A STUDY OF MICELLAR/POLYMER FLOODING USING A COMPOSITIONAL SIMULATOR

APPROVED BY SUPERVISORY COMMITTEE:

A STUDY OF MICELLAR/POLYMER FLOODING USING A COMPOSITIONAL SIMULATOR

by

EUGENE CHING-TSAO LIN, B.E., M.S. IN CH.E.

DISSERTATION

Presented to the Faculty of the Graduate School of The University of Texas at Austin in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

THE UNIVERSITY OF TEXAS AT AUSTIN

December, 1981

Dedicated to

My Parents, Wife and Daughter

ACKNOWLEDGEMENT

I would like to express my sincere appreciation to my supervising professor, Dr. Gary A. Pope, for his guidance and valuable discussions throughout this work. I would also like to thank my supervisory committee members, Drs. L.W. Lake, R.C. MacDonald, K. Sepehrnoori and I.H. Silberberg, for their valuable comments and suggestions on preparing the manuscript. To Dr. B. Rouse, I am most grateful for his technical assistance in the laboratory work.

Appreciation is expressed to Phillips Petroleum Company for providing excellent experimental core flood data, and to the Department of Energy, Chevron, Cities Service, Core Laboratories, Exxon, Marathon, Mobil, Shell, and Tenneco Oil for the funding that made this study possible.

Finally, I would give my heartfelt appreciation to my wife, Ruth, for her understanding and sacrifices during this work. She also typed the entire dissertation.

Eugene Ching-Tsao Lin

The University of Texas Austin, Texas September, 1981

A STUDY OF MICELLAR/POLYMER FLOODING

USING A COMPOSITIONAL SIMULATOR

Publication No.

Eugene Ching-Tsao Lin, Ph.D. The University of Texas at Austin, 1981

Supervising Professor: Gary A. Pope

An existing compositional chemical flooding simulator was modified and extended to include: 1) the effects of non-Newtonian behavior of polymer solutions, inaccessible pore volume and permeability reduction; 2) physical dispersion; 3) alcohol as a new component; and 4) relative pressure drop, which was modeled to study the mobility control of the process.

Micellar/polymer oil recovery experiments were conducted and were history matched using the modified compositional simulator. The water flooding histories were matched using input parameters which were close to the laboratory measured values. The same parameters were employed for the simulation of the micellar/polymer oil recovery experiments and provided a good match of the oil breakthrough time. Other published micellar/polymer laboratory experiments were also matched.

The senstivity of the oil recovery for these and similar floods to several process variables was investigated. These variables

y

included salinity gradient, oil content of the slug, polymer buffer grading, and relative permeability.

TABLE OF CONTENTS

Chapter		
I.	INTRODUCTION	1
II.	GENERAL STATEMENT OF THE PROBLEM AND REVIEW OF LITERATURE	6
	 2.1 Overview of Reservoir Simulation 2.1.1 Historical Perspective 2.1.2 Type of Reservoir Simulator 2.2 Review of Compositional Simulators 2.3 Review of The Treatment of The Convection- Diffusion Equation 2.4 Review of Micellar/Polymer Flood Experiments 	6 6 7 8 12 14
III.	DESCRIPTION OF SIMULATION MODEL CHANGES	18
	 3.1 Inaccessible Pore Volume 3.2 Permeability Reduction 3.3 Non-Newtonian Rheology of a Polymer Solution 3.3.1 Shear Rate Dependent Viscosity 3.3.2 Concentration and Salinity Dependent 	18 21 23 24 26
	3.4 The Effects of Alcohol3.5 Physical Dispersion3.6 The Derivation of the Pressure Equation	29 30 34
IV.	EXPERIMENTAL WORK	48
	 4.1 Introduction 4.2 Experimental Set-up 4.3 Chemicals 4.4 Preparation of Core 4.5 Production Sample Analysis 4.6 Experimental Results 4.6.1 Run MPF-01 4.6.2 Run MPF-05 4.6.3 Run MPF-02 4.6.4 Run MPF-06 	48 50 52 53 56 56 57 59 64 65
۷.	HISTORY MATCHING STUDY	104
	5.1 Matching of Trushenski's Experiment	106

Chapter			Page
5	5.2 5.3	Matching of Rathmell's and Holm's Experiments History Matching of Experiments MPF-02, MPF-05 and MPE-06	110 113
		5.3.1 Matching Study of MPF-02 5.3.2 Matching Study of MPF-05 5.3.3 Matching Study of MPF-06	114 117 119
VI. S	SENSI	TIVITY STUDY	297
6 6 6	5.1 5.2 5.3	Introduction Electrolyte Gradient Sensitivity Study of Microemulsion Versus Aqueous Slugs	297 299 301
6	5.4 5.5	Sensitivity Study of Mobility Control Other Sensitivity Studies 6.5.1 Base Case MPF-02 6.5.2 Base Case MPF-05 6.5.3 Base Case MPF-06	303 304 304 306 307
VII. C	CONCL	USIONS AND RECOMMENDATIONS	334
NOMENCL	ATUR	RE	340
APPENDI	CES		347
μ	١.	DERIVATION OF GOVERNING EQUATIONS WITH TRUNCA- TION ERROR ESTIMATION	348
E	3.	COMPUTER PROGRAM LISTING	360
C	- - •	TABULATED RESULTS OF OIL RECOVERY EXPERIMENTS	427
D),	CALCULATION OF THE CONTINUOUSLY GRADED DRIVE USED BY HEDGES AND GLINSMANN	457
REFEREN	NCE		461
VITA			

LIST OF TABLES

Table		Page
3.1	COMPARISON OF ACTUAL DISPERSION WITH NUMERICAL DISPERSION FOR TRACER DISPLACEMENT AT 100% BRINE SATURATION	37
3.2	COMPARISON OF ACTUAL DISPERSION WITH NUMERICAL DISPERSION FOR TRACER DISPLACEMENT AT RESIDUAL OIL SATURATION	38
4.1	SUMMARY OF OIL RECOVERY EXPERIMENTS	70
5.1	SUMMARY OF HISTORY MATCHED EXPERIMENTS	124
5.2	TYPICAL CORE PROPERTIES AND TEST CONDITIONS AS SIMULATION INPUT FOR BASE CASE SP	125
5.3	SUMMARY OF INJECTION SLUG COMPOSITIONS AND SLUG SIZES FOR BASE CASE RUNS	126
5.4	LIST OF SIMULATION INPUT PARAMETERS FOR BASE CASE RUNS	129
6.1	SUMMARY OF SIMULATION RESULTS WITH DIFFERENT SURFACTANT SLUG DESIGNS FOR RUNS 173, 174, 188 AND 189	309
6.2	SUMMARY OF THE SIMULATED OIL RECOVERY WITH DIFFERENT BUFFER BANK DESIGN FOR RUNS 179, 181, 184 AND 185	310
6.3	LIST OF SOME OF THE INPUT PARAMETERS AND SIMULATED OIL RECOVERIES FOR RUNS 48, 61, 62, 64, 65 AND 66	311

LIST OF FIGURES

Figure		Page
3.1	RUN 265 AQUEOUS CONCENTRATION PROFILES AT 0.5 P.V.	39
3.2	PERMEABILITY REDUCTION FACTORS VERSUS POLYMER	40
3.3	RHEOLOGICAL BEHAVIOR OF POLYMER SOLUTION	41
3.4	EXPERIMENTAL AND SIMULATED XANFLOOD VISCOSITIES VERSUS SHEAR RATE AT VARIOUS CONCENTRATIONS	42
3.5	COMPARISON OF HI-VIS, CYANATROL WF 950S AND PUSHER 700 VISCOSITIES VERSUS SALINITY	43
3.6	COMPARISON OF CONCENTRATION PROFILES AT 0.5 P.V. FOR DIFFERENT PECLET NUMBERS	44
3.7	SIMULATION PROFILES OF NORMALIZED TRACER CONCEN- TRATION AT 0.5 P.V. VERSUS DISTANCE	45
3,8	RUN 89 AQUEOUS CONCENTRATION PROFILES AT 0.5 P.V.	46
3,9	RUN 100 AQUEOUS CONCENTRATION PROFILES AT 0.5 P.V.	47
4.1	SIMULATED POLYMER DRIVES FOR EXPERIMENTS MPF-01 AND MPF-05	72
4.2	SIMPLIFIED SCHEMATIC DIAGRAM OF THE EXPERIMENTAL SET-UP	73
4.3	LONGITUDINAL SECTION THROUGH INJECTION SAMPLE CONTAINER FOR SURFACTANT	74
4.4	RESULTS OF OIL RECOVERY EXPERIMENT MPF-01 SHOWING OIL CUT AND OIL RECOVERY VERSUS INJECTED PORE VOLUMES	75
4.5	TERNARY DIAGRAM FOR TRS10-410/NBA/N-DECANE AT 0.6 WT% NaCl	76
4.6	TERNARY DIAGRAM FOR TRS10-410/NBA/N-DECANE AT 0.8 WT% NaCl	77

•

.

X

age and

Figure		Page
4.7	TERNARY DIAGRAM FOR TRS10-410/NBA/N-DECANE AT 1.0 WT% NaCl	78
4.8	TERNARY DIAGRAM FOR TRS10-410/NBA/N-DECANE AT 1.8 WT% NaCl	79
4.9	VOLUME FRACTIONAL DIAGRAM OF TRS10-410/NBA MICELLAR SOLUTIONS AS A FUNCTION OF SALINITY	80
4.10	INTERFACIAL TENSION AS A FUNCTION OF SOLUBILIZATION RATIO	81
4.11	RELATIVE PERMEABILITY CURVES FOR BRINE AND N-DECANE AS A FUNCTION OF WATER SATURATION IN BEREA	82
4.12	HI-VIS VISCOSITY VERSUS CONCENTRATION AT 0.86 WT% NaCl	83
4.13	DISPERSION CURVE AT 100% BRINE SATURATION FOR MPF-05	84
4.14	λ CURVE AT 100% BRINE SATURATION FOR MPF-05	85
4.15	DISPERSION CURVE AT RESIDUAL OIL SATURATION FOR MPF-05	86
4.16	NORMALIZED PRESSURE DROPS VERSUS PORE VOLUME INJECTED FOR EXPERIMENT MPF-05	87
4.17	RESULTS OF OIL RECOVERY EXPERIMENT MPF-05 SHOWING OIL CUT, OIL RECOVERY AND NORMALIZED POLYMER CONCENTRATION VERSUS PORE VOLUME INJECTED	88
4.18	TERNARY DIAGRAM FOR TRS10-410/IBA/N-DECANE AT 0.6 WT% NaCl	89
4.19	TERNARY DIAGRAM FOR TRS10-410/IBA/N-DECANE AT 1.0 WT% NaCl	90
4.20	TERNARY DIAGRAM FOR TRS10-410/IBA/N-DECANE AT 1.5 WT% NaCl	91

. .

xi

Figure		Page
4.21	PHASE VOLUME FRACTION OF TRS10-410/IBA MICELLAR SOLUTIONS AS A FUNCTION OF SALINITY	92
4.22	VISCOSITY OF 1000 PPM XANFLOOD VERSUS SHEAR RATE FOR MPF-02	93
4.23	DISPERSION CURVE AT RESIDUAL OIL SATURATION FOR MPF-02	94
4.24	λ CURVES AT RESIDUAL OIL SATURATION FOR MPF-02	95
4.25	RESULTS OF OIL RECOVERY EXPERIMENT MPF-02 SHOWING OIL CUT, OIL RECOVERY AND NORMALIZED POLYMER CONCENTRATION VERSUS PORE VOLUME INJECTED	96
4.26	NORMALIZED PRESSURE DROPS VERSUS PORE VOLUME INJECTED FOR EXPERIMENT MPF-02	97
4.27	DISPERSION CURVE AT 100% BRINE SATURATION FOR MPF-05	9 8
4.28	LEADING EDGE λ CURVE AT 100% BRINE SATURATION FOR MPF-06	99
4.29	DISPERSION CURVE AT RESIDUAL OIL SATURATION FOR MPF-06	100
4.30	RESULTS OF OIL RECOVERY EXPERIMENT MPF-06 SHOWING OIL CUT, OIL RECOVERY, NORMALIZED POLYMER CONCEN- TRATION AND NORMALIZED OVERALL PRESSURE DROP VERSUS PORE VOLUME INJECTED	101
4.31	RESULTS OF ION CONCENTRATION HISTORIES FOR EXPERI- MENT MPF-06	102
4.32	DISPERSION CURVE AFTER POLYMER DRIVE FOR EXPERI- MENT MPF-06	103
5.1	INTERFACIAL TENSIONS ALONG BINODAL CURVE FOR BASE CASE SP	133
5.2	VISCOSITIES ALONG BINODAL CURVE FOR BASE CASE SP	134

,

xii

Figure	r	Page
5.3	POLYMER VISCOSITY VERSUS POLYMER CONCENTRATION FOR BASE CASE SP	135.
5.4	POLYMER VISCOSITY VERSUS SHEAR RATE FOR BASE CASE SP	136
5.5	SURFACTANT ADSORPTION AS A FUNCTION OF SURFACTANT CONCENTRATION AT VARIOUS SALINITIES FOR BASE CASE SP	137
5.6	RESIDUAL SATURATION OF WATER AND OIL VERSUS INTER- FACIAL TENSION TIMES TOTAL MOBILITY	138
5.7	RELATIVE PERMEABILITY CURVES OF WATER AND OIL FOR BASE CASE SP	139
5.8	FRACTIONAL FLOW CURVE OF WATER AS A FUNCTION OF WATER SATURATION FOR BASE CASE SP	140
5.9	RUN 004 TOTAL CONCENTRATION HISTORIES	141
5.10	RUN 004 OIL RECOVERY HISTORIES	142
5.11	RUN 148 TOTAL CONCENTRATION HISTORIES	143
5.12	RUN 148 OIL RECOVERY HISTORIES	144
5.13	RUN 165 TOTAL CONCENTRATION HISTORIES	145
5.14	RUN 165 OIL RECOVERY HISTORIES	146
5.15	COMPOSITION PATH HISTORY FOR RUN 165	147
5.16	RUN 167 TOTAL CONCENTRATION HISTORIES	148
5.17	RUN 167 OIL RECOVERY HISTORIES	149
5.18	COMPOSITION PATH HISTORY FOR RUN 167	150
5.19	COMPOSITION PATH HISTORY FOR RUN 173	151
5.20	RUN 185 TOTAL CONCENTRATION HISTORIES	152
5.21	RUN 185 OIL RECOVERY HISTORIES	153

xiii

:

Figure		Page
5.22	RUN 282 AQUEOUS CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE SP	154
5.23	RUN 282 OLEIC CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE SP	155
5.24	RUN 282 TOTAL CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE SP	156
5.25	RUN 282 TOTAL MOBILITY AND RELATIVE PRESSURE DROP PROFILES AT 0.5 P.V. FOR BASE CASE SP	157
5.26	RUN 282 INTERFACIAL TENSION PROFILE AT 0.5 P.V. FOR BASE CASE SP	158
5.27	RUN 282 AQUEOUS CONCENTRATION HISTORIES FOR BASE CASE SP	159
5.28	RUN 282 OLEIC CONCENTRATION HISTORIES FOR BASE CASE SP	160
5.29	RUN 282 TOTAL CONCENTRATION HISTORIES FOR BASE CASE SP	161
5.30	RUN 282 OIL RECOVERY HISTORY FOR BASE CASE SP	162
5.31	RUN 282 OVERALL RELATIVE PRESSURE DROP HISTORY FOR BASE CASE SP	163
5.32	RUN 282 COMPOSITION PATH HISTORY FOR BASE CASE SP	164
5.33	TERNARY DIAGRAM AT 0.053 N NaCl FOR BASE CASES QPH AND QPR	165
5.34	INTERFACIAL TENSION AT 0.053 N ^{NaCl} FOR BASE CASES QPH AND QPR	166
5.35	VISCOSITY ALONG BINODAL CURVE FOR BASE CASES QPH AND QPR	167
5.36	RELATIVE PERMEABILITY CURVES OF WATER AND OIL FOR BASE CASES QPH AND QPR	168

xiv

Figure		Page
5.37	FRACTIONAL FLOW CURVE OF WATER FOR BASE CASES QPH AND QPR	169
5.38	RUN 007 AQUEOUS CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE QPR	170
5.39	RUN 007 OLEIC CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE QPR	171
5.40	RUN 007 TOTAL CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE QPR	172
5.41	RUN 007 TOTAL MOBILITY AND RELATIVE PRESSURE DROP PROFILES AT 0.5 P.V. FOR BASE CASE QPR	173
5.42	RUN 007 INTERFACIAL TENSION PROFILE AT 0.5 P.V. FOR BASE CASE QPR	174
5.43	RUN 007 AQUEOUS CONCENTRATION HISTORIES FOR BASE CASE QPR	175
5.44	RUN 007 TOTAL CONCENTRATION HISTORIES FOR BASE CASE QPR	176
5.45	RUN 007 OIL RECOVERY HISTORIES FOR BASE CASE QPR	177
5.46	RUN 007 OVERALL RELATIVE PRESSURE DROP HISTORY FOR BASE CASE QPR	178
5.47	RUN 029 AQUEOUS CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE QPH	179
5.48	RUN 029 OLEIC CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE QPH	180
5.49	RUN 029 TOTAL CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE QPH	181
5.50	RUN 029 TOTAL MOBILITY AND RELATIVE PRESSURE DROP PROFILES AT 0.5 P.V. FOR BASE CASE QPH	182
5.51	RUN 029 INTERFACIAL TENSION PROFILE AT 0.5 P.V. FOR BASE CASE QPH	183

x٧

Figure		Page
5.52	RUN 029 AQUEOUS CONCENTRATION HISTORIES FOR BASE CASE QPH	184
5.53	RUN 029 OLEIC CONCENTRATION HISTORIES FOR BASE CASE QPH	185
5.54	RUN 029 TOTAL CONCENTRATION HISTORIES FOR BASE CASE QPH	186
5.55	RUN 029 OIL RECOVERY HISTORIES FOR BASE CASE QPH	187
5.56	RUN 029 OVERALL RELATIVE PRESSURE DROP HISTORY FOR BASE CASE QPH	188
5.57	SURFACTANT CONCENTRATION ON THE PHASE ENVELOPE AS A FUNCTION OF SALINITY FOR BASE CASE MPF-02	189
5.58	MICROEMULSION VISCOSITY AS A FUNCTION OF SALINITY FOR BASE CASE MPF-02	190
5.59	MICROEMULSION VOLUME FRACTION AS A FUNCTION OF SALINITY FOR BASE CASE MPF-02	191
5.60	COMPARISON OF SIMULATED AND EXPERIMENTAL FRACTIONAL VOLUME DIAGRAM OF TRS10-410/IBA/N-DECANE SYSTEM FOR BASE CASE MPF-02	192
5.61	SOLUBILIZATION RATIOS AS A FUNCTION OF SALINITY FOR BASE CASE MPF-02	193
5.62	INTERFACIAL TENSION AS A FUNCTION OF SALINITY FOR BASE CASE MPF-02	194
5.63	INTERFACIAL TENSION AS A FUNCTION OF SOLUBILIZATION RATIO FOR BASE CASE MPF-02	195
5.64	TERNARY DIAGRAM FOR BASE CASE MPF-02 AT 0.6 WT% NaCl (0.103 N)	196
5.65	TERNARY DIAGRAM FOR BASE CASE MPF-02 AT 1.5 WT% NaCl (0.26 N)	197
5.66	TERNARY DIAGRAM FOR BASE CASE MPF-02 AT 1.0 WT% NaCl	198

xvi

Figure		Page
5.67	INTERFACIAL TENSION AT 0.18 N NaCl FOR BASE CASE MPF-02	199
5.68	VISCOSITY ALONG BINODAL CURVE FOR BASE CASE MPF-02	200
5.69	SIMULATED INJECTION POLYMER VISCOSITY VERSUS POLYMER CONCENTRATION FOR BASE CASE MPF-02	201
5.70	RESIDUAL SATURATIONS OF AQUEOUS AND OLEIC PHASES VERSUS INTERFACIAL TENSION TIMES TOTAL MOBILITY FOR BASE CASE MPF-02	202
5.71	RELATIVE PERMEABILITY CURVES OF WATER AND OIL FOR BASE CASE MPF-02	203
5.72	FRACTIONAL FLOW CURVE OF WATER FOR BASE CASE MPF-02	204
5.73	WATER FLOOD TOTAL CONCENTRATION HISTORIES FOR BASE CASE MPF-02	205
 5.74	WATER FLOOD PHASE CUT AND OIL RECOVERY HISTORIES FOR BASE CASE MPF-02	206
5.75	WATER FLOOD RELATIVE PRESSURE DROP HISTORIES FOR BASE CASE MPF-02	207
5.76	RUN 48 AQUEOUS CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-02	208
5.77	RUN 48 OLEIC CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-02	209
5.78	RUN 48 MICROEMULSION CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-02	210
5.79	RUN 48 TOTAL CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-02	211
5.80	RUN 48 TOTAL MOBILITY AND RELATIVE PRESSURE DROP PROFILES AT 0.5 P.V. FOR BASE CASE MPF-02	212
5.81	RUN 48 INTERFACIAL TENSION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-02	213

