

# Contents

Preface.....	xix
Acknowledgments.....	xxiii
Author .....	xxv
<b>Chapter 1</b> Introduction .....	1
1.1 Petroleum Reservoir Rock and Fluids .....	1
1.2 Formation of Petroleum Reservoirs.....	1
1.3 Typical Characteristics of Petroleum Reservoirs .....	2
1.4 Unconventional Oil and Gas Resources .....	4
1.5 Significance of Petroleum Reservoir Rock and Fluid Properties.....	5
References .....	8
<b>Chapter 2</b> Preamble to Petroleum Reservoir Rock Properties.....	11
2.1 Introduction .....	11
2.2 Coring Methods.....	12
2.2.1 Rotary Method .....	12
2.2.2 Sidewall Coring.....	12
2.2.3 High-Pressure Coring.....	12
2.3 Important Issues Related to Coring Methods.....	13
2.4 Types of Cores .....	13
2.4.1 Whole Core .....	14
2.4.2 Core Plug.....	14
2.5 Allocation of Core Data for Measurement of Reservoir Rock Properties .....	14
2.6 Handling of Reservoir Rock Core Samples.....	14
2.7 Types of Core Tests .....	16
2.7.1 Routine or Conventional Core Analysis.....	16
2.7.2 Special Core Analysis .....	16
References .....	17
<b>Chapter 3</b> Porosity.....	19
3.1 Significance and Definition .....	19
3.2 Types of Porosities.....	19
3.2.1 Total or Absolute Porosity .....	21
3.2.2 Effective Porosity .....	21
3.2.3 Ineffective Porosity.....	22
3.3 Classification of Porosity .....	22

3.4	Parameters That Influence Porosity.....	23
3.5	Laboratory Measurement of Porosity .....	24
3.5.1	Porosity Determination Using Routine Core Analysis.....	25
3.5.1.1	Bulk Volume Measurement .....	25
3.5.1.2	Pore Volume Measurement.....	25
3.5.1.3	Grain Volume Measurement.....	28
3.6	Nonconventional Methods of Porosity Measurements .....	29
3.7	Averaging of Porosity .....	31
3.8	Examples of Typical Porosities.....	32
	Problems.....	33
	References .....	34
<b>Chapter 4</b>	<b>Absolute Permeability .....</b>	<b>37</b>
4.1	Significance and Definition .....	37
4.2	Mathematical Expression of Permeability: Darcy's Law .....	37
4.3	Dimensional Analysis of Permeability and Definition of a Darcy .....	40
4.4	Application of Darcy's Law to Inclined Flow and Radial Flow .....	41
4.5	Averaging of Permeabilities .....	44
4.5.1	Parallel Flow .....	44
4.5.2	Series Flow .....	46
4.6	Permeability of Fractures and Channels .....	48
4.7	Darcy's Law in Field Units .....	50
4.8	Laboratory Measurement of Absolute Permeability .....	51
4.8.1	Measurement of Absolute Permeability Using Liquids.....	53
4.8.2	Measurement of Absolute Permeability Using Gases....	55
4.9	Factors Affecting Absolute Permeability .....	58
4.9.1	Rock-Related Factors.....	58
4.9.2	Fluid Phase-Related Factors.....	60
4.9.3	Thermodynamic Factors .....	61
4.9.4	Mechanical Factors .....	61
4.10	Porosity and Permeability Relationships.....	63
4.11	Permeabilities of Different Types of Rocks .....	64
	Problems.....	65
	References .....	66
<b>Chapter 5</b>	<b>Mechanical and Electrical Properties of Reservoir Rocks .....</b>	<b>69</b>
5.1	Introduction .....	69
5.2	Mechanical Properties.....	70
5.2.1	Stress .....	70
5.2.2	Strain .....	71

