermore	
	Copper Leaching Experiments	356
	Nonsteady State Model Comparative Results	356
	Reaction Zone Model Comparative Results	358
	Simulated Parametric Leaching of Fragmented	
	Primary Copper Ore	360
	Further Mixed Kinetics Ore Leaching Models	
	with Macro-Extensions to Ore Heaps	364
THIRTEEN	Evaporites, Brine and Sulfur	369
	Evaporite Deposits and Mineralogy	369
	Marine Evaporite Deposits	369
	Marine Salt Deposit Structures	371
	Alkali Evaporite Deposits	372
	Solution Mining Permeable Evaporites	373
	Solution Mining Impermeable Evaporites	374
	Searles Lake Brine	377
	Fort Cady Borate In Situ Leaching	382
	Brine Evaporative Crystallization Paths	384
	Salt Recovery and Separation Processes	384
	Sodium Chloride	384
	Soda Ash	385
	Potash and Borates	385
	Sodium Sulfate	386
	Magnesium	386
	Lithium	387
	Sulfur Deposits	387
	The Frasch Process	388
FOURTEEN	Solar Evaporation Ponds	393
 	•	
	Introduction	393
	Evaporation Rates	394
	Salt Deposits and Brine Entrainment	396
	Solar Pond Leakage	396
	Topography and Engineering Considerations	400
	Harvesting Salt Deposits	401

FIFTEEN	Remediation of Contaminated Ground	
	and Water	403
	Introduction	403
	Contaminants	404
	Mine Water and Acid Mine Drainage	405
	Groundwater Plume Movement	406
	Contaminant Removal with a Water Carrier	408
	In Situ Soil Washing	409
	Volatile Contaminant Removal	
	with an Air Carrier	409
	In Situ Contaminant Fixation	412
	Bioremediation	415
	Passive Systems for Treatment of Acid	
	Mine Drainage	422
	Miscellaneous Contaminant Fixation Methods	423
Appendix		427
Index		437