1

xyii

Figure	·	Page
5.82	RUN 48 AQUEOUS CONCENTRATION HISTORIES FOR BASE CASE MPF-02	214
5.83	RUN 48 MICROEMULSION CONCENTRATION HISTORIES FOR BASE CASE MPF-02	215
5.84	RUN 48 TOTAL CONCENTRATION HISTORIES FOR BASE CASE MPF-02	216
5.85	RUN 48 PHASE CUT AND OIL RECOVERY HISTORIES FOR BASE CASE MPF-02	217
5.86	RUN 48 RELATIVE PRESSURE DROP HISTORIES FOR BASE CASE MPF-02	218
5.87	RUN 49 TOTAL CONCENTRATION HISTORIES (ϕ_3 =0.3)	219
5.88	RUN 49 MICROEMULSION CONCENTRATION HISTORIES ($\phi_3 = 0.3$)	220
5.89	SURFACTANT CONCENTRATION ON THE PHASE ENVELOPE AS A FUNCTION OF SALINITY FOR BASE CASE MPF-05	221
5.90	TERNARY DIAGRAM FOR BASE CASE MPF-05 AT 0.6 WT% NaCl	222
5.91	TERNARY DIAGRAM FOR BASE CASE MPF-05 AT 1.0 WT% NaCl	223
5.92	TERNARY DIAGRAM FOR BASE CASE MPF-05 AT 0.8 WT% NaCl	224
5.93	INTERFACIAL TENSION AT 0.11 N NaCl FOR BASE CASE MPF-05	225
5.94	VISCOSITIES ALONG BINODAL CURVE AT 0.11 N NaCl FOR BASE CASE MPF-05	226
5.95	MICROEMULSION VISCOSITY AS A FUNCTION OF SALINITY FOR BASE CASE MPF-05	227
5.96	MICROEMULSION VOLUME FRACTION AS A FUNCTION OF SALINITY FOR BASE CASE MPF-05	228
5.97	FRACTIONAL VOLUME DIAGRAM FOR BASE CASE MPF-05	229

xviii

Figure		Page
5.98	SOLUBILIZATION RATIOS AS A FUNCTION OF SALINITY FOR BASE CASE M₽F-05	230
5.99	INTERFACIAL TENSIONS AS A FUNCTION OF SALINITY FOR BASE CASE MPF-05	231
5.100	INTERFACIAL TENSION AS A FUNCTION OF SOLUBILIZATION RATIOS FOR BASE CASE MPF-05	232
5.101	SIMULATION INPUT POLYMER VISCOSITY VERSUS POLYMER CONCENTRATION FOR BASE CASE MPF-05	233
5.102	RESIDUAL SATURATION OF AQUEOUS AND OLEIC PHASES VERSUS INTERFACIAL TENSION TIMES TOTAL MOBILITY FOR BASE CASE MPF-05	234
5.103	RELATIVE PERMEABILITY CURVES OF WATER AND OIL FOR BASE CASE MPF-05	235
5.104	FRACTIONAL FLOW CURVE OF WATER FOR BASE CASE MPF-05	236
5.105	WATER FLOOD PHASE CUT AND OIL RECOVERY HISTORIES FOR BASE CASE MPF-05	237
5.106	WATER FLOOD RELATIVE PRESSURE DROPS FOR BASE CASE MPF-05	238
5.107	RUN 145 AQUEOUS CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-05	239
5.108	RUN 145 OLEIC CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-05	240
5.109	RUN 145 MICROEMULSION CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-05	241
5.110	RUN 145 TOTAL CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-05	242
5.111	RUN 145 TOTAL MOBILITY AND RELATIVE PRESSURE DROP PROFILES AT 0.5 P.V. FOR BASE CASE MPF-05	243
5.112	RUN 145 INTERFACIAL TENSION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-05	244

xix

Figure		Page
5.113	RUN 145 AQUEOUS CONCENTRATION HISTORIES FOR BASE CASE MPF-05	245
5.114	RUN 145 OLEIC CONCENTRATION HISTORIES FOR BASE CASE MPF-05	246
5.115	RUN 145 MICROEMULSION CONCENTRATION HISTORIES FOR BASE CASE MPF-05	247
5.116	RUN 145 TOTAL CONCENTRATION HISTORIES FOR BASE CASE	248
5.117	RUN 145 PHASE CUT AND OIL RECOVERY HISTORIES FOR BASE CASE MPF-05	249
5.118	RUN 145 RELATIVE PRESSURE DROP HISTORIES FOR BASE CASE MPF-05	250
5.119	RUN 146 TOTAL CONCENTRATION HISTORIES	251
5.120	RUN 146 OIL RECOVERY HISTORIES	252
5.121	SURFACTANT CONCENTRATION ON THE PHASE ENVELOPE AS A FUNCTION OF SALINITY FOR BASE CASE MPF-06	253
5.122	COMPARISON OF THE SIMULATED AND EXPERIMENTAL RELATIVE PERMEABILITY CURVES OF WATER AND OIL FOR BASE CASE MPF-06	254
5.123	FRACTIONAL FLOW CURVE OF WATER FOR BASE CASE MPF-06	255
5.124	MICROEMULSION VISCOSITY AS A FUNCTION OF SALINITY FOR BASE CASE MPF-06	256
5.125	MICROEMULSION VOLUME FRACTION AS A FUNCTION OF SALINITY FOR BASE CASE MPF-06	257
5.126	COMPARISON OF SIMULATED AND EXPERIMENTAL FRACTIONAL VOLUME DIAGRAM OF TRS10-410/IBA/NECTON 37 SYSTEM FOR BASE CASE MPF-06	258
5.127	SOLUBILIZATION RATIOS AS A FUNCTION OF SALINITY FOR BASE CASE MPF-06	259

хх

Figure		Page
5.128	INTERFACIAL TENSION AS A FUNCTION OF SALINITY FOR BASE CASE MPF-06	260
5.129	INTERFACIAL TENSION AS A FUNCTION OF SOLUBILIZATION RATIO FOR BASE CASE MPF-06	261
5.130	TERNARY DIAGRAM FOR BASE CASE MPF-05 AT 0.6 WT% NaCl	262
5.131	TERNARY DIAGRAM FOR BASE CASE MPF-06 AT 3.4 WT% NaCl	263
5.132	TERNARY DIAGRAM FOR BASE CASE MPF-06 AT 2.0 WT% NaCl	264
5.133	SIMULATED TERNARY DIAGRAM AT 0.26 N NaCl FOR BASE CASE MPF-06	265
5.134	SIMULATED INTERFACIAL TENSION VERSUS OIL CONCENTRA- TION FOR BASE CASE MPF-06	266
5.135	SIMULATED VISCOSITIES ALONG THE BINODAL CURVE FOR BASE CASE MPF-06	267
5.136	POLYMER VISCOSITY VERSUS POLYMER CONCENTRATION FOR BASE CASE MPF-06	268
5.137	SIMULATED POLYMER VISCOSITIES VERSUS SHEAR RATE FOR BASE CASE MPF-06	269
5.138	COMPARISON OF SIMULATED AND EXPERIMENTAL WATER FLOOD HISTORY ($e_1^{=1.0}, e_2^{=1.0}$)	270
5.139	COMPARISON OF SIMULATED AND EXPERIMENTAL WATER FLOOD HISTORY ($e_1^{=1.2}, e_2^{=1.2}$)	271
5.140	COMPARISON OF SIMULATED AND EXPERIMENTAL WATER FLOOD HISTORY (e ₁ =2.0, e ₂ =1.0)	272
5.141	WATER FLOOD AQUEOUS CONCENTRATION HISTORIES FOR BASE CASE MPF-06	273
5.142	WATER FLOOD OLEIC CONCENTRATION HISTORIES FOR BASE CASE MPF-06	274
5.143	WATER FLOOD TOTAL CONCENTRATION HISTORIES FOR BASE	275

.

xxi

Figure		Page
5.144	WATER FLOOD PHASE CUT AND OIL RECOVERY HISTORY FOR BASE CASE MPF-06	276
5.145	WATER FLOOD RELATIVE PRESSURE DROPS FOR BASE CASE MPF-06	277
5.146	RUN 133 AQUEOUS CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-06	278
5.147	RUN 133 OLEIC CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-06	279 ⁻
5.148	RUN 133 MICROEMULSION CONCENTRATION PROFILES AT 0.5 Pave For BASE CASE MPF-06	280
5.149	RUN 133 TOTAL CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-06	281
5.150	RUN 133 TOTAL MOBILITY AND RELATIVE PRESSURE DROP PROFILES AT 0.5 P.V. FOR BASE CASE MPF-06	282
5.151	RUN 133 INTERFACIAL TENSION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-06	283
5.152	RUN 133 AQUEOUS CONCENTRATION HISTORIES FOR BASE CASE MPF-06	284
5.153	RUN 133 OLEIC CONCENTRATION HISTORIES FOR BASE CASE MPF-06	285
5.154	RUN 133 MICROEMULSION CONCENTRATION HISTORIES FOR BASE CASE MPF-06	286
5.155	RUN 133 TOTAL CONCENTRATION HISTORIES FOR BASE CASE MPF-06	287
5.156	RUN 133 PHASE CUT AND OIL RECOVERY HISTORIES FOR BASE CASE MPF-06	288
5.157	RUN 133 RELATIVE PRESSURE DROP HISTORIES FOR BASE CASE MPF-06	289
5.158	RUN 75 TOTAL CONCENTRATION HISTORIES	290

•

xxii

Figure		Page
5.159	RUN 75 OIL RECOVERY HISTORIES	291
5.160	INTERFACIAL TENSION AS A FUNCTION OF SOLUBILIZA- TION RATIOS FOR RUN 220	292
5.161	INTERFACIAL TENSION AS A FUNCTION OF SALINITY FOR RUN 220	293
5.162	RESIDUAL SATURATION AS A FUNCTION OF CAPILLARY NUMBER	294
5.163	RUN 220 TOTAL CONCENTRATION AND OIL RECOVERY HISTORIES	295
5,164	RUN 220 OVERALL PRESSURE DROP HISTORIES	296
6.1	RUN 189 INTERFACIAL TENSION PROFILES AT 0.5 P.V.	312
6.2	RUN 173 INTERFACIAL TENSION PROFILES AT 0.5 P.V.	313
6.3	RUN 174 INTERFACIAL TENSION PROFILES AT 0.5 P.V.	314
6.4	RUN 188 INTERFACIAL TENSION PROFILES AT 0.5 P.V.	315
6.5	RUN 156 AQUEOUS CONCENTRATION HISTORIES	316
6.6	RUN 156 TOTAL CONCENTRATION HISTORIES	317
6.7	RUN 156 PHASE CUT AND OIL RECOVERY HISTORIES	318
6.8	RUN 156 RELATIVE PRESSURE DROP HISTORIES	319
6.9	RUN 157 AQUEOUS CONCENTRATION HISTORIES	320
6.10	RUN 157 TOTAL CONCENTRATION HISTORIES	321
6.11	RUN 157 PHASE CUT AND OIL RECOVERY HISTORIES	322
6.12	RUN 157 RELATIVE PRESSURE DROP HISTORIES	323
6.13	RUN 191 TOTAL CONCENTRATION HISTORIES SHOWING EXPERIMENTAL OIL OF HEDGES AND GLINSMANN	324
6.14	RUN 191 PHASE CUT AND OIL RECOVERY HISTORIES SHOWING EXPERIMENTAL OIL RECOVERY OF HEDGES AND GLINSMANN	325

Figure		Page
6.15	RUN 74 TOTAL CONCENTRATION HISTORIES	326
6.16	RUN 74 OIL RECOVERY HISTORIES	327
6.17	RUN 71 TOTAL CONCENTRATION HISTORIES	328
6.18	RUN 71 OIL RECOVERY HISTORIES	329
6.19	RUN 96 TOTAL CONCENTRATION HISTORIES	330
6.20	RUN 96 OIL RECOVERY HISTORIES	331
6.21	RUN 102 TOTAL CONCENTRATION HISTORIES	332
6.22	RUN 102 OIL RECOVERY HISTORIES	333

CHAPTER I

INTRODUCTION¹⁻¹⁹

Since 1973, the OPEC oil price increase along with the decline of domestic crude oil production have caused oil prices to soar. Today, the discovery of new oil reservoirs in the United States is difficult and discovery of large oil reservoirs seems unlikely. New reservoirs discovered offshore and in Alaska are expensive to produce. The insufficient oil supply from domestic sources increases the dependency on imported oil. This skyrocketing of the oil prices really hurts the nation's growth.

It is estimated that at a relatively low economic growth rate of 2.7%, domestic demand for petroleum could go as high as 25 million B/D in early 1990^2 . The domestic production, including north slope Alaskan oil, in contrast, could drop to about four million B/D by that time and three million B/D by 1995. About two-thirds of the existing oil in place remains unrecovered by conventional recovery methods and it is crucial that this be recovered to meet the needs.

To recover this remaining oil, several so-called "enhanced" oil recovery methods such as miscible, thermal, chemical, etc. have

been used. In general, the main mechanisms of these methods are:

- . to reduce the interfacial tension between the oil and water phases,
- . to achieve miscibility, and
- . to improve mobility control.

Currently, thermal methods account for the most of the enhanced oil production, accounting for 70% of the domestic and 68% of the world enhanced oil production in 1977^2 . Any method (such as polymer flood, surfactant flood, caustic flood) involving the use of chemicals to achieve higher oil recovery can be included in chemical method. For instance, water soluble polymers such as polysaccharides and polyacrylamides are used as water thickeners to improve the water flood sweep efficiency. Surface active agents or surfactants have also been used to improve oil recovery since as early as the late 1920's by the reduction of interfacial tension between the water and oil phases so that the oil is easier to produce 10 . More recently, micellar or micellar/polymer $^{20-59}$ processes have been developed and been subjected to both pilot and commercial scale tests. In general, these processes involve a sequence of: a preflush slug to condition the reservoir salinity; a surfactant slug to achieve low interfacial tension; a polymer slug to achieve mobility control requirement and a chase brine as a drive for the previously injected slugs. This process seems promising due to the potential of

producing all the contacted oil. Polymers may also be added to the surfactant slug to obtain a favorable mobility ratio between the surfactant slug and the oil bank in front of it.

However, the main disadvantage of chemical flooding is the comparatively high cost of the chemicals involved. Thus, it becomes imperative to determine the conditions that provide maximal oil recovery, in order that expenses might be reduced. In determining these conditions, as applied to a complex reservoir, the fastest and most efficient solution is to be found using a mathematically based computer simulation. After an appropriate model is developed, the complex behavior of micellar/polymer flooding can be simulated in a relative short time with lower costs than expensive and time consuming laboratory experiments.

Reservoir simulation, in general, refers to the development and operation of a model whose behavior assumes the characteristics of actual reservoir behavior. Basically, to do reservoir simulation, the first step is to prepare input data which will include both the reservoir properties such as permeability and porosity and the injection fluids properties such as viscosity, density, salinity, etc. By using these input data, history matching runs are conducted with the input data being adjusted until there is agreement between the simulated results and the actual experimental results. The simulator is then used to predict the performance of alternative

plans of operation or is used to predict performance of other reservoirs of similar characteristics. In general, the longer the mathed history period, the more reliable the predictions will be. It is advisible that during prediction of actual performance the input parameters be adjusted constantly according to new developments in the history in order to obtain more accurate and up-dated predictions. Although, the goal is to obtain a good match on all the quantities, it usually is not as good as desired. However, if a reasonably good match is unattainable, this may imply that the simulator is not capable of simulating this particular experiment. In this case it may be necessary to modify the numerical model and hope that a better match can be achieved.

To study the micellar/polymer processes, Pope and Nelson⁶⁰ developed a one-dimensional, compositional simulator which accounted for the phase behavior as a function of salinity. This simulator enables calculation of oil recovery as a function of several major process variables, namely, interfacial tension, relative permeability, dispersion, adsorption, cation exchange, chemical slug size, polymer transport, etc. Later, Wang⁶¹ and Pope, Wang and Tsaur⁶² modified and extended the original simulator to allow calculation of a number of additional effects. However, some other effects, such as inaccessible pore volume, permeability reduction of the

polymer-rich phase, non-Newtonian behavior, the effect of alcohol on phase behavior, etc. were not included.