5.2.3	Stress–Strain Relationship .....	72
5.2.3.1	Factors Affecting the Stress–Strain Relationship .....	72
5.2.4	Rock Strength.....	73
5.2.5	Rock Mechanics Parameters .....	74
5.2.5.1	Poisson's Ratio .....	74
5.2.5.2	Young's Modulus .....	74
5.2.5.3	Modulus of Rigidity.....	74
5.2.5.4	Bulk Modulus .....	75
5.2.6	Laboratory Measurement of Rock Strength.....	75
5.2.6.1	Triaxial Cell.....	76
5.2.7	Reservoir Rock Compressibility.....	78
5.2.7.1	Empirical Correlations of Formation Compressibility.....	80
5.3	Electrical Properties .....	81
5.3.1	Fundamental Concepts and the Archie Equation.....	81
5.3.1.1	Formation Factor .....	82
5.3.1.2	Tortuosity .....	82
5.3.1.3	Cementation Factor.....	82
5.3.1.4	Resistivity Index .....	84
5.3.2	Effect of Wettability on Electrical Properties .....	85
5.3.3	Effect of Clay on Electrical Properties .....	88
Problems.....		89
References .....		91
<b>Chapter 6</b>	<b>Fluid Saturation .....</b>	<b>93</b>
6.1	Significance and Definition .....	93
6.2	Distribution of Fluid Saturation in a Petroleum Reservoir.....	94
6.3	Definition and Mathematical Expressions for Fluid Saturation.....	94
6.4	Reservoir Rock Samples Used for Fluid Saturation Determination.....	96
6.5	Laboratory Measurement of Fluid Saturation .....	97
6.5.1	Retort Distillation.....	98
6.5.2	Dean–Stark Extraction.....	100
6.6	Assessing the Validity of Fluid Saturation Data Measured on the Plug-End Trim for the Core Plug Sample.....	102
6.7	Special Types of Fluid Saturations.....	103
6.7.1	Critical Gas Saturation .....	104
6.7.2	Residual Oil Saturation .....	104
6.7.3	Irreducible Water Saturation .....	107
6.8	Saturation Averaging .....	108
6.9	Factors Affecting Fluid Saturation Determination .....	109
6.9.1	Effect of Drilling Muds on Fluid Saturation .....	109
6.9.1.1	Skin Effect .....	111

6.9.2	Effect of Fluid Expansion on Fluid Saturation.....	112
6.9.3	Combined Effects of Mud Filtrate Invasion and Fluid Expansion on Fluid Saturation.....	113
6.9.4	Mitigation of Mud Filtrate Invasion and Fluid Expansion Effects on Fluid Saturation.....	115
6.9.4.1	Measures That Avoid or Account for Mud Filtrate Invasion.....	117
6.9.4.2	Measures That Avoid or Account for Fluid Expansion.....	119
	Problems.....	122
	References .....	123
<b>Chapter 7</b>	<b>Interfacial Tension and Wettability .....</b>	<b>125</b>
7.1	Introduction and Fundamental Concepts .....	125
7.2	Interfacial and Surface Tension.....	126
7.2.1	Effect of Pressure and Temperature on Interfacial Tension and Surface Tension .....	128
7.2.2	Laboratory Measurement of Interfacial Tension.....	130
7.3	Wettability .....	132
7.4	Fundamental Concepts of Wettability.....	133
7.5	Discussion on Practical Aspects of Wettability .....	136
7.5.1	Classification/Types of Wettability .....	138
7.5.1.1	Water Wet .....	138
7.5.1.2	Oil Wet.....	138
7.5.1.3	Intermediate Wet .....	138
7.5.1.4	Fractional Wettability .....	139
7.5.1.5	Mixed Wettability.....	139
7.6	Measurement of Reservoir Rock Wettability .....	139
7.6.1	Contact Angle Measurement.....	140
7.6.1.1	Effect of Pressure and Temperature on Contact Angles.....	141
7.6.2	Core Samples Used for Amott Test and USBM Methods .....	142
7.6.3	Amott Test .....	143
7.6.3.1	Modification of the Amott Test (Amott–Harvey Test) .....	145
7.6.4	USBM Method .....	147
7.7	Factors Affecting Wettability .....	149
7.7.1	Composition of the Reservoir Oil .....	149
7.7.2	Composition of the Brine .....	150
7.7.3	Reservoir Pressure and Temperature .....	151
7.7.4	Depth of the Reservoir Structure .....	151
7.8	Relationship between Wettability and Irreducible Water Saturation and Residual Oil Saturation .....	152
7.8.1	Wettability and Irreducible Water Saturation .....	153