The purpose of this study was to extend Pope's simulator to account for some effects not previously included. A series of oil recovery experiments were designed and conducted for history matching purposes. Many of the important physical properties of the core as well as the surfactant and polymer solutions were measured to provide the necessary input parameters encountered during the history matching of other published works. A history matching study was conducted in order to calibrate the simulator and to test its capability of matching the actual laboratory results. A sensitivity study was conducted to identify the most important parameters accounting for the oil recovery.

CHAPTER II

GENERAL STATEMENT OF THE PROBLEM AND REVIEW OF LITERATURE

2.1 Overview of Reservoir Simulation

2.1.1 Historical Perspective

Reservoir simulation has been known and applied by petroleum engineers to study reservoir problems for years. The model can be mathematical or physical. One example was the use of a zero dimensional "tank" model. This model is based upon a conservation principle which states that the total fluid in minus the total fluid out equals the net change of volume in the tank. From this, it is possible to estimate the oil in place, gas in place, and the amount of water influx. Furthermore, it has provided a means to predict oil production under various driving mechanisms such as solution gas drive, gas cap drive, etc. The weakness of this model is that it can be used only for reservoirs with relatively homogeneous properties such as porosity and permeability. However, this "tank" can be treated as the basic building block in the extension to the multi-dimensional model in which the porosity and permeability can be specified for each individual "tank". Recently, even more complex

reservoir problems such as encountered in enhanced oil recovery can be simulated numerically utilizing the hight-speed computer.

2.1.2 Type of Reservoir Simulator

Reservoir simulators can be classified according to the type of reservoirs simulated, for example, gas reservoir simulator, blackoil reservoir simulator, and condensate reservoir simulator. Gas reservoir simulators deal with either single phase gas flowing problems or two-phase gas and water flowing problems. A black-oil reservoir simulator, on the other hand, is capable of handling gas, oil and water flow. Usually, only the gas is allowed to transport into or out of the oil phase. Due to the complex compositional effects of condensate and volatile oil reservoirs, a special purpose simulator, refered to as a compositional simulator, which accounts for the compositional behavior of individual components. is usually required. This type of model focuses on individual components rather than phases; in consequence, more calculations and computation time are involved then for a black-oil model. The advantage of using the compositional model is in the increased accuracy of the description of the fluids. This is critical in the simulation of micellar processes as well as other enhanced oil recovery processes.

2.2 Review of Compositional Simulators

Compositional simulators have been used by many authors $^{60-86}$ to simulate reservoir behavoir.

Kossack and Bilhartz⁷³ constructed a miscible, five-component (i.e. oil, water, surfactant, polymer, and preflush), finitedifference reservoir simulator to conduct a sensitivity study of micellar flooding of reservoirs with different heterogeneities. In their simulator, the pressure equations are solved implicitly using either Gaussian elimination or the strongly implicit procedure and the saturations then are calculated explicitly. This simulator simulates the effects of adsorption of surfactant and polymer, permeability reduction, generation of miscibility, and the mixing of miscible fluids.

Nolen^{//} developed a three-dimensional, multi-component, compositional simulator focusing on the study of the consistent and accurate treatment of fluid properties and phase behavior. He also used the implicit pressure, explicit saturation, finite-difference technique to solve the governing equations. He concluded that consistent fluid properties are required to perform accurate compositional simulations on fluids that are near their critical state.

In his study of interphase mass transfer phenomena in a reservoir, MacDonald⁷⁵ developed a finite-difference, compositional simulator to solve the diffusivity equations for the oil, gas and

water phases using an implicit pressure-explicit saturation technique. The mass transfer between phases is accounted for implicitly by an interative solution with the pressure distribution equation. In an example study in a nine-component system, he stated that the compositional simulator required 10-20 times more computation time than required by a more conventional solution-gas type reservoir simulator. He also stated that the phase behavior algorithm accounted for most of this additional computation time.

Two companion chemical flooding simulators were developed by Chase⁸⁶ (a variational model) and Todd and Chase⁸² (a finitedifference model). Basically, the finite-difference model solved the governing equations up to n-components and three fluid phases. Recovery mechanisms of swelling, solubilization and interfacial effects were presented. Physical dispersion can be simulated with a reasonable number of grid blocks because of the second-order accuracy in space discretization. An earlier version of this model was used in the design of the Gary Operating Company/DOE micellar-polymer demonstration pilot undertaken in the Bell Creek Field⁸¹. It was also used by Gupta³⁸ in this study of dispersive mixing effects on the Sloss Field micellar system. The variational model, on the other hand, solves from two to six coupled nonlinear parabolic partial differential equations in two space dimensions and time. Variable order function spaces were considered; however, when the local accuracy was not a

problem, a piecewise bilinear function spaces was employed. Due to the high accuracy formulation used, this model allows the tracking of small slugs of material from injector to producer without numerical dispersion. In addition, the grid orientation effects could be eliminated by proper use of the variational formulation. Computer results showed sharp concentration fronts using the variational model compared with the use of a finite-difference program using an equivalent spatial discretization.

Pope and Nelson's⁶⁰ one-dimensional, compositional simulator used an explicit finite-difference technique to describe a chemical flooding process of up to six components and three phases. Their simulator emphasizes such effects as interfacial tension, cation exchange, chemical slug size, polymer transport, and phase behavior. This simulator has been modified and extended to include additional effects^{61,149,150}. The efficiency of the oil displacement has been calculated as a function of slug size, polymer drive size, surfactant concentration, phase type, relative permeability, dispersion, adsorption of surfactant and polymer, amount of surfactant injected, etc. However, many other important factors such as inaccessible pore volume, permeability reduction, non-Newtonian behavior, effect of alcohol, phase behavior with polymer, etc. were not investigated. Also, additional studies of preflooding, salinity gradient, aqueous versus microemulsion type slugs, dispersion,

polymer grading, mobility control criteria and optimization, and phase behavior are all called for. Some of these factors were studied in this work.

Pang and Caudle⁷⁸ developed a multi-dimensional, multicomponent, multi-phase model to simulate the micellar/polymer process. Their model takes into account capillary pressure, unsteadystate flow of fluids, and pressure-dependent and concentrationdependent variables such as average mass velocity, effective dispersivity and formation volume factor that many compositional models do not. For the one-dimensional case, the model treats two fluid phases (i.e. oleic and aqueous) and up to five components (i.e. oil, brine, surfactant, polymer and fresh water). Surfactant partitions in both phases, and other components (i.e. brine, polymer and water) are assumed to be only in the aqueous phase. One published oil recovery experiment was matched for the oil cut and the oil recovery. No two-dimensional results were available.

Two two-dimensional micellar/polymer simulators were developed at The University of Texas at Austin. One is a finite-difference model developed by $Hong^{70,79}$ and the other is a streamline model developed by $Wang^{84,85}$. Both are multi-component, multi-phase, compositional simulators and use similar phyical properties routines as used in the one-dimensional simulator which is also available at The University of Texas at Austin. Hong's simulator is

capable of simulating reservoir heterogeneity, crossflow, dispersion, injection rate, and various process variables. However, this simulator is limited by storage requirements to relatively smallereservoir problems. Wang's simulator involves both streamline and finitedifference techniques and is capable of simulating large field scale micellar/polymer processes.

2.3 Review of The Treatment of The Convection-Diffusion Equation

The numerical treatment of the convection-diffusion (C-D) equation is important and is investigated by numerous authors $^{88-100}$. In general, a numerical dispersion term is always involved in the discretized C-D equation and may be employed to represent the physical dispersion 87,91,92 . However, this representation may not be an adequate approximation of the real physical system. It is then necessary to eliminate the numerical dispersion in order to introduce the real physical dispersion into the simulation.

Usually, the numerical dispersion can be reduced to a less significant level by using a higher order of numerical approximation. But unfortunately, this will simultaneously increase the computation time and sometimes will present oscillations near the vicinity of a large gradient of the dependent variable. Improved techniques for treating this C-D equation have been reported $^{86-100}$. Garder <u>et al</u>⁸⁸ used the method of characteristics to eliminate
numerical dispersion. However, the calculation of moving points that must be tracked in his method is somewhat complicated. In addition, the problem of the stability of a time step limitation is involved due to the explicit form employed. Naiki⁹⁴ applied a similar technique to study polymer flooding in stratified reservoirs. He claimed that the method of characteristics used in solving the convection-diffusion equations provided a good numerical approximation for a wide Peclet number range and grid size.

The use of the variational method was reported by Price <u>et al</u>.⁹⁶ in reducing numerical dispersion. They claimed that the use of their method yielded greater accuracy in less computation time than the use of the method of characteristics. But again, oscillation still is a problem. Other methods such as the truncation cancellation procedure (TCP) proposed by Laumbach⁹³ and Chaudhari's method⁸⁷ introduced an extra term to cancel the numerical dispersion resulting from the truncation error of the convection term.

The idea of Laumbach's method is to cancel a portion of the error in the convective term with that in the accumulation term. He introduced an arbitrary parameter w. By adjusting w, the second-order truncation error in space and time can be eliminated by each other and the final equation obtained fourth-order accuracy in time and space as the Peclet number becomes large.

Chaudhari, on the other hand, introduced an addition of a

negative dispersion term to the continuity equation. The negative dispersion term, which is called the numerical dispersion coefficient, depends on the flow velocity, the time-step size and the block size. The approach eliminates almost all the numerical dispersion and leaves only the effect of the physical dispersion in the solution. The procedure is also extended to multi-dimensional systems.

Todd and Chase⁸² used an automatic time-step size control in their chemical flooding simulator. This method varied the time-step size based on the relative changes of variables during the last time step. The same technique was also used by Coats^{65} in a steam flood simulator and Grabowski <u>et al</u>⁶⁹ in a general purpose thermal model for in-situ combustion and steam processes. This method is not the same as the semidiscrete method used by Sepehrnoori and Carey⁹⁸, and Ohno¹⁵⁰. Basically, in the semidiscrete method, only the spatial variable, but not the time variable, is discretized. As a result, various integration techniques can be used to solve the resulting system of ordinary differential equations. Time-step size can be controlled and varied without sacrificing accuracy. A large timestep size can be selected in the region of small local error; therefore, computation time can be saved.

2.4 Review of Micellar/Polymer Flood Experiments

Numerous micellar/polymer flood experiments have been

conducted in the laboratory to study the process and to obtain optimal oil recovery. Emphasis has been placed on collecting detailed experimental data. Only a few of these will be discussed here.

Healy <u>et al</u>.³⁹ conducted a series oil recovery experiments in Berea cores to study the rate dependence effect. Microemulsions, both continuous and as slugs, were injected at various flow rates. They found that for continuous injection of microemulsions of different compositions, the rate dependence of oil cut and oil breakthrough was marked at relatively high interfacial tension, whereas the low interfacial tension floods showed much less rate dependence. Differential pressure was measured, to verify adequate mobility control, however, only the oil cut and oil recovery data were published. For some cases, a surfactant production curve was also reported. Most of their runs were at constant salinity. Tracers of tritium, sulfur-35 and C-14 were used. However, sulfur-35 and C-14 were not used simultaneously due to their similar beta energy spectra.

In his study of sulfonate-polymer interaction, Trushenski⁵⁶ conducted a series of oil recovery experiments using Berea cores ranging from 4 to 16-foot long. He found that the sulfonate-polymer incompatibility can be controlled by careful selection of the sulfonate, co-surfactant, water and salt concentrations in the micellar and mobility buffer banks. Isopropyl alcohol (co-surfactant) and ethanol (tracer) were added to the micellar and polymer slugs respectively.

Both oil cut and concentrations of tracer, alcohol, sulfonate and polymer were reported. Phase changes with polymer present were extensively studied. Comparative mobility was also measured.

Two laboratory designs of the Bell creek micellar/polymer pilot project were conducted by $Holm^{46}$ and Rathmell <u>et al</u>⁵² The former design was a high surfactant concentration, small volume, soluble oil type of slug while the latter was a low surfactant concentration, large volume, aqueous type of slug. Oil cut, cumulative oil recovery and surfactant production histories were reported. Simulation efforts were also made to match the laboratory results⁸¹. The oil cut and cumulative oil recovery were properly matched but not the early breakthrough of the surfactant. The reason for the disagreement of the surfactant breakthrough was attributed to the improper simulation of the complex polymersurfactant interaction.

Hedges and Glinsmann^{30,42} conducted oil recovery experiments to study the optimal salinity design (called unique salinity). The experiments were conducted using 3 inch diameter, 3-foot long Berea cores operated in a rotating fashion to reduce the gravity effect. Aqueous slugs were injected followed by polymer drive slugs at the same salinity. Volume fractions and interfacial tensions were measured. Sodium tripolyphosphate and sodium carbonate were added to the preflush as well as the surfactant slug to prevent large

surfactant losses. Polymer solution was graded back logarithmically by continuous dilution of the injection polymer. Phase volume studies were done at a one-to-one ratio of injection slug, usually at optimal salinity, to oil to provide a means of identification of injection slug composition. Usually three phases developed because the injection slug was at optimal salinity. Unfortunately, the mobility ratio between the oil bank and injection slug was not reported.

Gupta³⁸ presented results of laboratory experiments and computer simulation studies of the micellar/polymer fluids injected in the Sloss field, Nebraska. He found: 1) the dispersion coefficient for the partitioned sulfonate in the oil phase can be an order of magnitude larger than that in the water phase, and 2) polymer in the injected micellar fluid does not necessarily provide the needed viscosity for displacement where a sulfonate-rich oil phase is generated. The breakthrough of sulfonate was much earlier than polymer and the produced sulfonate was concentrated in the oil phase. A two-phase, compositional finite-difference simulator was used to simulate the experimental results. The two-phase model was used because only a narrow three-phase region was present.

CHAPTER III

DESCRIPTION OF SIMULATION MODEL CHANGES

The capability of a simulator to match the complex behavior of the micellar/polymer flooding process depends on both the physical property models and the numerical solution techniques employed. The models which are considered suitable to the simulator should be simple and easy to interpret for a variety of experimental data. The numerical techniques to be selected must provide accurate and stable solutions.

3.1 Inaccessible Pore Volume

It has been observed experimentally $^{35,55,101-104}$ for flow in porous media that polymer molecules usually flow faster than the solvent or smaller non-interacting components such as chloride in the solution. This phenomenon is called the inaccessible pore volume (IPV) of the polymer.

In general, the amount of inaccessible pore volume strongly depends on the characteristics of the porous medium, especially its permeability, and to a lesser degree on polymer type and concentration, electrolyte, temperature, and velocity. Lower permeabilities

result in larger inaccessible pore volume. Other factors, such as polymer gels, trapped phases, surfactant/polymer interaction, and emulsions may be significant and sometimes may completely dominate the effect of IPV. Dawson and Lantz¹⁰² in their study of IPV observed that on the order of 30% of the pore volume may be inaccessible. To account for this effect, an effective pore volume should be introduced in the polymer component mass balance equation. It should be pointed out, however, that these were single-phase flow experiments, so the other factors mentioned above were not present. Also, an apparent inaccessible pore volume of 30% even in this type of experiment does not imply that 30% of the pore volume is not contacted by the polymer, but rather only that the polymer velocity was 30% higher than for a reference tracer. Although several studies have been done, the detailed mechanisms are not well understood and modelled. But it seems likely that most of the effect is caused by a pore wall exclusion of the polymer molecule relative to the very small molecules such as water that make up the polymer solvent. Only a very small fraction of the pores, probably less than 3%, are actually too small for the polymer molecules to enter in the typical 200 or 300 md Berea core experiment. There may be a rheological component as well, since the shear rate is considerably different in different parts of a given pore and also from pore to pore. The amount and type of retention probably affects

the inaccessible pore volume as well. For example, an adsorbed polymer coil effectively excludes a certain volume of the pore to further penetration by a mobile polymer coil. None of these phenomena are directly modelled here, but rather a velocity correction factor is inserted as below, which is intended to model the lumped result, whatever the cause.

For our problem the governing equation can be written (see Appendix A)

$$\phi_{i} \frac{\partial \tilde{C}_{i}}{\partial t} + U_{T} \frac{\partial}{\partial x} \{ \sum_{j} (f_{j}C_{ij} - \alpha_{j}f_{j} \frac{\partial C_{ij}}{\partial x}) \} = 0$$
(3.1)

where,

i = 1, 2, ..., n_c

$$\hat{C}_{i} = (1 - \hat{C}_{3}) C_{i} + \hat{C}_{i}$$

 $C_{i} = \sum_{j=1}^{3} S_{j}C_{ij}$

The inaccessible pore volume is usually reported as a ratio to the total pore volume as follows

$$\phi_{i,inacc} = \frac{\phi - \phi_i}{\phi} = 1 - \frac{\phi_i}{\phi}$$
define,
$$\phi_{i,eff} = \frac{\phi_i}{\phi}$$

Using this same factor $\phi_{i,eff}$ in eq. (3.1) and converting to non-

dimensional form in the usual way, we get

$$\frac{\partial C_{i}}{\partial t_{D}} + \frac{1}{\phi_{i,eff}} - \frac{\partial}{\partial x_{D}} \{ \sum_{j} (f_{j}C_{ij} - \alpha_{Dj}f_{j} - \frac{\partial C_{ij}}{\partial x_{D}}) \} = 0 (3.2)$$

Single-phase polymer solution with a tracer was simulated as a test run. The polymer slug was injected continuously into the reservoir which originally contained only water. It was assumed that the inaccessible pore volume for polymer was 20% and there was no polymer absorption. The aqueous concentration profile at 0.5 P.V. injection (Figure 3.1) shows both polymer and tracer concentrations. The 50% value of tracer concentration appeared at about 0.5 fractional distance and the 50% value of polymer concentration is at about 0.625 fractional distance, as expected. The inaccessible pore volume for surfactant is also modelled in a similar way even though there is little evidence that the inaccessible pore volume for surfactant is significant.

3.2 Permeability Reduction

Polymers such as partially hydrolyzed polyacrylamide (HPAM) adsorb on the porous media and reduce its own mobility beyond what could be expected from the viscosity alone, and also reduce the mobility of a brine following the polymer. The former is called permeability reduction and the latter is called residual resistance factor. These are defined as follows:

Permeability reduction factor (R_k) ,

$$R_k = \frac{Effective permeability of water}{Effective permeability of polymer solution}$$

Residual resistance factor (R_{rf}) ,

R_{rf} = Brine mobility before polymer flood Brine mobility after polymer flood

Many workers $^{105-126}$ have observed and investigated these phenomena.

A model is proposed here to simulate the reduction assuming that:

- . R_k is a function of polymer concentration only for any given permeability, porosity, temperature, polymer, surfactant, alcohol and velocity,
- . only the polymer-rich phase is affected by this reduction in permeability,

 R_{ν} is irreversible.

For partially hydrolyzed polyacrylamide, the permeability reduction factor R_k can be represented by the following equation:

$$R_{k} = 1.0 + \frac{(R_{k,max} - 1.0) b_{p}C_{4j}}{1.0 + b_{p}C_{4j}}$$
(3.3)

where C_{4j} refers to the polymer concentration in the polymer-rich phase only. This is always the most water-rich phase. When C_{4j} decreases, R_k does not, since the reduction is assumed irreversible and permanent.

This equation has a form similar to that of a polymer adsorption isotherm. When the polymer concentration C_{4j} approachs zero, the value of R_k approachs one, and when C_{4j} approachs infinity, R_k approachs $R_{k,max}$. Figure 3.2 shows the relationship between R_k and C_{4j} with b_p as a parameter. The reduction effect is usually small for xanthan gum, but the same equation could be used if desired. In general, the dependence on other variables such as permeability would be necessary, but in this 1-D homogeneous simulator, these are fixed for a given run. Since they do vary from run to run, so the input parameters $R_{k,max}$ and b_p will also. See Naiki⁹⁴ for a description of how these other variables can be handled.

3.3 Non-Newtonian Rheology of a Polymer Solution¹⁰⁵,112-115,117, 120,124-126

A non-Newtonian fluid is defined as a fluid in which the shear stress is not proportional to the corresponding rate of shear. Polymer solutions used to control mobility in enhanced oil recovery typically exhibit non-Newtonian behavior. A modified

Darcy's law for a non-Newtonian fluid can be formally experssed in terms of apparent viscosity, i.e.:

$$\mu_{app} = \frac{k_p \Delta P}{U L}, \quad and \quad U = q/A \quad (3.4)$$

In the above expression, ΔP is the pressure drop across the entire length L, k_p is the permeability to polymer and U is the volumetric flux of the fluid.

Usually, the apparent viscosity of a polymer solution is a function of shear rate, polymer concentration, and electrolyte concentrations. These will be discussed as follows:

3.3.1 Shear Rate Dependent Viscosity

The viscosity curve of a dilute polymer solution with varying shear rate can be divided into three major regions (Figure 3.3). At low shear rate, the viscosity is a constant. At intermediate shear rate, the viscosity decreases with increasing shear rate. At high shear rate, the viscosity either reaches a limiting value which is greater than or equal to the viscosity of the solvent (e.g. xanthan gum), or for some polymers, shows "dilatant" or "viscoelastic" behavior, in which case the apparent viscosity increases with increasing shear rate (e.g. HPAM). In the intermediate region, the viscosity of the fluid can often be modelled by a power-law equation 120 . Other models include Ellis's, Oldroyd's, Bogue's and Meter's 115,120 .

Meter's equation is written as:

$$\mu = \mu_{\infty} + \frac{\mu_{0} - \mu_{\infty}}{1 + (\dot{\gamma}/\dot{\gamma}_{m})^{p_{\alpha}-1}}$$
(3.5)

If the value of μ_{∞} is very small compared with $\mu_{0},$ then eq.(3.5) can be simplified to:

$$\mu = \mu_{\infty} + \frac{\mu_{0}}{1 + (\dot{\gamma}/\dot{\gamma}_{1})^{p_{\alpha}-1}}$$
(3.6)

Xanthan gum viscosity simulated using eq.(3.6) is shown in Figure 3.4.

An equivalent shear rate, $\dot{\gamma}_{c}$, for flow in a porous medium must be calculated in order to obtain the apparent viscosity. For single-phase, one-dimensional flow of a power-law fluid¹¹⁰

$$\dot{\gamma}_{c} = \left(\frac{3n'+1}{4n'}\right)^{\frac{n'}{n'-1}} \left(\frac{4V}{R_{eq.}}\right)$$
 (3.7)

where,

 $V = \frac{U}{\phi}$, $R_{eq.} = \sqrt{(8k/\phi)}$

In a one-dimensional, multiphase flow system, we generalize this

by setting $v_j = u_j/\phi S_j$, where j refers to the jth phase. By definition, $u_j = U_T f_j$, thus

$$v_j = \frac{U_T f_j}{\phi S_j}$$
, and

$$R_{eq.,j} = \sqrt{(8k_j/\phi S_j)}, \quad j = 1, 2, ..., n_p$$
 (3.8)

As a result,

$$\dot{\gamma}_{cj} = \left(\frac{3n'+1}{4n'}\right)^{\frac{n'}{n'+1}} \left(\frac{4v_j}{R_{eq.,j}}\right)$$
 (3.9)

dividing eq.(3.9) by eq.(3.7),

$$\frac{\dot{\gamma}_{cj}}{\dot{\gamma}_{c}} = \frac{R_{eq.} v_{j}}{R_{eq.,j} v} = \sqrt{(f_{j}^{2} k)/(S_{j} k_{j})}$$
(3.10)

by definition, $k_j = kk_{rj}$, thus, eq.(3.10) becomes,

$$\dot{\gamma}_{cj} = \dot{\gamma}_{c} \sqrt{(f_{j}^{2}/(k_{rj}S_{j}))}$$
 (3.11)

3.3.2 Concentration and Salinity Dependent Viscosity

Figure 5.3 shows an example plot of viscosity versus polymer concentration. These curves can be approximated by polynomials. According to Huggin's equation¹²⁷ for a dilute polymer solution,

$$\frac{\mu_{sp}}{C_p} = \left[\mu\right] + k' \left[\mu\right]^2 C_p \qquad (3.12)$$

This is a second order polynomial when viscosity is expressed as a function of polymer concentration. For polymer concentrations above 500 ppm or so, a third-order term (C_p^3) is sometimes required.

The viscosity of hydrolyzed polyacrylamide (HPAM) is very sensitive to salinity, especially at low salinity^{117,128}. On a log-log plot of polymer viscosity versus salinity, a linear relationship is often obtained in the range of interest. Three examples of HPAM (i.e. Pusher 700^{129} , Cyanatrol⁸¹ and Hi-Vis) viscosity as a function of salinity are shown on Figure 3.5. For xanthan gum, however, the viscosity depends only slightly on salinity and sometimes has the opposite slope except at very low salinity. This is reported by Jeanes¹³⁰ in her study of the rheology of B-1459 (xanthan gum), and by Tsaur¹²⁸. For practical purposes, only salinities higher than about 100 ppm are of interest.

In the simulator, the model developed calculating the polymer viscosity at a certain shear rate as a function of polymer concentration and salinity is as follows:

$$\mu_{po} = \mu_{w} \{1 + (A_{p1}C_{4j} + A_{p2}C_{4j}^{2} + A_{p3}C_{4j}^{3}) C_{SEM}^{S_{p}}\}$$
(3.13)

The above equation is used for any polymer concentration and for salinity ranging from a low value C_{SE1} , say 0.01 meq/ml, to infinity. Actually, the salinity C_{SEM} is set equal to C_{SE1} whenever the salinity is lower than C_{SE1} . In other words, the model implies that the polymer viscosity is constant when the salinity is lower than C_{SE1} . The reason for this is that the model is not valid at very low salinity. The viscosity approachs either zero or infinity depending on whether the sign of the slope S_p is positive or negative. This is physically unrealistic. Although in practice such a low salinity is not usually encountered, we have to allow for it.

To estimate the parameters (i.e. A_{p1} , A_{p2} , A_{p3} and S_p) in eq.(3.14), zero shear rate is assumed. If the raw data reported are not at zero shear rate, they have to be corrected to zero shear rate values by Meter's equation. Usually the parameter S_p is easy to obtain and is always determined first by simply reading off (on log-log plot) the slope of the polymer viscosity versus salinity (Figure 3.5). For example, the slope of Cyanatrol is about -0.66, and the slope of Hi-Vis is about -1.0. Other parameters, i.e., A_{p1} , A_{p2} and A_{p3} , can be obtained by either trial and error or solving three simultaneous equations. For the Cyanatrol case, the viscosities were reported at 10⁻¹ (Figure 5.3). They were corrected to zero shear rate values using Meter's equation (the dashed curve).

3.4 The Effects of Alcohol

Many different kinds of alcohol are used in micellar/ polymer flooding. The general functions of the alcohol are to increase the surfactant solubility and adjust the microemulsion phase viscosity. The alcohol affects the adsorption of both surfactant and polymer and also alters the phase behavior. The change in the phase behavior is also reflected in the interfacial tension, which increases.

To study the effects of alcohol, Healy, Reed and Stenmark⁴⁰ used a ternary diagram to represent a surfactant/alcohol system. They utilized a fixed ratio of surfactant to alcohol as a pseudocomponent in the study of phase behavior. Other authors¹⁶, ¹³¹⁻¹³³ applied the "optimal salinity" concept to study the effect of alcohol. Recently, quaternary representation of phase behavior ¹³⁴⁻¹³⁷ was introduced, which demonstrates the nature of phase behavior in a more complicated but more precise way.

Because of the importance of alcohol, it was made a new component. To do this, some additional assumptions were made:

- . no adsorption of alcohol on rock phase,
- . no chemical reaction between alcohol and other components,
- . no coupling between the effects of alcohol and the other components.

In the current modified simulator, the alcohol volume is counted

and is combined with surfactant as a new pseudocomponent in determining the ternary phase diagram. But the effects of alcohol and surfactant on phase viscosity are different. The contribution of alcohol on phase viscosity was modelled by adding a new term $(\alpha_6 c_{7,i})$ as follows:

$$\mu_{j} = \mu_{p} C_{1j} + \mu_{0} C_{2j} + \alpha_{1} C_{3j} + \alpha_{2} C_{1j} C_{2j} + \alpha_{3} C_{1j} C_{3j} + \alpha_{4} C_{2j} C_{3j} + \alpha_{5} C_{1j} C_{2j} C_{3j} + \alpha_{6} C_{7j} \quad (3.14)$$

where, j = 1, 2, 3

The effect of alcohol on surfactant adsorption was not modelled. Engelsen¹⁴⁹ added a term to the effective salinity equation to account for the "dilution effect" of alcohol. He based it on Salager's equation¹⁶ for the shift in optimal salinity with alcohol concentration. The effect of alcohol on IFT was assumed to be implicit in its effect on phase behavior. Obviously, all of these assumptions and approximations need to be refined.

3.5 Physical Dispersion

The original 1-D compositional simulator approximated physical dispersion by numerical dispersion. In this study, a simple finite-difference scheme, three-point center for the dispersion term and two-point backward for the convection term, was selected. The governing equation (eq.(A.17)) is derived in Appendix A.

$$\frac{\partial}{\partial t_{D}}(C_{i}) + \sum_{j} \left\{ \frac{\partial}{\partial x_{D}}(f_{j}C_{ij}) - \alpha_{Dj}\frac{\partial}{\partial x_{D}}(f_{j}\frac{C_{ij}}{x_{D}}) \right\} = 0 \quad (A.17)$$

For the physical dispersion term, $F_{ui} = \sum_{j} \alpha_{Dj} \frac{\partial}{\partial x_{D}} (f_{j} \frac{\partial C_{ij}}{\partial x_{D}})$,

a three-point central difference formula for kth block was used,

$$F_{ui} = \sum_{j}^{\alpha} \frac{\alpha_{Dj}}{(\Delta x_{D})^{2}} \{f_{jk+\frac{1}{2}}(C_{ijk+1} - C_{ijk}) - f_{jk-\frac{1}{2}}(C_{ijk} - C_{ijk-1})\}$$
(3.15)

Using single-point upstream weighting, $f_{jk+\frac{1}{2}} = f_{jk+1}$ and $f_{jk-1} = f_{jk}$,

$$F_{ui} = \sum_{j} \frac{\alpha_{Dj}}{(\Delta x_{D})^{2}} \{f_{jk+1}(C_{ijk+1} - C_{ijk}) - f_{jk}(C_{ijk} - C_{ijk-1})\}$$
(3.16)

For the convection term, $F_{Gi} = \sum_{j} \frac{\partial}{\partial x_{D}} (f_{j}C_{ij})$, a two-point

backward difference formula was used for all blocks, i.e.:

$$F_{Qi} = \sum_{j} \{f_{jk+1} c_{ijk+1} - f_{jk} c_{ijk}\}$$
(3.17)

The above numerical treatment will give only first order accuracy in space for the convection-diffusion equations. However, a negative dispersion can be used as input to sharpen the concentration front.

For small time steps (actually for $\Delta t_D / \Delta x_D <<1$), the effective dispersivity is given by:

$$(\alpha_{\rm D})_{\rm eff} = (\alpha_{\rm D})_{\rm phy} + (2N)^{-1}$$
 (3.18)

Thus, if one wishes to produce an effective $\alpha_{\rm D}$ of 0.025, a value typical of core floods, N must be on the order of 200 for the numerical contribution, $(2N)^{-1}$, to be below 10%. In other words, the Peclet number, Pe, must be larger than 2N = 400. The actual effective dispersivity, $\alpha_{\rm D}$, was calculated from the equation¹³⁸

$$\alpha_{\rm D} = \left[\frac{\lambda_{90} - \lambda_{10}}{3.625} \right]^2 \tag{3.19}$$

where

 $\lambda = \frac{t_{D} - 1}{(t_{D})^{\frac{1}{2}}}$

The value of ${\rm t}^{}_{\rm D}$ at the 90% and 10% normalized concentration values

can be read off of a history plot directly. A more precise method is to make a plot of C/C_0 for a trace component on probability paper (Figure 3.7). To calculate α_D from a profile plot, the following equation,

$$\alpha_{\rm D} = \frac{1}{t_{\rm D}} \left[\frac{x_{\rm D,90} - x_{\rm D,10}}{3.625} \right]^2$$
(3.20)

can be used. A non-interacting aqueous phase tracer is best. For single-phase flow, even if a residual phase is present, the probability plot should give a straight line since the solution to the convection-diffusion equation is an "error function".

Simulated single-phase tracer displacements for different dispersivities have also been made in order to check the quality of the numerical solution. This is the same as solving the convection-diffusion equation. The results of these simulations are presented in Figure 3.6. Oscillation was observed for run 34 in which the negative physical dispersivity of -0.01 is close to the theoretical numerical dispersivity of 0.012. This suggests that the negative physical dispersivity can not exceed the numerical dispersivity to obtain a stable numerical solution. Figure 3.7 shows two straight lines in the range of 10% to 90% of tracer concentrations for physical dispersivities of 0.0 (run 265) and 0.02 (run 266). The midpoint values of the tracer concentrations are at a fractional distance slightly greater than the expected values of 0.5. The actual dispersivities have also been calculated and are very close to the total theorectical dispersivities (Table 3.1).

Simulations have been conducted to study the dispersion model when varying the number of grid blocks and the dispersivity (Table 3.2). The test runs were micellar/polymer floods with Type II(-) phase behavior. An aqueous solution was injected continuously with tracer in it. The resulting tracer concentration profiles at 0.5 P.V. were available (Figure 3.8 and 3.9). Compare runs 89 and 100. No physical dispersion was input for run 89 ($\alpha_D = 0$) and 20 blocks used (N = 20). Therefore, a numerical dispersivity of 0.025 was expected and did actually result. For run 100, α_D was input as 0.025, and N made large to minimize numerical dispersion. The actual α_D turned out to be 0.021, which is close to the expected 0.025.

3.6 The Derivation of the Pressure Equation

Pressure profiles and pressure history of a micellar/ polymer flooding study are important. They reflect the relationship between volumetric flow rate, permeability and viscosity at various times and positions. From the change of pressure, the mobility control can also be studied.

In this section, the pressure equation is derived in order to simulate the pressure history. To do this, in a one-dimensional flood, the assumptions are:

- . permeability and viscosity are not a function of pressure under the operating conditions,
- . gravity and capillary pressure are negligible,
- . constant flow rate.

The point-centered grid system is selected. At the initial time, only water and oil are present, so total relative mobility, $\lambda_{\rm rT},$ is:

$$(\lambda_{r\bar{l}})_{t=0} = \frac{(k_{r1})_{t=0}}{\mu_{w}} + \frac{(k_{r2})_{t=0}}{\mu_{o}}$$
 (3.21)

where $k_{r1} = k_{r1}^{0} s_{1R}^{e_1}$

$$k_{r2} = k_{r2}^{0} (1 - S_{1R})^{e_2}$$

$$S_{1R} = \frac{S_1 - S_{1r}}{1 - S_{1r} - S_{2r}}$$

To calculate the relative pressure drop between blocks ${\bf k}_1$ and ${\bf k}_2$, $(\Delta P_{r,t})_{k_1,k_2}$ can be expressed as: k

$$(\Delta P_{r,t})_{k_1,k_2} = \sum_{k=k_1}^{k_2} (\lambda_{rT,t=0})_k / \sum_{k=k_1}^{k_2} (\lambda_{rT,t})_k$$
 (3.22)

This model provides a means of recording the relative pressure drop anywhere in the reservoir simply by setting ${\bf k}_1$ and ${\bf k}_2$ at the desired blocks.

TABLE 3.1

COMPARISON OF ACTUAL DISPERSION WITH THEORETICAL DISPERSION FOR TRACER DISPLACEMENT AT 100% BRINE SATURATION

Run No.	Numerical ^Q D	Input Physical ^Q D	Theoretical Total ^Q D	Theoretical Peclet No.	Actual Peclet No.	
265	0.012	0.0	0.012	83	78	
266	0.012	0.020	0.032	31	32	
036	0.012	-0.005	0.007	142	135	
034	0.012	-0.010	0.002	500	-	

TABLE 3.2

COMPARISON OF ACTUAL DISPERSION WITH THEORETICAL DISPERSION FOR TRACER DISPLACEMENT AT RESIDUAL OIL SATURATION

, ÷.

Run	0ld New Program Program Input		Theoretical Time		Actual	CPU	Maximum Material Balance	
	∞ _D N [∶]	αD	N	Step (P.V.)	αD	αD	Time (Sec)	Error (%)
92	40			0.001	0.012	0.0108	39.030	0.05
91		0.0	40	0.001	0.012	0.0108	47.528	0.05
89	20			0.001	0.0245	0.0247	28.677	0. 0 5
9 8		0.0	. 200	0.0001	0.00245	0.00135	512.229	0.001
100	C	0.0245	200	0.0001	0.02695	0.0212	519.019	4.356







FIGURE 3.2 PEAMEABILITY REDUCTION FACTORS VERSUS POLYMER CONCENTRATION



ddo*r*/ 607



AT VARIOUS CONCENTRATION





PROFILES AT 0.50 P.V. FOR AQUEOUS PHASE

FIGURE 3.6 COMPARISON OF CONCENTRATION PROFILES AT 0.5 P.V. FOR DIFFERENT PECLET NUMBERS







FIGURE 3.8

RUN 89 AQUEOUS CONCENTRATION PROFILES AT 0.5 P.V.