7.8.2	Wettability and Residual Oil Saturation .....	154
7.8.2.1	Low-Salinity Waterflooding— Wettability–Residual Oil Saturation.....	156
Problems.....		157
References .....		158
<b>Chapter 8</b>	<b>Capillary Pressure.....</b>	<b>163</b>
8.1	Introduction .....	163
8.2	Basic Mathematical Expression of Capillary Pressure .....	164
8.3	The Rise of Liquid in Capillaries and the Plateau Equation ....	165
8.4	Dependence of Capillary Pressure on Rock and Fluid Properties.....	168
8.5	Capillary Pressure and Saturation History.....	169
8.6	Laboratory Measurement of Capillary Pressure .....	171
8.6.1	Leverett's Capillary Pressure Experiments.....	172
8.6.2	Porous Diaphragm Method .....	173
8.6.3	Mercury Injection Method .....	175
8.6.4	Centrifuge Method .....	177
8.7	Characteristics of Capillary Pressure Curves .....	179
8.7.1	Saturation Scale.....	179
8.7.2	Pressure Scale.....	180
8.7.3	Capillary Hysteresis .....	180
8.7.4	Capillary Pressure and Permeability.....	181
8.8	Converting Laboratory Capillary Pressure Data to Reservoir Conditions .....	182
8.9	Averaging Capillary Pressure: <i>J</i> Function.....	184
8.10	Calculation of Permeability from Capillary Pressure .....	186
8.11	Effect of Wettability on Capillary Pressure .....	189
8.12	Practical Application of Capillary Pressure.....	191
8.12.1	Pore Size Distribution .....	192
8.12.2	Pore Throat Sorting.....	194
8.12.3	Connate Water Saturation .....	195
8.12.4	Zonation, Fluid Contacts, and Initial Saturation Distribution in a Reservoir .....	196
8.12.4.1	Free Water Level.....	198
8.12.4.2	Oil–Water Contact .....	198
8.12.4.3	Transition Zone .....	199
8.12.4.4	Oil Pay Zone or Clean Oil Zone.....	199
8.12.4.5	Fluid Saturation in the Gas Zone.....	200
Problems.....		200
References .....		202
<b>Chapter 9</b>	<b>Relative Permeability .....</b>	<b>205</b>
9.1	Fundamental Concepts of Relative Permeability .....	205
9.2	Mathematical Expressions for Relative Permeability.....	206

9.3	Salient Features of Gas–Oil and Water–Oil Relative Permeability Curves .....	207
9.3.1	End-Point Fluid Saturations .....	208
9.3.2	Base Permeabilities .....	210
9.3.3	End-Point Permeabilities and Relative Permeability Curves .....	210
9.3.3.1	Gas–Oil Relative Permeability Curves....	210
9.3.3.2	Oil–Water Relative Permeability Curves....	210
9.3.4	Direction of the Relative Permeability Curves .....	211
9.4	Laboratory Measurement of Relative Permeability .....	212
9.4.1	Flowchart for Relative Permeability Measurements.....	213
9.4.2	Core Plug Samples Used in Relative Permeability Measurements .....	214
9.4.3	Displacement Fluids and Test Conditions .....	215
9.4.3.1	Room Condition Tests.....	215
9.4.3.2	Partial Reservoir Condition Tests .....	216
9.4.3.3	Reservoir Condition Tests.....	216
9.4.4	Establishment of Initial Water Saturation .....	216
9.4.4.1	Preserved Core Plug Samples .....	217
9.4.4.2	Cleaned Core Plug Samples.....	217
9.4.5	Determination of Base Permeability .....	218
9.4.6	Displacement Apparatus for Relative Permeability .....	219
9.4.7	Steady-State Technique .....	220
9.4.8	Unsteady-State Technique .....	223
9.4.8.1	Buckley–Leverett to Welge to Johnson–Bossler–Naumann .....	225
9.4.8.2	Relative Permeabilities from the Alternate Method.....	238
9.4.9	Capillary End Effect.....	238
9.5	Determination of Relative Permeability from Capillary Pressure Data.....	241
9.6	Factors Affecting Relative Permeability Measurements.....	243
9.6.1	Effect of Fluid Saturation, History of Saturation, and Initial Water Saturation .....	244
9.6.2	Effect of Wettability on Relative Permeability .....	246
9.6.3	Effect of Rock Pore Structure .....	247
9.6.4	Effect of Overburden Stress (Confining Stress) .....	248
9.6.5	Effect of Clay Content and Movement of Fines .....	248
9.6.6	Effect of Temperature.....	249
9.6.7	Effect of Interfacial Tension, Viscosity, and Flow Velocity .....	249
9.7	Peculiarities of Relative Permeability Data.....	251
9.8	Assessing the Validity of Relative Permeability Data and Determination of Corey Exponents .....	253