CHAPTER IV

EXPERIMENTAL WORK

4.1 Introduction

During the history matching study, discussed in the Chapter V, the main problem was the lack of input data for the simulator, especially those of partially incomplete phase behavior, interfacial tension, surfactant adsorption, relative permeability, phase trapping, etc. These data were estimated from other published studies in which similar systems were used or, when no such data existed, values of a reasonable magnitude were selected arbitrarily. Obviously, this is undesirable and a more definitive and reliable result based on more experimental data should be the objective. The main purpose of this laboratory study was to obtain more such data. The more data that are obtained, the more confidence can be placed on the simulation result.

Basically, there were two sets of oil recovery experiments conducted (these are summarized in Table 4.1):

 Runs MPF-01 and MPF-05 were modifications of one of the experiments done by Hedges and Glinsmann⁴² (Exp. No. 24212-11 with TRS10-410/ n-Butanol/n-Decane/brine). However, the apparent differences were:
- a) The cores used in these experiments were 2 inches by 2 inches square and 3 feet long, whereas their cores were 3 inches in diameter and 3 feet long;
- b) These experiments were conducted statically, whereas their cores were operated in a rotating fashion with a speed of 0.25 rpm to eliminate or at least reduce the gravity effect;
- c) Their polymer slug was graded back logarithmically by continuous dilution of a 2250 ppm prepared polymer solution. In this work, the polymer slug was divided into four subslugs at concentrations of 1900, 1200, 700, and 300 ppm (Figure 4.1). However the total amount of polymer injected was maintained about the same as they injected (see Appendix D for details).

The following additional data were collected in this work: a) The dispersion coefficient for each core was measured. From the dispersion curves, the uniformity of the cores can be assessed;

- b) The pressure drop across a segment of the core as well as the entire length of the core was measured by Validyne transducers. The pressure data are the best indication of the relative mobilities;
- c) Additional effluent concentrations were measured. These were sodium, calcium, magnesium, polymer, and tritium. Not all were measured in all cases, however;
- d) Furthermore, measurements were made to determine the ternary

phase behavior, microemulsion viscosity along the binodal curve, and polymer viscosity as a function of polymer concentration, salinity, and shear rate since these were not previously available. In other words, as many of the physical properties as feasible were measured to fill in the gap of input parameters for the simulator.

2) Runs MPF-02 and MPF-06 were relatively simple designs of a micellar/polymer process. The amount of surfactant employed was calculated to be the same as employed in the previous experiments. Middle phase microemulsions were injected followed by continuous polymer slugs. Due to the high surfactant concentration in the microemulsion, a relatively small slug was used. Necton 37/TRS10-410/brine middle phase microemulsion with a viscosity of 35 cp. at 30^oC was used in Run MPF-06 to obtain a favorable mobility control without the complication of adding polymer in the slug.

4.2 Experimental Set-up

The experimental set-up consists of a pump, injection sample reservoir, core, production sample collector, and pressure recording system (Figure 4.2). The pump employed was either Ruska or Zenith, which provide constant flow rate of fluid. The injection sample reservoir was either a one inch or two inch diameter, two foot long glass column. The surfactant, however, was stored in a special device which contains a diaphragm inside the reservoir (Figure 4.3) so that the driving mineral oil was separated from the surfactant solution. Brine and polymer solution were driven by mineral oil, while oil was driven by brine followed by mineral oil. This procedure was followed so that the fluid going through the pump would always be mineral oil and the fluid being injected into the core would always be in the air bath at 30° C. The simplified diagram of Figure 4.2 does not reflect these details. This procedure is better for the pump and for the fluids going into the core. The injected oil, brine, and polymer solutions were aspirated and degased into the sample columns by applying a vacuum at the top of the columns.

Plastic end-pieces were mounted permanently at the time the epoxy coating was applied to the core. A nylon screen between the end-piece and core face allowed a uniform distribution of fluids at the core faces. Two pressure taps, 1/8 inch NPT fittings, were mounted on the top of the core and divided the core into three equal regions. To provide a means of zeroing pressure, several by-pass lines were added. As shown on Figure 4.2, to zero the pressure on transducer II, both valves 4 and 5 should be closed with valve 7 opened. All the transducers were calibrated against Heise pressure gauges. A linear relationship was observed between the actual pressure and the recorded pressure during the calibration procedure.

The production samples were collected in 10 ml graduated

test tubes using a Gilson automatic sample collector. Rubber stoppers were used to cap the collected samples. It was found that some unknown materials in the rubber stoppers could be extracted by oil. This unknown materials interfere with the surfactant analysis by UV spectrometry. Therefore, silicone stoppers were used in place of rubber stoppers for later experiments.

4.3 Chemicals

The chemicals used for these experiments were sulfonate, alcohol, oil, polymer, and salts. The surfactant, about 60% active TRS10-410, was obtained from Witco Chemical Company. Different stock samples vary in composition and, in consequence, result in somewhat different properties. The oils selected were n-decane and Necton 37. The decane was obtained from both ChemSamp Company and Phillips Chemical Company. Both sources are about 95% pure. The sample from Phillips Chemical Company produced a absorbance peak at 270 nm by ultra-violet spectrometry. This interfered with the analysis of sulfonate. The Necton 37 is a solvent-refined naphthenic oil supplied by Exxon. The alcohols used were analytical grade n-Butanol and i-Butanol. Polymer samples included Betz Hi-Vis, a hydrolyzed polyacrylamide from The Improved Oil Recovery Company (TIORCO) and Xanflood, a xanthan gum from Kelco Company. The salts used were reagent grade sodium chloride, sodium carbonate, and sodium tripoly-

phosphate. The sodium carbonate and sodium tripolyphosphate were used as sacrificial agents for reducing the surfactant adsorption. The epoxy, which consists of 70% by weight of R-828 Resin and 30% by weight of Versamid 125, is from the Ring Chemical Company.

4.4 Preparation of Core

The core must be saturated with brine, oil flooded to the residual water saturation, and waterflooded to residual oil saturation before micellar injection.

Square (2 inches by 2 inches), 4-foot long Berea samples were first cut into 3-foot long samples, then dried at 82^oC in an oven. After cooling to room temperature, they were coated with three epoxy layers. Both ends of the core were fitted with a 50 mesh nylon screen and plastic end piece to allow uniform fluid distribution. The epoxy was painted over all the core so that the end pieces and pressure taps were permanently mounted.

Pressure test for leaks and the hardness of the epoxy was performed using pressurized nitrogen. In general, the test pressure was maintained at 50 psi, which was higher than the maximum operating pressure encountered. One core, i.e. MPF-04, failed this test when several bubbles developed between the core and the coating layers. It is believed that the first coat of epoxy was too thin to hold the core surface under the test pressure.

Usually, the core was subjected to vacuum overnight to ensure that all of the air had time to diffuse out of the small pores of the core. Brine was introduced into the evacuated core from a burette until the core was at 100% brine saturation. The advancing brine front is clearly visible through the epoxy coating. The endpoint of brine saturation is taken when no change in the level of brine in the burette is observable over a minimum of a 10 minute interval. The porosity of the core can be calculated by knowing the total volume of the core and total volume of brine introduced. The measured porosities of the cores were very close to 20% of a pore volume, which agrees well with the published data for Berea rock.

The saturated core along with all other injection samples were moved into a temperature controlled air bath (at 30^OC) for at least 12 hours to reach a constant temperature. A constant flow rate pump was used to drive the brine through the core to obtain an absolute permeability measurement. The absolute brine permeability was calculated using Darcy's relationship. The cores showed permeabilities raging from 287 md to 610 md.

The Zenith pump was used at flow rates greater than 500 ml/hr. The Ruska pump was employed at lower flow rates. All samples were filtered before injecting into the core to avoid any undissolved materials in the samples which might plug the core.

A dispersion curve was determined by measuring tritium con-

centrations in the effluent samples and normalizing to the injected concentration (12,056-101,109 cpm/ml). Tritium was measured by a liquid scintillation counting technique using a Packard Model 3400 Liquid Scintillation Counter. If plotted on probability paper, a linear relationship will be obtained for an ideal dispersion curve. From the curve, the dispersion coefficient can be assessed. If the dispersion curve shows highly asymmetric appearance, this means that the core is not homogeneous and the results can not be readily interpreted. It was not desirable to use highly heterogeneous cores for this type of experiment.

The oil flood was performed at high flow rates to reach the residual water saturation. A pressure drop of about 10 psi/ft was maintained. Less than 1% final water cut and a steady pressure drop were the two requirements for stopping the oil injection. Usually, more than four pore volumes of oil were injected before reaching these requirements.

Brine was injected immediately after the oil flood at a relatively low flow rate, less than 6 ft/day. The final oil cut in this water flood was always zero and the pressure drop was steady soon after water breakthrough. The end point permeabilities were calculated for both water and oil floods. A second dispersion curve was determined at this time to double check the residual oil saturation. The core was then ready for the micellar/polymer oil recovery

experiment.

4.5 Production Sample Analysis

Production samples were analyzed using the equipment and techniques which are available in this laboratory 51,124,139,140.

Generally, the amount of oil was obtained by direct reading of the top phase volume for two-phase samples. For three-phase samples, ethanol or acetic acid was added to break up the middle microemulsion phase into two phases and the top phase was assumed to be oil.

Tritium was analyzed by liquid scintillation counting. Sodium, calcium and magnesium were measured by atomic adsorption spectrometry. Xanflood polymer concentration was measured by colorimetry¹⁴¹ which is applicable to the analysis of any simple sugars, oligosaccharides, polysaccharides, and their derivatives. When Hi-Vis was used, only viscosity of the produced phase was used to indicate polymer, even though this is not too precise, because a good technique for HPAM was not readily available in our laboratory at the time. Alcohol and water were measured by Gas Chromatography. The interfacial tension was measured by the spinning drop technique²².

4.6 Experimental Results

The core properties, injection data, and results of the oil

recovery experiments are summarized in Table 4.1.

It was found that the properties of cores MPF-01, MPF-02 and MPF-05 were similar. Their absolute brine permeabilities were at about 300 md and the relative permeabilities at residual water saturation were about 0.7. The absolute brine permeability and relative permeability at residual water saturation for core MPF-06, however, were 610 md and 0.98, respectively, which do not agree with those of the others. The middle phase microemulsions used in MPF-02 and MPF-06 were obtained by the equilibration of a large quantity of the desired overall compositions at optimal salinity. After no change of phase volume with time (ranging from days to weeks), both top, middle and bottom phases were separated and stored in 30^oC. The middle phase was used as the injection samples. The detailed experimental results for all runs are tabulated in Appendix C.

4.6.1 Run MPF-01

This preliminary experiment was similar to the experiment reported by Hedges and Glinsmann⁴² (Exp. No. 24212-11). No extensive phase behavior studies were yet available and dispersion curves were not generated. Only oil cut and cumulative oil recovery up to 0.75 pore volume were obtained. It was decided not to conduct any microemulsion analysis due to contamination of the oil phase by the addition of a red dye which was added to oil to enhance the visuali-

zation of the oil bank. Fortunately, most of the oil had already been produced before the contamination and the results could be compared with those of Hedges and Glinsmann.

During preflush, it was observed that the overall pressure drop increased steadily up to 1.5 times the waterflood pressure drop. This could be due to plugging caused by precipitation or emulsions in the presence of sodium tripolyphosphate and sodium carbonate in the preflush solution.

Before surfactant injection, a phase volume study was conducted by mixing the aqueous slug with decane at a one-to-one volume ratio. The surfactant solution involved 3 wt% of active TRS10-410; 3 wt% of n-Butanol as a co-surfactant; 0.2 wt% of sodium tripolyphosphate and 0.1 wt% of sodium carbonate as sacrificial agents to reduce the surfactant loss; and 0.86% of NaCl. The phase volume study showed that a Type II(+) phase environment was encountered instead of a Type III phase environment as reported by Hedges and Glinsmann. This difference could be the result of the use of a different lot of sulfonate from Witco than what they used. The optimal salinity was estimated to be 0.75 wt% NaCl (Figure 4.9), which is lower than the 0.86 wt% NaCl reported by Hedges and Glinsmann. This difference is not very great all things considered and is also not very important if properly taken into account. A salinity of 0.75 wt% NaCl in the slug was employed for the later

Run MPF-05.

Figure 4.4 shows the oil cut and cumulative oil recovery vs. pore volume injected for this experiment. The experimental results of Hedges and Glinsmann are also included for comparison. The oil breakthrough at about 7% of a pore volume is much early than the 18% of a pore volume as reported by Hedges and Glinsmann. Although relative permeability affects oil breakthrough, this is probably not the reason for the difference in these experiments because the relative permeabilities were probably not that much different. Since the slug is not very viscous when diluted, gravity was more likely to be the cause of the early breakthrough. Recall that they rotated their cores. Either polymer in the slug or a more viscous microemulsion would be better in this respect. Notice the later oil bank breakthrough in MPF-06 (Table 4.1). The oil cut level at about 40%, however, was very close to that of Hedges and Glinsmann's experiment.

4.6.2 Run MPF-05

Some improvements were made for this experiment in light of the information learned from the last experiment. The main change was the use of 0.75 wt% NaCl for the surfactant and polymer slugs.

Physical properties measured were ternary diagrams (Figures 4.5 through 4.8), volume fraction diagram (Figure 4.9), and inter-

facial tension (Figure 4.10). Figure 4.10 also includes data on other formulations and a comparison with the data of Hedges and Glinsmann. Although the agreement is good, there is some scatter. Relative permeability curves for water and oil (Figure 4.11) were measured by Delshad¹⁴⁰ on a different core sample than used for MPF-05 but it was from the same lot of Berea as used for MPF-05. These imbibition relative permeability curves were measured under steady state flow condition using a 2 foot Berea core. The core was set horizontally and the frontal velocity employed was 6 ft/day(q/(A ϕ)). The phase saturations were checked by both material balance and tracer study. The data points presented on Figure 4.11 were the results of material balance calculations.

Ternary diagrams were made at salinities of 0.6 wt%, 0.8 wt%, 1.0 wt%, and 1.8 wt% NaCl concentration. At 0.8 wt% NaCl, Type III behavior was observed. As shown on Figure 4.6, the squares were the invariant points calculated by material balance corresponding to the compositions indicated by the triangles. The material balance was made by assuming all of the sulfonate and alcohol were in the middle microemulsion phase. This is a convenient but not very accurate assumption, because the alcohol partitions into the lower brine phase in significant amounts for this formulation. Although not measured in most cases, from Table 4.1, Experiment MPF-02, the result measured by gas chromatography at 1.1 wt% NaCl

is seen to be only 1.0 v% IBA, versus about 3.8 v% which would have been in the middle phase (slug) if all of the alcohol had been in the middle phase. This partitioning of the alcohol means that the pseudo-ternary representation being used is not very good in this instance. One consequence of this is the large difference in the positions of the calculated invarient points such as in Figure 4.6. There are other reasons as well. There is some experimental error involved in reading the small phase volumes associated with most of the samples prepared for this purpose. Incomplete equilibration is another possible source of error. There may be some effects of the impurities in the sulfonate also.

The ternary representation was used despite all this because it appears to be consistent with the observed qualitative trends for this formulation and is the representation available in the simulator used. Furthermore, it is not clear how much this type of discrepancy really would make in the final simulated result. Only additional research using better representations can answer this question. Given all the other uncertainties in the process models, such as, for the microemulsion relative permeability and viscosity, this is not an easy question to answer. To date, the emphasis on modelling has been to treat the many complex physical properties in the simplist way that appears to be consistent with known trends and has a reasonable chance of working. This is why we treat alcohol as a separate component with respect to material

balance, adsorption, and viscosity, but not with respect to phase behavior. We know that the alcohol does not adsorb as much as the sulfonate and this is easy to account for by simply treating adsorption differently for the sulfonate than for the alcohol.

A simple but approximate empirical method for improving on the fixed pseudo-ternary representation is to allow the entire diagram to in effect shift with dilution. Specifically, C_{SE} can be made a function of alcohol as well as calcium (as done previously). In such a case, the definition of C_{SE} must be different for polymer than for surfactant. This approach is discussed elsewhere^{51,79,149}. Going to a quaternary or higher order representation is both very complex and requires far more data than usually available.

The dispersion curve showed a nice characteristic and the dispersion coefficient was calculated to be 0.22 inch for the 3-foot core, which is normal for Berea sandstone core (Figures 4.13 and 4.14). Tritiated brine was injected as water flood to reach the residual oil saturation. Brine was then injected to displace tritiated brine and generate another dispersion curve. The dispersion curve at residual oil saturation (Figure 4.15) showed about the same dispersion as at 100% brine saturation. However, due to insufficient tritiated brine injected (0.3 P.V.), the maximum tritium concentration barely reached the injected concentration. Breakthrough of tritiated brine was at 0.66 P.V. This implies a

residual oil saturation of 34%. This value is very close to that of 34.2% for residual oil saturation from material balance calculation.

The pressure drops normalized by the final pressure drop for the preflush are presented on Figure 4.16. The pressure data points plotted correspond to a time interval of five samples, except for the region of rapid change, when more data were plotted. Both pressure drops suggest an unfavorable mobility ratio between the oil bank and the surfactant slug. Clearly, once the more viscous polymer drive was started, the pressure drop increased. But because the polymer is graded back in steps, it soon decreased again. The normalized overall pressure drop fell below 1.0 at 0.6 P.V., which means the drive was not stable after that point. The normalized pressure drop for the middle section is even lower, indicating lack of a stable displacement at all times.

Almost identical oil cut and cumulative oil recovery were observed when compared with Run MPF-01 (Figures 4.4 and 4.17). The oil cut decreased rapidly after surfactant breakthrough, which is usually the case. Aqueous phase viscosities were measured and the polymer concentration estimated from these values. Polymer viscosity of Hi-Vis was measured as a function of concentration (Figure 4.12).

4.6.3 <u>Run MPF-02</u>

This oil recovery experiment was designed for our history matching purpose. A microemulsion of TRS10-410/i-Butanol/n-decane with tritium was used to obtain valuable information on the dispersion of the surfactant slug. A continuous slug of polymer buffer, 1000 ppm Xanflood at 0.5 wt% NaCl, was injected. No sacrificial agents were added in order to reduce the complexity. A relatively high flow rate, i.e. 6 ft/day, was employed for the entire experiment.

Ternary diagrams and a volume fraction diagram were available (Figure 4.18 through 4.21). Polymer viscosity at 1000 ppm Xanflood was measured (Figure 4.22). More polymer viscosity data were available in Tsaur's thesis¹²⁸. Different polymer batchs, the storage time of concentrated and/or injection polymer solutions, and the preparation procedures can cause the polymer viscosity to vary. The dispersion curve at residual oil saturation was measured (Figures 4.23 and 4.24). The residual oil saturation was double checked from the dispersion curve in addition to that from material balance. Usually they were agree.

A microemulsion slug of 0.0825 P.V. was injected. The amount of surfactant in the slug was about the same as that of previous experiments. This was done to compare the oil displacement efficiency of this slug with the previously used aqueous slug with

the previously used aqueous slug with the understanding that the mobility buffer bank was not identical. In addition, in order to obtain good oil recovery, a salinity of 0.5 wt% NaCl was used in the polymer slug compared with 1.1 wt% NaCl in microemulsion slug.

The oil recovery results presented in Figure 4.25 showed nearly 93% of oil recovered. After correcting for the oil in the injected microemulsion, 82% recovery of the resident oil was achieved and it is close to the 84% oil recovery achieved in Run Oil breakthrough was also close at 7% of a pore volume. MPF-05. Due to the low microemulsion viscosity, the mobility ratio between oil bank and surfactant slug was unfavorable (pressure drop data on Figure 4.26). The oil bank displaced a high peak at the front and continuously decreased. Surfactant was detected as early as 0.35 injected P.V. by the large change in interfacial behavior of water and oil in produced samples. Polymer breakthrough was at about 0.7 P.V. and no significant inaccessible P.V. to polymer was observed. From both viscosity and concentration measurements, the polymer in the effluent did not reach the injection level. This same observation has been reported by other researchers 81,142 .

4.6.4 Run MPF-06

Since all the oil recovery experiments conducted so far were unstable displacements between oil bank and surfactant slug,

it was decided to shift to a Necton 37 system due to the high viscosity of its middle phase microemulsion. Fifteen hundred ppm of Xanflood was injected continuously to ensure a favorable mobility ratio between surfactant slug and drive slug. Physical properties measured included ternary diagrams (Figures 5.130 through 5.132), a volume fraction diagram (Figure 5.126), viscosity versus salinity (Figure 5.124), and IFT (Figure 5.128). A major problem was that Necton 37 shows a strong adsorption peak at 270 nm by U.V. analysis, which precludes analysis of the surfactant. An unsuccessful attempt was made to partition the surfactant into the aqueous phase for analysis.

Tracer data suggested that the core was homogeneous (Figures 4.27 through 4.29). Absolute brine permeability was 610 md compared with about 300 md for previous cores. A high residual oil saturation of 0.4 was obtained. The middle phase microemulsion showed a viscosity of 35 cp., which is high enough to maintain a favorable displacement.

Water flood histories along with history matching curves were shown in Figures 5.144 and 5.145. The pressure drop curves (Figure 5.139) showed slightly unfavorable displacement due to the high oil viscosity. However, a reasonably good displacement with a short tail on the oil cut was obtained. The breakthrough of water occurred at about 30% pore volume.

The results of this oil recovery experiment are presented

in Figure 4.30. Oil breakthrough occurred at 0.23 P.V., which is late compared to all the previous experiments. The oil cut reached 0.62 at the oil bank front. Oil cut continued to decrease to about 0.4 at 0.6 P.V., rose to 0.46 at 0.7 P.V. and then decreased again until zero oil cut. Clear three-phase samples were collected during the last period of oil production. Surfactant was detected at about 0.7 P.V. which is much later than that of Run MPF-02, in which, surfactant breakthrough was as early as 0.35 P.V. Overall oil recovery was about 73%, 65% when corrected for the amount of oil in the surfactant slug, which is relatively low compared with other oil recoveries previously observed. The amount of surfactant was maintained at about the same level for all experiments. However, much less alcohol was injected in this case (see Table 4.1).

Effluent ion (sodium, calcium and magnesium) concentrations were measured for the aqueous phase. For three phase samples, however, they were separated into two phases by adding 10 v% acetic acid and the resulting bottom phase concentrations were measured (Figure 4.31). Therefore, the data shown in the three phase region are only qualitatively correct for the aqueous phase, These data were converted to a total fluid basis and are plotted this way on Figure 5.163.

The divalent ion concentrations were about 30 ppm, 45 ppm

and 5 ppm before, in, and after the three-phase sample region respectively (Figure 4.31). Such a low level will not affect the oil recovery significantly. The peak value of these ions in the three-phase region was very low compared to that of Gupta's experiment 37,38 . A small slug, 4% P.V. in this case, may not be enough to pick up these ions to a significantly high level.

The effluent polymer concentration did not reach the injection concentration. Reduction of polymer viscosity should be considered when designing micellar/polymer process for appropriate mobility control.

After polymer solution, brine was introduced again to wash out the remaining polymer in the core in order to determine S_{orc} . More than four pore volumes of brine through-put was required to bring the polymer concentration down to insignificant levels. It was found that S_{orc} was 0.19 obtained by tracer study (Figure 4.32) and was 0.13 calculated by material balance. It is believed that the water bounded by the small amount of remaining polymer may contribute to such a difference.

The overall pressure drop disclosed that favorable displacement was achieved during the entire flooding sequence. Later computer simulation did not predict the high pressure drop before oil breakthrough. It is believed, however, that the capillary pressure between water and oil may explain this, while in the simu-

lator no capillary pressure was included. This also explains why, after oil breakthrough, the pressure dropped noticeably before rising again due to the contribution of polymer. It is observed that the pressure drop was about five times greater at the end of flood than the initial water flood pressure drop.

Other data obtained were the interfacial tensions of the effluent sample. An average of 5 dyne/cm was obtained for the uncontaminated Necton 37 and brine samples and dropped to about 0.00016 dyne/cm between middle and bottom phases in the threephase region. Only one interfacial tension was measured for the three-phase samples due to an insufficient amount of those samples.

١

EXPERIMENT NUMBER	MPF-01	MPF-02	MPF-05	MPF-06
TEMPERATURE, ^O C	30	30	30	30
CORE DATA, Dimension, inches	2x2x33.6	2x2x36	2x2x36	2x2x36
Total Pore Volume, ml	451.8	468.6	467.0	506.0
Absoluto Rnino Donmoshility md	0.205	200	0.198	0.214 610
Residual Water Saturation S	0 443	290 0 410	0 438	0 294
Residual Oil Saturation, S	0.325	0.359	0.343	0.386
End-Point Perm at S, md or	145	210	202	600
End-Point Perm at Sor, md	21.5	20.5	18.6	35.0
Initial Salinity, ^{Or} wt% NaCl	0.86	1.10	0.75	2.00
REFLOOD, P.V. Injected Composition	0.598	0	0.607	0
	0.2 wt% Na ₅ P ₃ O ₁₀		0.2 wt% Na ₅ P ₃ 0 ₁₀	
	0.1 wt% Na ₂ CO ₃		0.1 wt% Na ₂ CO ₃	
Salinity, wt% NaCl	0.86		0.75	
CHEMICAL SLUG, P.V. Injected Composition	0.105 3 wt% TRS10-410	0.0825 3.8 v% TRS10-410	0.098 3 v% TRS10-410	0.040 8.0 v% TRS10-410
	3 wt% NBA 94 wt% Brine	1.0 v% IBA 38.4 v% n-Decane	3 v% NBA 94 v% Brine	1.0 v% IBA 42.0 v% Necton 37
	0.2 wt% Na ₅ P ₃ 0 ₁₀	56.8 v% Brine	0.2 wt% Na ₅ P ₃ 0 ₁₀	49.0 v% Brine
	0.1 wt% Na ₂ CO ₃		0.1 wt% Na ₂ CO ₃	
Viscosity, cp. Salinity. wt% NaCl	20 at 1 sec ⁻¹ 0.86	4.2 at 1 sec ⁻¹ 1.10	 0.75	35 at 0.024-128 sec ⁻
Type of Slug	Aqueous	Middle Phase Microemulsion	Aqueous	Middle Phase Microemulsion

SUMMARY OF OIL RECOVERY EXPERIMENTS

TABLE 4.1

(to be continued)

.

EXPERIMENT NUMBER	MPF-01	MPF-02	MPF-05	MPF-06
POLYMER SLUG				······································
Polymer Type Concentration, ppm (P.V. Injected)	HI-VIS 1900 (0.21 P.V.) 1200 (0.20 P.V.) 700 (0.41 P.V.) 300 (0.62 P.V.)	Xanflood 1000 (1.42 P.V.)	H1-VIS 1900 (0.19 P.V.) 1200 (0.20 P.V.) 700 (0.40 P.V.) 300 (0.62 P.V.)	Xanflood 1500 (1.46 P.V.)
Viscosity, cp.	95 (2250 ppm 1 0 sec ⁻¹)	53 (1.0 sec ⁻¹)	85 (1900 ppm, 1, 0, sec ⁻¹	$\frac{89}{(3,23,5ec^{-1})}$
Salinity, wt% NaCl	0.86	0.50	0.75	0.60
FRONTAL VELOCITY, ft/day	0.6	6.0	0.6	1.0
OIL TYPE	n-Decane	n-Decane	n-Decane	Necton 37
OIL BREAKTHROUGH, P.V. Injected	0.065	0.07	0.075	0.23
FINAL OIL RECOVERY, fraction of S _{or}		82	84	65
FINAL RESIDUAL OIL, fraction		0.065	0.055	0.135

· · · · ·

TABLE 4.1 (continued) ا به موجع معد در فرو روز مان از در در ارو مان ارو ارو ارو ارو ارو ارو مان ارو ارو مان ارو ارو ارو مان ارو ارو م در ارو

ķ



FIGURE 4.1 SIMULATED POLYMER DRIVES FOR EXPERIMENTS MPF-01 AND MPF-05



FIGURE 4.2 SIMPLIFIED SCHEMATIC DIAGRAM OF THE EXPERIMENTAL SET-UP



FIGURE 4.3 LONGITUDINAL SECTION THROUGH INJECTION SAMPLE CONTAINER FOR SURFACTANT



IGURE 4.4 RESULTS OF OIL RECOVERY EXPERIMENT MPF-01 SHOWING OIL CUT AND OIL RECOVERY VERSUS INJECTED PORE VOLUMES



FIGURE 4.5 TERNARY DIAGRAM FOR TRS10-410/NBA/N-DECANE AT 0.6 WT% NaCl



FIGURE 4.6 TERNERY DIAGRAM FOR TRS10-410/NBA/N-DECANE AT 0.8 WT% NaCl



FIGURE 4.7 TERNARY DIAGRAM FOR TRS10-410/NBA/N-DECANE AT 1.0 WT% NaCl



FIGURE 4.8 TERNARY DIAGRAM FOR TRS10-410/NBA/N-DECANE at 1.8 WT% NaCl



FIGURE 4.9 VOLUME FRACTIONAL DIAGRAM OF TRS10-410/NBA MICELLAR SOLUTIONS AS A FUNCTION OF SALINITY















. -




FIGURE 4.14 λ CURVE AT 100% BRINE SATURATION FOR MPF-05





NORMALIZED PRESSURE DROPS VERSUS PORE VOLUME INJECTED FOR EXPERIMENT MPF-05





FIGURE 4.18 TERNARY DIAGRAM FOR TRS10-410/IBA/N-DECANE AT 0.6 WT% NaCl



FIGURE 4.19 TERNARY DIAGRAM FOR TRS10-410/IBA/N-DECANE AT 1.0 WT% NaCl



FIGURE 4.20 TERNARY DIAGRAM FOR TRS10-410/IBA/N-DECANE AT 1.5 WT% NaCl





FIGURE 4.22

VISCOSITY OF 1000 PPM XANFLOOD VERSUS SHEAR RATE FOR MPF-02



FIGURE 4.23 DISPERSION CURVE AT RESIDUAL OIL SATURATION FOR MPF-02







FIGURE 4.25 RESULTS OF OIL RECOVERY EXPERIMENT MPF-02 SHOWING OIL CUT, OIL RECOVERY AND NORMALIZED POLYMER CONCENTRATION VERSUS PORE VOLUME INJECTED









FIGURE 4.29

DISPERSION CURVE AT RESIDUAL OIL SATURATION FOR MPF-06





FIGURE 4.31 RESULTS OF ION CONCENTRATION HISTORIES FOR EXPERIMENT MPF-06



FIGURE 4.32 DISPERSION CURVE AFTER POLYMER DRIVE FOR EXPERIMENT MPF-06

CHAPTER V

HISTORY MATCHING STUDY

The main purpose of this history matching study was to test the capability of the 1-D simulator to simulate the complex compositional effects of micellar/polymer flooding. Generally, to conduct this study we have to do the following:

1) Search for micellar/polymer flooding experiments which have been conducted and published in the literature. Among them, only the ones providing the most detailed experimental data can be used for this study. We are not only interested in the raw data on phase behavior, interfacial tension, surfactant and polymer adsorption, relative permeability curves, etc. but also in the available quantities which can be history matched. The quantities to be matched are not just oil production and oil cut history, but include concentrations of surfactant, polymer, chloride, and alcohol, and the pressure drop history, etc. In fact, we want to match as many quantities as we possibly can obtain. Unfortunately, most of the experiments do not provide a complete set of data, therefore; our own experiments are essential to achieve the goal. The idea is to first compare our laboratory results with their results and then to generate

our own data which are otherwise not available for the history matching study.

- 2) The raw data must be prepared into a form which can be used as input data for the simulator. Sometimes the simulation input data can be obtained directly from the primary source of the data published, or they can be obtained from other related secondary sources. For those data not available from any reliable sources, reasonable estimates must be made and generally those data are subject to adjustment first during the simulation. A property program which generates and plots the physical properties, such as phase behavior, interfacial tension, and viscosity, is run before the simulation run. This provides an easy and rapid means of checking the input data for errors or inconsistencies, as well as examining trends and comparing the results of different runs. There are too many variables and runs necessary for this plotting to be feasible without computer assistance. The experimental result was plotted on the same scale as the simulation result to enable us to overlay and compare the results.
- 3) The first input data set prepared from raw data usually does not give a satisfactory match to the experiment. At this time, input parameters are adjusted and the case rerun until a satisfactory match is accomplished. The cumulative oil pro-

duction history is usually the first and easiest quantity to be matched. To obtain the correct oil breakthrough time, one can adjust the relative permeability curves for oil and water. To obtian the correct oil cut and/or the correct level of oil recovery, one can adjust the phase behavior, interfacial tension, surfactant adsorption, mobility ratio between the surfactant slug and oil bank, etc. It is somewhat difficult to match other quantities such as the concentration histories of surfactant, polymer, chloride, alcohol, etc. without affecting the previously matched oil recovery curve.

The experiments done by $Holm^{46}$, Rathmell⁵², Trushenski⁵⁶, Healy <u>et al</u>³⁹, and Hedges and Glinsmann's^{30,42} were studied. Among them, Holm's, Rathmell's, Trushenski's and Hedges and Glinsmann's have been studied extensively and will be discussed in this chapter. Experiments similar to those of Hedges and Glinsmann were conducted to obtain additional history matching data. A summary of history matched experiments is listed in Table 5.1.

5.1 Matching of Trushenski's Experiment

Trushenski's experiment was reported in Shah and Schechter's book, page 567, Figure 6⁵⁶. It is one of several micellar/polymer flooding experiments using Berea sandstone. Their main purpose was to evalute the sulfonate-polymer interaction. The cores were

4 to 16 feet in length. Generally, the experiments were run at or near the optimal salinities. The quantities reported were the surfactant, polymer, alcohol, tracer concentrations, and oil cut. This experiment is one of two reported to be without sulfonatepolymer interaction. All the experimental effluent concentrations are assumed to be reported on a total basis (rather than as phase concentrations) and all reported oil cuts are assumed to be the oil concentration in the effluent rather than the true oil phase cut.

The properties of a representative core and test conditions are tabulated Table 5.2. These were used as part of the simulation input parameters, such as the crude oil viscosity, connate water and residual oil saturations, and the end-point brine permeability at residual oil. Table 5.3 shows the composition of the injection slugs for base case runs. A list of all the input parameters for the base case runs is tabulated (Table 5.4). The prepared input data of phase behavior (Figure 5.18), interfacial tension (Figure 5.1), viscosities along the binodal curve (Figure 5.2), polymer viscosities vs. concentration (Figure 5.3) and shear rate (Figure 5.4), surfactant adsorption (Figure 5.5), trapping of oil and water (Figure 5.6), relative permeability of water and oil (Figure 5.7) and fractional flow of water (Figure 5.8) are also included. The phase behavior, interfacial tension, viscosities along the binodal curve as well as the surfactant adsorption are purely estimated quantities due to the lack of adequate data.

These quantities have been adjusted during the simulation study to obtain good matches.

Figure 5.3 shows a plot of polymer viscosity for Kelzan MF assuming it is salinity independent. The solid curve corresponds to the viscosity at zero shear rate while the dashed curve corresponds to the viscosity which is corrected by the Meter's equation at 10 sec^{-1} . For instance, the polymer viscosity for 1000 ppm, i.e. 0.1 wt%, is 13.64 cp. at zero shear rate. After correction by Meter's equation using the selected parameters, the viscosity becomes 11.2 cp. at 10 sec⁻¹, which is very close to the actual data.

The trapping curves for oil and water were prepared as functions of interfacial tension and total mobility. The data of Gupta³⁶ for oil trapping in Berea were used as shown in Figure 5.6. It is assumed that a straight line drawn by hand through the data points is the oil trapping curve for the simulation. The water trapping curve was assumed to be two orders of magnitude to the left of the oil curve. Both of these curves are highly uncertain.

Due to the lack of direct information, the relative permeability curves for water and oil reported in the first annual report of Bell Creek Field micellar-polymer pilot demonstration project¹⁴³ were used. In order to match the oil breakthrough, the oil relative permeability curve was adjusted as shown on Figure 5.7. At the beginning of the history matching study, Type III phase

behavior was assumed and the simulation result did not match the experiment for either oil recovery (Figure 5.10) or surfactant and alcohol concentrations (Figure 5.9). Simulated surfactant and alcohol concentrations were late about 0.2 P.V.