9.9	Significance of Relative Permeability Data.....	255
9.9.1	Example of Practical Application of Relative Permeability Data.....	255
9.10	Three-Phase Relative Permeability .....	258
9.10.1	Representation of Three-Phase Relative Permeability Data.....	258
9.10.2	Empirical Models for Three-Phase Relative Permeability .....	260
	Problems.....	262
	References .....	266
<b>Chapter 10 Introduction to Petroleum Reservoir Fluids.....</b>		269
10.1	Introduction .....	269
10.2	Chemistry of Petroleum.....	269
10.2.1	Paraffins or Alkanes.....	270
10.2.2	Naphthenes or Cycloparaffins .....	272
10.2.3	Aromatics .....	272
10.3	Solid Components of Petroleum.....	272
10.3.1	Gas Hydrates .....	273
10.3.2	Waxes .....	273
10.3.3	Asphaltenes .....	274
10.3.4	Diamondoids .....	275
10.4	Classification of Reservoir Gases and Oils .....	275
10.4.1	Chemical Classification of Reservoir Oils or Crude Oils .....	276
10.4.2	Physical Classification of Crude Oils.....	276
10.4.3	Impact of Crude Oil Characteristics on Refining.....	277
10.5	Five Reservoir Fluids.....	277
10.5.1	Other Unconventional Oils.....	278
10.6	Other Hydrocarbon Fluids of Interest .....	279
10.6.1	Compressed Natural Gas.....	280
10.6.2	Liquefied Natural Gas .....	280
10.6.3	Liquefied Petroleum Gas .....	280
10.6.4	Natural Gas Liquids .....	280
10.7	Formation Waters .....	281
	Problems.....	281
	References .....	282
<b>Chapter 11 Introduction to Phase Behavior .....</b>		285
11.1	Introduction .....	285
11.2	Definition of Terms Used in Phase Behavior .....	286
11.2.1	Phase.....	286
11.2.2	Intermolecular Forces, Pressure, and Temperature.....	286
11.2.3	Equilibrium .....	286

11.2.4	Component and Composition.....	286
11.2.5	Distinction between Gases and Liquids.....	287
11.2.6	Types of Physical Properties .....	287
11.2.7	Phase Rule .....	287
11.3	Phase Behavior of a Pure Component.....	288
11.3.1	Phase Diagram of a Pure Component .....	288
11.3.1.1	Vapor Pressure Curve.....	289
11.3.1.2	Critical Point .....	289
11.3.1.3	Triple Point .....	289
11.3.1.4	Melting Point Curve.....	289
11.3.1.5	Sublimation-Pressure Curve .....	290
11.3.1.6	Conditions Outside the $P_c-T_c$ Boundary.....	290
11.3.2	Pressure-Volume Diagram.....	291
11.3.3	Density-Temperature Behavior of a Pure Component .....	292
11.3.4	Determination of Vapor Pressure.....	293
11.4	Phase Behavior of Two-Component or Binary Systems .....	294
11.4.1	Phase Diagram of a Binary System.....	295
11.4.1.1	Critical Point .....	295
11.4.1.2	Bubble Point and Dew Point.....	296
11.4.1.3	Bubble-Point and Dew-Point Curves.....	296
11.4.1.4	Cricondenbar and Cricondentherm .....	296
11.4.1.5	Retrograde Dew Point and Condensation .....	297
11.4.1.6	Behavior of a Mixture in the Two-Phase Region .....	297
11.4.2	Effect of Changing the System Composition .....	301
11.5	Phase Behavior of Multicomponent Mixtures.....	302
11.6	Construction of Phase Envelopes .....	304
Problems .....	305	
References .....	307	
<b>Chapter 12</b>	<b>Phase Behavior of Petroleum Reservoir Fluids.....</b>	<b>309</b>
12.1	Introduction .....	309
12.2	Preamble to the Phase Behavior of Petroleum Reservoir Fluids .....	309
12.3	Brief Description of the Plus Fraction.....	310
12.4	Classification and Identification of Fluid Type.....	311
12.5	Black Oils .....	311
12.6	Volatile Oils.....	313
12.7	Gas Condensates.....	315
12.8	Wet Gases .....	318
12.9	Dry Gases .....	319
12.10	Behavior of Petroleum Reservoir Fluids in the Two-Phase Region .....	320