Due to the lack of evidence supporting three phase production, it was assumed that Type II(-) behavior occurred during the process and $\mathrm{C}_{\mathrm{SEL}}$ was increased so that the slug salinity would be less than $\mathrm{C}_{\underline{\mathrm{SEL}}}$. This change did not improve the match, but created an alcohol peak at about 1.0 P.V. injected (Figure 5.11) which was not observed in the experiment. In addition, the oil cut (i.e. the total oil concentration at the effluent) did not match at the trailing edge (Figure 5.11), nor did the oil recovery (Figure 5.12). It was decided to simplify the simulation by modeling the surfactant component as a combined surfactant and alcohol pseudo-component instead of modeling alcohol as a separate component. Figures 5.13 and 5.14 show the results. The oil bank with a long tail (lasting about 1.0 P.V.) at the trailing edge still did not match. By study of the composition path history (Figure 5.15), it was found that the path only took about one-tenth of a pore volume to pass through the two-phase region. In addition, the composition path did not follow any of the tie-lines, which it usually does 61,74. The zig-zag path also suggested that numerical instability might exist, even though a small time-step (0.001 P.V.) was used.

The maximum surfactant concentration at optimal salinity on the binodal curve (C_{3MAX1}) was increased from 0.0683 to 0.15 with the hope that the composition path would stay in the two phase region longer. This resulted in a surfactant peak (Figure 5.16) as previously observed before about 1.0 P.V. (Figure 5.17). The composition path (Figure 5.18) was still zig-zag even with a smaller time step of 0.00025 (Figure 5.19) instead of 0.001. So, the time step size was not considered the cause of the zig-zag.

Another change which might help to create the oil bank tail is to move the plait point away from the oil apex. In this case, less oil will be present in the oleic phase (otherwise pure oil is in the oleic phase). As a consequence, oil may be produced slower by solubilization. In order to give a significant effect, the plait point was shifted to the point of 80% oil on the binodal curve. As expected, the oil tail appeared, although the oil recovery was low (Figures 5.20 and 5.21). The tail even occurred when the plait point was at 95% oil on the binodal curve.

The final simulation results (plait point at 85% oil on binodal curve), including profiles and histories for various phases, is shown on Figures 5.22 through 5.31. The composition path (Figure 5.32) now follows a particular tie-line and no zig-zag shape appeared.

5,2 Matching of Rathmell's and Holm's Experiments

These core floods^{46,52,81} were reported in the First Annual

DOE Report ¹⁴³ on the Bell Creek Pilot Test and were the two competing designs for the Bell Creek micellar/polymer field test. Relatively fewer experimental input data were available for history matching purposes. The variables available to be matched were only surfactant concentration, oil cut and cumulative oil recovery.

Rathmel1⁵² used an aqueous surfactant slug with constant salinity design, whereas Holm⁴⁶ used a soluble oil surfactant slug with a reduced salinity in the polymer drive. In Rathmell's experiment, about 75% of the oil was displaced, whereas nearly 87% of the oil was displaced in Holm's experiment, although about the same amount of surfactant was injected. Later, in the sensitivity study, a simulation of Rathmell's experiment shows nearly 89% oil recovery if designed with a similar salinity gradient as Holm employed.

Selected simulation input data are plotted in Figures 5.33 through 5.37. Polymer viscosity data were available from reference 81 and were previously given in Figure 3.5. A major omission is that we do not know how the ternary diagram changes with salinity. For the sake of simplicity, a constant phase diagram (i.e. a phase diagram which is not a function of salinity) was input for the simulation. Some other assumptions made to accomplish a complete set of input parameters were:

. no polymer adsorption (later changed to 10 $\mu\text{g/g}$ of polymer absorbed)

- . no permeability reduction (later changed to a maximum value, $R_{k,max}$, of 1.5)
- . plait points are at corners of the ternary diagrams
- . symmetrical phase envelopes
- no ion exchange occurs and also no sulfonate complex is present (i.e. no effects due to divalent cations).

Basically, these two experiments are assumed to be Type II(-) cases with surfactant, polymer and chase water injected. In the simulation, component six was used as a tracer. Core properties were assumed identical for both simulation cases.

The oil breakthroughs were matched by shifting the relative permeability for oil to the right of actual data points (Figure 5.36). Cumulative oil recoveries then were matched by adjusting the interfacial tension curve. The breakthrough time of surfactant was about two-tenths of a pore volume earlier than the simulated value in both cases. After assuming 20% inaccessible pore volume to the surfactant, good matches were achieved.

The final simulation results for both experiments are presented (Figures 5.38 through 5.56). These include both profiles at 0.5 P.V. and histories for different phases. Overall, these two experiments provide only few items for history matching so it was not too difficult to match them. As mentioned earlier, the oil breakthrough times and the oil production histories were matched first, which left only surfactant concentrations to be matched. One interesting point worth making is that by changing only the interfacial tension and the injection slug compositions, but with identical core properties, both experiments were matched properly.

These experiments (HWC for Rathmell's and SO for Holm's experiments) have also been simulated by Todd <u>et al</u>⁸¹ using INTERCOMP's Chemical Flood Simulator. In general, their simulated cumulative oil recovery is within the reproducibility error and the simulated surfactant peak is in agreement with the experiment in adsorption level and dispersion, but their simulated surfactant peak breakthrough was late. They claimed that this is due to an incorrect model of the interaction between the surfactant and polymer. They also claimed that the HWC process would be markedly improved by lowering the surfactant adsorption and/or increasing the polymer drive viscosity.

5.3 History Matching of Experiments MPF-02, MPF-05 and MPF-06

Simulation efforts have been extended to study the oil recovery experiments conducted in this laboratory. A detailed discussion of the experiments is presented in Chapter IV. Basically, these experiments were designed for the purpose of history matching studies as previously described. Experiments MPF-01 and MPF-05 were similar runs and only MPF-05 was matched. A detailed discussion of each history matching study is provided in the following sections.

Relatively good matches were obtained for all three oil recovery experiments (MPF-02, MPF-05 and MPF-06). This also includes the match of each water flood history. Using the same parameters for relative permeability as obtained from matching the waterfloods, the simulator predicts the correct oil breakthroughs for all three micellar oil recovery experiments. Pressure histories were not matched using the measured viscosities of water, oil, slug and polymer drive. The use of the measured polymer solution viscosity (as simulation input) resulted in a simulated pressure drop higher than the experimental values. For example, in the case of MPF-05, an input polymer viscosity of 20 cp. (compared with 85 cp. measured for the injected solution) was needed in order to match the final experimental pressure drop (Figure 5.101). A drastic decrease of polymer viscosity in the presence of calcium in the core may explain the low apparent viscosity. As shown on Figure 5.116, the actual viscosity of the produced polymer was low compared with the simulated values. This also explains why the measured pressure drop was lower than the simulated value until the input was adjusted.

5.3.1 Matching Study of MPF-02

This was an unfavorable displacement of water and oil. The

injected surfactant slug viscosity of 4.2 cp. at 1.0 sec⁻¹ was not high enough to maintain the required mobility ratio between the slug and the oil bank. Surfactant was detected as early as 0.32 P.V. Total oil recovery was 82% after correction for injected oil. Oil breakthrough at 0.08 P.V. was close to that of MPF-01 and MPF-05. The oil bank showed a high oil cut at its front and continuously decreased up to 1.1 P.V. injected. This was not observed in MPF-01 and MPF-05.

Figure 5.57 shows the excellent agreement between the simulated and experimental data for the surfactant concentration on the phase envelope. Figure 5.58 shows the microemulsion phase viscosity as a function of salinity. The two peaks shown in the three-phase region was uncommon. Two peaks were also seen in Figure 5.59 (microemulsion volume fractional diagram)

A good match of the phase volume fraction diagram was achieved (Figure 5.60). Solid circles and squares represent the experimental data, while the curves with crosses and squares are the simulated results. Figure 5.61 and 5.62 showed the solubilization ratios and IFT as a function of salinity and Figure 5.63 shows the IFT as a function of the two solubilization ratios. Figure 5.66 shows a ternary diagram near optimal salinity. The solid squares are the calculated middle phase compositions. The IFT's and viscosities along the binodal curves are shown in

Figures 5.67 and 5.68. Relative permeability curves and a fractional flow curve are presented in Figures 5.71 and 5.72. Experimental data for water and oil relative permeability¹⁴⁰ on Figure 5.71 were matched by the calculated curves.

The water flood history matched was the oil cut, oil recovery, and overall pressure drop (Figures 5.73 through 5.75). Simulation run 48 (Figures 5.76 through 5.86) was considered the base case run of this experiment. It was a three-phase run with the same relative permeability parameters as used in the water flood. A good match of oil breakthrough, oil recovery and polymer history was observed. Oscillations were found near the oil bank tail. The biggest discrepancy was for the surfactant breakthrough. The simulator did not predict the early surfactant breakthrough (at 0.32 P.V. injection) which may have occurred as a result of fingering under unfavorable mobility ratio conditions. Simple dispersion would not predict such an early breakthrough using the simulator. An artificial inaccessible proe volume as high as 70% was assumed to match the surfactant breakthrough. It was hoped that due to the salinity dependent surfactant adsorption the adsorbed surfactant (higher salinity in slug) would be desorbed at a later time when the lower salinity polymer slug was encountered. It was also hoped that the surfactant peak would still remain at about 0.8 P.V. injection. The surfactant did breakthrough early

(0.3 P.V., Figure 5.87); however, the peak of surfactant was also early, which was not desired. The oil bank was not matched even though the oil cut did reach the high value at bank front. In addition, a large three-phase volume was produced in the simulation which was contary to the experimental result (Figure 5.88).

The pressure drop data of the base case run were matched only at the early stages of the run. The differences after oil breakthrough were probably due to the unmatched oil bank result and the improper model of the microemulsion phase viscosity.

5.3.2 Matching Study of MPF-05

This experiment was run under the conditions similar to MPF-01 and Experiment no. 24212-11 of Hedges and Glinsmann. As mentioned earlier, the oil breakthrough of Hedges and Glinsmann's experiment was about 0.18 P.V. injected while the oil breakthroughs of both MPF-01 and MPF-05 were about 0.07 P.V. injected. It was believed that the relative permeability curves of water and oil could cause such variation. In a sensitivity study, section 6.6, simulations show that oil breakthrough at 0.18 P.V. can be achieved simply by changing the exponents of water and oil relative permeability curve. However, this is probably not the real reason for the difference.

A constant salinity was employed through the entire experiment. Four polymer slugs with concentrations of 1900 ppm, 1200 ppm, 700 ppm and 300 ppm were injected.

The experimental result showed a stable oil bank with oil cut at about 0.42 (Figure 5.116). An oil bank tail developed beginning with the breakthrough of surfactant, which is normally the case. The results of this experiment were found to be close to those of MPF-01 except that a lower oil recovery was obtained in MPF-05.

Overall pressure drop was normalized by the final preflush value. The pressure drop during the preflush increased continuously and reached a value about 1.5 times higher than that of the waterflood. Precipitation of calcium carbonate and calcium tripolyphosphate is the most likely reason for this. The "kick" in the intermediate pressure drop near 0.06 P.V. (as shown on Figure 5.118) is not clearly understood.

Physical property plots are given on Figures 5.86 through 5.100. As shown on Figure 5.98, the injected polymer viscosity was assumed to be about 75% less than that of the measured value in order to match the pressure data.

Numerical oscillations were serious in many of the simulation runs (Figure 5.119). A smaller time step of 0.0001 P.V. was used and the oscillations decreased (Figure 5.116). The oscillations tend to be worse when polymer breakthroughs before surfactant.

Using the relative permeability parameters based on the data

of Delshad¹⁴⁰, the water flood history was matched. The oil breakthrough of the micellar/polymer flood was also matched using the identical relative permeability parameters employed in the water flood simulation.

The simulated oil bank cut was low at early times and high at later times (Figure 5.116). The points labelled experimental polymer are actually normalized viscosity for the produced aqueous phase samples. The simulated polymer concentration shows later breakthrough and a higher peak than these viscosity data converted to polymer concentration. This comparison is less precise than a direct comparison with experiment polymer concentration.

5.3.3 Matching Study of MPF-06

The use of a high viscosity middle phase microemulsion of TRS10-410/IBA/Necton 37 in this experiment provided favorable mobility control between the oil bank and the surfactant slug. The polymer buffer solution contained 1500 ppm Xanflood in 0.6 wt% NaCl brine solution, ensuring favorable mobility control between the surfactant slug and polymer buffer bank. Comparisons between calculated and measured physical properties are shown on Figures 5,121 through 5.137. The oil cut, polymer and cation concentrations, interfacial tensions and viscosities of effluent samples were measured.

A comparison of experimental waterflood history with

simulated history for several sets of relative permeability parameters is shown in Figures 5.138 through 5.140. Figures 5.141 through 5.145 show the final simulation results of the water flood. Figure 5.144 shows the match for oil cut and oil recovery. Pressure drop data suggested that an unfavorable mobility was encountered during flooding due to the high viscosity (20 cp. at 30° C) of Necton 37. Water cut and water breakthrough were found to be sensitive to the relative permeability curves. For instance, a long water cut tail developed when the exponents e_1 and e_2 of the permeability curves of water and oil were both at 1.2 (Figure 5.139). The water breakthrough was at about 0.22 P.V. In another case $(e_1 \text{ and } e_2 \text{ were both at 1.0})$, the water cut tail shortened and the water breakthrough occurred at about 0.15 P.V. (Figure 5,138). The change of the exponents essentially changed the fractional flow of water and oil and, as a result, the breakthrough of water shifted and the characteristics of the water cut were affected. The final values for e_1 and e_2 were 2.5 and 1.0, which fit the oil breakthrough better than the case of $e_1=2.0$ and $e_2=1.0$ (Figures 5.140 and 5.143). However, there is not very much difference between these results.

The oil breakthrough for the micellar flood was matched without any difficulty using the water flood relative permeability parameters. It was somewhat difficult to match the oil bank. Run 75 using the phase behavior parameters C_{3MAX0} , C_{3MAX1} and C_{3MAX2} equal to 0.2, 0.08 and 0.2, respectively, produced a relatively good
match (Figure 5.158). The use of 0.2, 0.16 and 0.2 for C_{3MAXO} , C_{3MAX1} and C_{3MAX2} which were suggested by the laboratory measurements also produced a good match (Figure 5.155) when the interfacial tension and oil phase trapping were adjusted.

The experimental oil cut of about 0.65 at the oil bank front was matched. The simulated oil cut decreases, but not enough to match the experimental data. A discrepancy on the oil bank tail between 0.7 and 1.0 P.V. injected was observed. Surfactant and polymer breakthroughs were reasonably well matched. Inaccessible pore volume of 20% was assumed for polymer in order to obtain this match. The higher experimental pressure drop (Figure 5.157) before the oil breakthrough could be the effect of capillary pressure, which was not modeled in the simulator. Therefore, a lower simulated pressure drop was obtained. The disagreement of the pressure drop curves between 0.7 and 1.0 P.V. is believed to be the inadequate model of the microemulsion phase viscosity and/or the polymer behavior. The experimental polymer did not reach its full strength, by either viscosity and direct concentration measurements, during that period of time, which would result in a lower pressure drop. See Engelsen¹⁴⁹ for an improved microemulsion viscosity model.

The simulation effort was extended to a more complex case which involved cation exchange and the presence of alcohol. Alcohol was allowed to partition into both the water and oil phases¹⁴⁹.

Due to the small amount of alcohol (1 v%) in the slug, the presence of alcohol may not affect the oil recovery significantly in the simulation. However, it is better to include alcohol to obtain a better description of the system.

In this simulation, cation exchange with both the clav and the micelles was assumed ¹⁴⁴. The exchange parameters (β^c , β^s and Q_{v}) for Berea core were those used by Hirasaki¹⁴⁴. Calcium was taken to be ten times more effective than sodium in terms of ionic strength for determining the effective salinity of phase behavior. The input initial divalent ion concentration (calcium plus magnesium) in the core was 1.6×10^{-3} N. This was obtained from measurements of the concentrations in single phase effluent samples during the oil recovery experiment (Figure 4.31). Concentrations of sodium, calcium and magnesium were to be matched. In order to match these concentrations, a simulated chloride (component five) concentration was used to represent the experimental sodium concentration. This approximation is valid because the majority of chloride ions are from the sodium chloride which makes up the brine solution. In addition, a simulated calcium (component six) concentration was used to represent the experimental total divalent ion concentration (calcium plus magnesium). No calcium or magnesium were in the injected slug or drive.

Basically, all the input parameters remained the same as

those used in base case MPF-06. The interfacial tension curves were adjusted to obtain a better fit with the measured data (Figure 5.160). The input slug composition (49 v% water, 42 v% oil, 8 v% surfactant and 1 v% alcohol) was also modified to agree with the best estimated values of the actual injected slug.

The early simulation results agreed with respect to the oil breakthrough. By adjusting the oil trapping curve, the final oil recovery was matched (Figure 5.163). The capillary desaturation curves used in this simulation are plotted in Figure 5.162. The simulated oil bank was relatively flat compared with the experimental oil bank. The last part of the oil bank (due to solubilization) was not matched properly. Simulated surfactant and alcohol were spread over about 0.2 P.V., as was the simulated calcium peak associated with the surfactant and alcohol. This did not agree with the observed spread of about 0.4 P.V. for the surfactant and calcium peaks (from about 0.7 to 1.1 P.V.). Simple physical dispersion can not explain this disagreement. Nevertheless, the maximum calcium concentration agreed with the simulated result. Moreover, the long calcium tail at about 5 ppm was also matched.

Final simulated overall pressure drop was close to that of base case MPF-06 (Figure 5.164).

TABLE 5,1 SUMMARY OF HISTORY MATCHED EXPERIMENTS

	Trushenski	Holm	RATHMELL	<u>MPF-02</u>	<u>MPF-05</u>	<u>MPF-06</u>
Oil	Second Wall Creek Crude	Bell Creek Crude	Bell Creek Crude	n-Decane	N-DECANE	Necton 37
Surfactant	Mahogany AA	PS465	PS465	TRS10-410	TRS10-410	TRS10-410
Polymer	1250 ppm Kelzan	950 ppm Cyanatrol 950s	1200 ppm Cyanatrol 950s	CONTINUEOUS 1000 PPM X.F.	4 Graded Slugs of HI-VIS	Continueous 1500 ppm X.F.
Slug Type	Aqueous	Soluble Oil	Aqueous	MIDDLE PHASE M.E.	Aqueous	Middle Phase m.e.
Preflush	NA	Yes	Yes	No	Yes	No
Polymer in Slug	No	No	No	No	No	No
Favorable Mobility Ratio	No	Yes	Yes	No	No	Yes
SALINITY GRADIENT	Yes	Yes	No	Yes	No	Yes

.