12.11	Saturated Hydrocarbon Reservoirs.....	322
12.12	Production Trends of Five Reservoir Fluids.....	322
Problems.....		324
References .....		325
<b>Chapter 13</b>	<b>Sampling of Petroleum Reservoir Fluids .....</b>	<b>327</b>
13.1	Introduction .....	327
13.2	Practical Considerations of Fluid Sampling.....	329
13.2.1	Well Conditioning .....	329
13.3	Methods of Fluid Sampling .....	330
13.3.1	Subsurface Sampling .....	331
13.3.2	Wellhead Sampling .....	331
13.3.3	Surface (Separator) Sampling .....	331
13.4	Evaluating the Representativity of Fluid Samples:	
Quality Checks .....		334
13.5	Factors Affecting Sample Representativity.....	335
Problems.....		337
References .....		337
<b>Chapter 14</b>	<b>Compositional Analysis of Petroleum Reservoir Fluids .....</b>	<b>339</b>
14.1	Introduction .....	339
14.2	Strategy of Compositional Analysis.....	340
14.2.1	Surface Samples of Separator Gas and Liquid.....	340
14.2.2	Blowdown Method .....	342
14.2.3	Direct Determination of Composition.....	343
14.3	Characteristics of Reservoir Fluid Composition .....	343
14.3.1	Well-Defined Components .....	344
14.3.2	Pseudo Fractions.....	345
14.3.3	Plus Fraction.....	345
14.4	Gas Chromatography.....	346
14.5	True Boiling-Point Distillation.....	348
14.5.1	Properties of TBP Cuts and Residue.....	350
14.5.2	Internal Consistency of TBP Data.....	350
14.5.3	Properties of TBP Cuts and Generalized Data .....	353
14.6	Characterization of Pseudo Fractions and Residue .....	356
14.7	Other Nonconventional Methods of Compositional Analysis.....	357
Problems.....		359
References .....		361
<b>Chapter 15</b>	<b>PVT Analysis and Reservoir Fluid Properties .....</b>	<b>363</b>
15.1	Introduction .....	363
15.2	Properties of Petroleum Reservoir Fluids .....	364
15.2.1	Gases and Liquids .....	365

15.2.2	Ideal Gases .....	365
15.2.2.1	Standard Volume .....	366
15.2.3	Real Gases.....	366
15.2.3.1	Gas Density.....	370
15.2.3.2	Specific Gravity .....	370
15.2.4	Mixtures of Gases .....	371
15.2.4.1	Apparent Molecular Weight .....	371
15.2.4.2	Critical Pressure and Temperature of Gas Mixtures .....	371
15.2.4.3	Determination of Compressibility Factor of Gas Mixtures .....	375
15.2.4.4	Determination of Density of Gas Mixtures.....	377
15.2.5	Dry Gases.....	378
15.2.5.1	Formation Volume Factor .....	378
15.2.5.2	Coefficient of Isothermal Compressibility .....	379
15.2.5.3	Viscosity .....	381
15.2.6	Wet Gases.....	382
15.2.6.1	Recombination Cases.....	382
15.2.6.2	Formation Volume Factor .....	386
15.2.7	Gas Condensates .....	387
15.2.8	Black Oils and Volatile Oils .....	388
15.2.8.1	Formation Volume Factor .....	388
15.2.8.2	Solution Gas–Oil Ratio or Gas Solubility .....	389
15.2.8.3	Total Formation Volume Factor.....	390
15.2.8.4	Coefficient of Isothermal Compressibility .....	392
15.2.8.5	Viscosity .....	393
15.2.8.6	Surface Tension.....	395
15.2.8.7	Volatile Oils .....	396
15.3	Laboratory Tests .....	396
15.3.1	PVT Equipment.....	397
15.3.2	Constant Composition Expansion .....	399
15.3.3	Differential Liberation .....	401
15.3.4	Constant Volume Depletion .....	404
15.3.4.1	Liquid Drop Out .....	406
15.3.4.2	Material Balance for Condensate Composition.....	406
15.3.4.3	Two-Phase Compressibility Factor .....	410
15.3.5	Separator Tests .....	410
15.3.5.1	Optimum Separator Conditions.....	412
15.4	Adjustment of Black Oil Laboratory Data .....	413
15.4.1	Combination Equations .....	415
15.4.1.1	Formation Volume Factor of Oil.....	416

15.4.1.2	Solution Gas–Oil Ratio.....	416
15.4.1.3	Formation Volume Factor of Gas .....	418
15.4.1.4	Total Formation Volume Factor.....	418
15.4.1.5	Coefficient of Isothermal Compressibility of Oil .....	418
15.4.2	Composite Liberation .....	419
15.5	Other Sources of Obtaining the Properties of Petroleum Reservoir Fluids.....	419
15.5.1	Empirical Correlations .....	419
15.5.1.1	Standing’s Empirical Correlations.....	420
15.5.2	Prediction of Viscosity from Compositional Data....	423
15.5.3	Prediction of Surface Tension .....	427
Problems.....		430
References .....		437
<b>Chapter 16</b>	<b>Vapor–Liquid Equilibria .....</b>	<b>439</b>
16.1	Introduction .....	439
16.2	Ideal Mixtures .....	440
16.2.1	Raoult’s Law.....	440
16.2.2	Dalton’s Law.....	441
16.2.3	Equilibrium Ratio.....	441
16.2.4	Concept of PT Flash.....	441
16.2.4.1	Flash Functions.....	443
16.2.5	Calculation of Bubble-Point Pressure .....	444
16.2.6	Calculation of Dew-Point Pressure .....	445
16.2.7	Drawbacks of the Ideal Mixture Principle .....	445
16.3	Empirical Correlations for Calculating Equilibrium Ratios for Real Solutions .....	446
16.3.1	Wilson Equation.....	447
16.3.2	Methods Based on the Concept of Convergence Pressure .....	447
16.3.2.1	K-Value Charts.....	451
16.3.2.2	Whitson–Torp Correlation .....	455
16.4	Equations-of-State (EOS) Models .....	457
16.4.1	Description of EOS Models .....	457
16.4.1.1	van der Waals Equation of State.....	458
16.4.1.2	Redlich–Kwong Equation of State.....	462
16.4.1.3	Soave–Redlich–Kwong Equation of State ...	463
16.4.1.4	Peng–Robinson Equation of State .....	464
16.4.2	Concept of Fugacity .....	464
16.4.3	Application of Equations of State to Pure Components.....	466
16.4.4	Extension of EOS Models to Mixtures .....	467
16.4.4.1	Determination of Equilibrium Ratios from EOS Models .....	470

16.4.5 VLE Calculations Using EOS Models .....	472
16.4.5.1 Calculation of Bubble-Point Pressure.....	472
16.4.5.2 Calculation of Dew-Point Pressure.....	475
16.4.5.3 PT Flash Calculations.....	475
16.4.5.4 Separator Calculations.....	478
16.4.5.5 A Note about the Application of EOS Models to Real Reservoir Fluids .....	483
16.5 Use of EOS Models in PVT Packages.....	484
Problems.....	485
References .....	486
 <b>Chapter 17 Properties of Formation Waters .....</b>	 489
17.1 Introduction .....	489
17.2 Compositional Characteristics of Formation Waters .....	490
17.3 Bubble-Point Pressure of Formation Water.....	492
17.4 Formation Volume Factor of Formation Water .....	492
17.5 Density of Formation Water .....	493
17.6 Viscosity of Formation Water.....	494
17.7 Solubility of Hydrocarbons in Formation Water .....	495
17.8 Solubility of Formation Water in Hydrocarbons .....	497
17.8.1 Water Content of Gaseous Hydrocarbons .....	497
17.8.2 Water Content of Liquid Hydrocarbons .....	499
17.9 Compressibility of Formation Water .....	499
Problems.....	500
References .....	501
 <b>Author Index.....</b>	 503
 <b>Subject Index.....</b>	 509