TABLE 5.2

1

TYPICAL CORE PROPERTIES AND TEST CONDITIONS AS SIMULATION INPUT FOR BASE CASE SP

Core Diameter	= 2 inches
Porosity	= 0.21
Temperature	= 110 ⁰ F
Crude Oil	= Second Wall Creek
Crude Oil Viscosity	= 4.0 cp @ 110 ⁰ F
Connate Water Saturation	= 44.6%
Residual Oil Saturation	= 34.4%
Absolute Permeability	= 571 md
Brine Permeability at Residual Oil	= 37 md

TABLE 5.3

SUMMARY TABLE OF INJECTION SLUG COMPOSITIONS AND SLUG SIZES FOR BASE CASE RUNS

t,

Соі	Composit io n for Base Case Run SP*								
Coi	nponent	<u>Unit</u> I	<u>nitial</u>	Surfactant Slug	Polymer Drive	Chase Brine Drive			
1.	Water	(vol.fraction)	0.656	0.89	1.0	1.0			
2.	0i1	(vol.fraction)	0.344	0.0	0.0	0.0			
3.	Surfactan	t(vol.fraction)	0.0	0.11	0.0	0.0			
4.	Polymer	(wt %)	0.0	0.0	0.125	0.0			
5.	Anions	(me q /ml)	0.23	0.23	0,05	0.05			
6.	Tracer		0.0	0.0	1.0	0.0			
7.	Alcohol	(vol.fraction)	0.0	0.0	0.0	0.0			
	Slug Size	(P.V.)	-	2.0	1.3	1.2			
Со	mposition [.]	for Base Case	Run Q	PR					

			Surfactant	Polymer
Component	<u>Unit</u>	<u>Initial</u>	Slug	Drive
1. Water	(vol.fract	ion) 0.65	0.972	1.0
2. 0il	(vol.fract	ion) 0.35	0.0	0.0
3. Surfacta	nt(vol.fract	ion) 0.0	0.028	0.0

1.	Water	(vol.fraction)	0.65	0.972	1.0	1.0
2.	0i1	(vol.fraction)	0.35	0.0	0.0	0.0
3.	Surfactant	(vol.fraction)	0.0	0.028	0.0	0.0
4.	Polymer	(wt %)	0.0	0.0	0.125	0.0
5.	Anions	(meg/ml)	0.0522	0.0522	0.0522	0.0522
6.	Tracer	x	0.0	0.0	0.0	0.0
7.	Alcohol	(vol.fraction)	0.0	0.0	0.0	0.0
	Slug Size	(P.V.)	-	0.12	0.6	0.78

(to be continued)

Chase Brine

Drive

Cor	nponent	<u>Unit</u>	<u>Initial</u>	Surfactant	Polymer Drive	Chase Brine Drive
1.	Water	(vol.fraction)	0.65	0.50	1.0	1.0
2.	0i1	(vol.fraction)	0.35	0.424	0.0	0.0
3.	Surfactant	t(vol.fraction)	0.0	0.076	0.0	0.0
4.	Polymer	(wt %)	0.0	0.0	0.095	0.0
5.	Anion	(meg/ml)	0.10	0.10	0.03	0.08
6.	Tracer		0.0	0.0	0.0	0.0
7.	Alcohol	(vol.fraction)	0.0	0.0	0.0	0.0
	Slug Size	(P.V.)	-	0.03	0.7	0.77

Composition for Base Case Run MPF-02

Composition for Base Case Run QPH

Cor	nponent	<u>Unit</u>	<u>Initial</u>	Surfactant Slug	Polymer Drive
1.	Water	(vol.fraction)	0.641	0.45	1.0
2.	0i1	(vol.fraction)	0.359	0.49	0.0
3.	Surfactant	t(vol.fraction)	0.0	0.06	0.0
4.	Polymer	(wt %)	0.0	0.0	0.1
5.	Anion	(meg/ml)	0.189	0.189	0.086
6.	Tracer		0.0	1.0	1.0
	Slug Size	(P.V.)	-	0.0825	1.4175

(to be continued)

Composition	for	Base	Case	Run	MPF-05
-------------	-----	------	------	-----	--------

			Surfactant	Po	olymer D	rive	
Cor	nponent	<u>Initial</u>	Slug	1	2	3	4
1.	Water (vol.fraction)	0.657	0.94	1.0	1.0	1.0	1.0
2.	0il (vol.fraction)	0.343	0.0	0.0	0.0	0.0	0.0
3.	Surfactant (vol.fraction)	0.0	0.06	0.0	0.0	0.0	0.0
4.	Polymer (wt %)	0.0	0.0	0.19	0.12	0.07	0.03
5.	Anion (meg/ml)	0.129	0.129	0.129	0.129	0.129	0.129
6.	Tracer	0.0	1.0	1.0	1.0	1.0	1.0
	Slug Size (P.V.)	÷	0.1	0.19	0.21	0.4	0.6

.....

Composition for Base Case Run MPF-06

<u>Cor</u>	nponent	Unit	<u>Initial</u>	Surfactant <u>Slug</u>	Polymer Drive
1.	Water	(vol.fraction)	0.6136	0.42	1.0
2.	0i1	(vol.fraction)	0.3864	0.42	0.0
3.	Surfactant	t(vol.fraction)	0.0	0.16	0.0
4.	Polymer	(wt %)	0.0	0.0	0.15
5.	Anion	(meg/ml)	0.345	0.40	0.103
6.	Tracer		0.0	1.0	1.0
	Slug Size	(P.V.)	-	0.04	1.46

					<u>_</u>	
PARAMETER	QPH	QPR	\$P	MPF-02	MPF-05	MPF-06
^a 31	1.0	0.7	3.0	0.0	0.3	0.1
^a 32	0.0	0.0	5.0	0.0	0.0	0.0
a ₄	100.0	100.0	0.1	0.1	0.1	0.1
A ₁₁	0.035	0.035	1029	-	-	-
A ₁₂	0.0	0.0	0.8139	-	-	-
A ₂₁	0.03	0.03	0.3529	-	-	-
A ₂₂	0.0	0.0	8139	-	-	-
A _{p1}	30.0	30.0	100.0	400.0	100.0	300.0
A _{p2}	300.0	300.0	1000.0	2000.0	-600.0	1000.0
А _{рЗ}	2000.0	2000.0	0.0	0.0	3000.0	20000.0
p ³	500.0	100.0	1000.0	1000.0	100.0	100.0
^b 4	100.0	100.0	100.0	100.0	100.0	100.0
B ₁	-1	-1	-1	-1	-1	-1
^B 2	-1	-1	-1	-1	-1	-1
B ₃	-1	-1	-1	-1	-1	-1
b _p	1000.0	1000.0	0.0	1000.0	1000.0	1000.0
C _{3MAXO}	-	-	-	0.20	0.20	0.20
C _{3MAX1}	-	-	-	0.08	0.10	0.16

LIST OF SIMULATION PARAMETERS FOR BASE CASE RUNS

TABLE 5.4

(to be continued)

PARAMETER	QPH	QPR	SP \$	MPF-02	MPF-05	MPF-06
C _{3MAX2}		-	-	0.20	0.20	0.20
C _{SEL}	0.21	0.21	0.26	0.1551	0.103	0.2069
C _{SEU}	0.30	0.30	0.30	0.2241	0.1551	0.4828
C _{SE1}	0.01	0.01	0.01	0.01	0.01	0.01
C _{2PLC}	0.0	0.0	0.15	0.0	0.0	0.0
C _{2PRC}	1.0	1.0	0.85	1.0	1.0	1.0
e ₁	1.0	1.0	1.0	1.2	1.2	3.0
e ₂	1.5	1.5	1.5	1.5	1.5	1.0
e ₃	-	-	4.0	1.0	1.0	1.0
F _{DV}	0.04	0.04	0.04	0.04	0.04	0.04
G ₁₁	12.167	12.167	12.167	13.127	13.127	13.127
G ₁₂	-12.856	-12.856	-12.256	-14.0	-13.2	-13.2
^G 13	0.013	0.013	0.013	0.022	0.022	0.022
^G 21	6.285	6.285	6.285	13.127	13.127	13.127
G ₂₂	-8.2	-7.5	-8.2	-14.0	-13.2	-13.2
G ₂₃	0.11	0.11	0.11	0.022	0.022	0.022
k ^o r1w	0.05	0.05	0.05	0.068	0.059	0.057
k ⁰ r2w	1.0	1.0	1.0	0.7	0.7	0.98
k ⁰ r3w	1.0	1.0	1.0	1.0	1.0	1.0
k ⁰ r1c	1.0	1.0	1.0	1.0	1.0	1.0
k ⁰ r2c	1.0	1.0	1.0	1.0	1.0	1.0
			(to be con	ntinued)		

PARAMETER	QPH	QPR	SP	MPF-02	MPF-05	MPF-06
k ^o r3c	1.0	1.0	1.0	1.0	1:0	1.0
ĥ	0.0	0.0	0.0	0.0	0.0	0.0
к ₈₆	0.0	0.0	0.0	0.0	0.0	0.0
к ₉₆	0.0	0.0	0.0	0.0	0.0	0.0
N	40	40	40	40	40	40
P α	1.67	1.67	1.67	1.8	1.5	1.8
R _{k,max}	1.5	1.5	1.0	1.0	1.0	1.0
S _{1rw}	0.4	0.4	0.446	0.41	0.438	0.2943
S _{2rw}	0.35	0.35	0.344	0.359	0.343	0.3864
s _p	45	66	0.0	0.0	2	0.2
T ₁₁	0.37	0.37	0.37	0.37	0.37	0.37
^T 12	2.87	2.87	2.87	2.87	2.87	2.87
^T 21	0.37	0.37	0.37	0.37	0.37	0.37
T ₂₂	0.90	0.90	0.90	1.37	0.6	0.7
т ₃₁	-	-	0.0	0.0	0.0	0.0
т ₃₂	-	-	0.0	0.0	0.0	0.0
^α 1	200.0	200.0	25.0	68.0	150.0	300.0
^α 2	0.0	0.0	0.0	0.0	0.0	0.0
α3	0.0	0.0	0.0	0.0	0.0	0.0
°∕4	0.0	0.0	0.0	0.0	0.0	0.0
^α 5	0.0	0.0	0.0	0.0	0.0	0.0
	(to be continued)					

PARAMETER	QPH	QPR	SP	MPF-02	MPF-05	MPF-06
^α 6	0.0	0.0	25.0	0.0	1.0	1.0
α _D	0.005	0.02	0.0	0.0	0.0	0.0
β	1.0	1.0	1.0	1.0	1.0	1.0
[¢] eff,3	0.80	0.80	1.0	1.0	1.0	1.0
[¢] eff,4	0.80	0.80	0.80	1.0	0.8	0.9
log r _{wo}	1.3	1.3	1.3	1.3	1.3	0.7
• Y ₁₂	13.0	13.0	100.0	8.2	30.0	8.2
μw	0.63	0.63	0.64	0.83	0.83	0.90
μo	4.8	4.8	4.0	0.85	0.88	20.0
Ϋ́ _c	10.0	10.0	10.0	25.0	2.5	3.0



CSER= .2275 N NaCl

C3MAX0=.229

INTERFACIAL TENSION ALONG BINODAL CURVE FOR BASE CASE SP FIGURE 5.1









POLYMER VISCOSITY VERSUS POLYMER CONCENTRATION FOR BASE CASE SP







FIGURE 5.6 RESIDUAL SATURATION OF WATER AND OIL VERSUS INTERFACIAL TENSION TIMES TOTAL MOBILITY





FIGURE 5.7 RELATIVE PERMEABILITY CURVES OF WATER AND OIL FOR BASE CASE SP

S1RW=	. 446	S2RW= .344
VIS1=	.64	VIS2= 4.00
P1RW=	.050	P2RW=1.000
E1 =	1.00	E2 = 1.50













FIGURE 5.11 RUN 148 TOTAL CONCENTRATION HISTORIES















FIGURE 5.16 RUN 167 TOTAL CONCENTRATION HISTORIES









FIGURE 5.18 COMPOSITION PATH HISTORY FOR RUN 167







FIGURE 5.20 RUN 185 TOTAL CONCENTRATION HISTORIES







FIGURE 5.22 RUN 282 AQUEOUS CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE SP






FIGURE 5.25

RUN 282 TOTAL MOBILITY AND RELATIVE PRESSURE DROP PROFILES AT 0.5 P.V. FOR BASE CASE SP



FIGURE 5.26 RUN 282 INTERFACIAL TENSION PROFILE AT 0.5 P.V. FOR BASE CASE SP













CSER= . 2275 N NaC1

FIGURE 5.32 RUN 282 COMPOSITION PATH HISTORY FOR BASE CASE SP





FIGURE 5.34 INTERFACIAL TENSION AT 0.053 N NaC1 FOR BASE CASES QPR AND QPH





FIGURE 5.36 RELATIVE PERMEABILITY CURVES OF WATER AND OIL FOR BASE CASES QPH AND QPR





AND QPR



FIGURE 5.38 RUN 007 AQUEOUS CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE QPR



FIGURE 5.39 RUN 007 OLEIC CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE QPR







FIGURE 5.41 RUN 007 TOTAL MOBILITY AND RELATIVE PRESSURE DROP PROFILES AT 0.5 P.V. FOR BASE CASE QPR







. **..** ...



FIGURE 5.45 RUN 007 OIL RECOVERY HISTORIES FOR BASE CASE QPR





GURE 5.47 RUN 029 AQUEOUS CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE QPH







FIGURE 5.50 RUN 029 TOTAL MOBILITY AND RELATIVE PRESSURE DROP PROFILES AT 0.5 P.V. FOR BASE CASE QPH





CASE QPH









RUN NO :	MPF-02		
C3MAX0=	. 20000	C3MAX1 =	. 08000
C3MAX2=	. 20000		



SURFACTANT CONCENTRATION ON THE PHASE ENVELOPE AS A FUNCTION OF SALINITY FOR BASE CASE MPF-02



58 MICROEMULSION VISCOSITY AS A FUNCTION OF SALINITY FOR BASE CASE MPF-02



MPF-02

MICROEMULSION VOLUME FRACTION AS A FUNCTION OF SALINITY FOR BASE CASE MPF-02



MPF-02


MPF-02

MPF-02	C1=.470 C2	2=.500	C3=.030
G11=13.1270	G12=-14.000	G13=	0220
G21=13.1270	G22=-14.000	G23=	.0220
C3MAX0=.20	C3MAX1=.08	СЗМАХ	(2=.20
C2PR=.99	C2PL=.01 C5	SEL= .80	CSEU=1.20



FIGURE 5.62 INTERFACIAL TENSION AS A FUNCTION OF SALINITY FOR BASE CASE MPF-02

MPF-02	C1=.470 C2=.	.500 C3=.030
G11=13.1270	G12=-14.000	G13= .0220
G21=13.1270	G22=-14.000	G23= .0220
C3MAX0=.20	C3MAX1=.08	C3MAX2=.20
C2PR=.99	C2PL=.01 CSE	_= .80 CSEU=1.20



FIGURE 5.63

INTERFACIAL TENSION AS A FUNCTION OF SOLUBILIZATION RATIO FOR BASE CASE MPF-02



CSER= .1134 N NaCl C3MAX2=.2 C3MAX0=.2C3MAX1=.08 C2PR=0.99





MPF-02

CSER=	.2646N	NaCl		
C3MAX0=.2		C3MAX1=.08		C3MAX2=.2
C2PR=0.99				





MPF-02





MPF-02

Salinity: 0.181 N

СЗМАХО=.2	C3MAX1=.08	C3M9X2=,2
C2PR=0.99		C2PL=0.01



FIGURE 5.68

VISCOSITY ALONG BINODAL CURVE FOR BASE CASE MPF-02















FIGURE 5.74

WATER FLOOD PHASE CUT AND OIL RECOVERY HISTORIES FOR BASE CASE MPF-02

































RUN NO : MPF-05

C3MAX0=	. 20000	C3MAX1=	. 10000
C3MAX2=	. 20000		







MPF-05

CSER= .1032 N NaCl C3MAX0=.2 C3MAX1=.1 C3MAX2=.2





TERNARY DIAGRAM FOR BASE CASE MPF-05 AT 0.6 WT% NaCl

MPF-05

CSER= ,1806 N NaCl C3MAX0=.2 C3MAX1=.1 C3MAX2=.2







MPF -05









MPF-05

Μ	Ρ	F		0	5
---	---	---	--	---	---

CSER=	.1135 N NaCl	
C3MAXO=.2	C3MAX1=.1	C3MAX2=.2
C2PR=0.99		C2PL=0.01





5.95 MICROEMULSION VISCOSITY AS A FUNCTION OF SALINITY FOR BASE CASE MPF-05

MPF-05

C1=.470	C2=.500 C3=.030
C3MAX0=.20	C3MAX1=.08 C3MAX2=.20
C2PR=.99 C2PL=.01	CSEL= .80 CSEU=1.20



.


	C1=.470	C2=.500	C3=.030	
СЗМА	XO=.20	C3MAX1=.0	8 C3MAX	(2=.20
C2PR=.99	C2PL=.01		CSEL= .80	CSEU=1.20



MPF-05

C1=	470	C2=.500	C3=.1	030		
C3MAXO=.	20	C3MAX1=.	08	СЗМАХ	(2=.20	
C2PR=.99 C2F	°L=.01		CSEL	= .80	CSEU=1.	20



FIGURE 5.98 SOLUBILIZATION RATIOS AS A FUNCTION OF SALINITY FOR BASE CASE MFF-05

MPF-05	C1=.470 C2=.	500 C3=.030
G11=13.1270	G12=-13.200	G13= .0220
G21=13.1270	G22=-13.200	G23= .0220
C3MAX0=.20	C3MAX1=.08	C3MAX2=.20
C2PR=.99	C2PL=.01 CSEL	_= .80 CSEU=1.20



FIGURE 5.99 INTERFACIAL TENSIONS AS A FUNCTION OF SALINITY FOR BASE CASE MPF-05

ì

MPF-05	C1=.470 C2=	.500 C3=.030
G11=13.1270	G12=-13.200	G13= .0220
G21=13.1270	G22=-13.200	G23= .0220
C3MAX0=.20	C3MAX1=.08	C3MAX2=.20
C2PR=.99	C2PL=.01 CSE	_= .80 CSEU=1.20





FIGURE 5.101 SIMULATION INPUT POLYMER VISCOSITY VERSUS POLYMER CONCENTRATION FOR BASE CASE MPF-05



. 438	S2RW=	.343
. 83	VIS2=	. 88
.059	P2RW=	. 700
1.20	E2 =	1.50
	.438 .83 .059 1.20	. 438 S2RW= . 83 VIS2= . 059 P2RW= 1. 20 E2 =



S1RW=	. 438	S2RW= .343	
VIS1=	.83	VIS2= .88	
P1RW=	.059	P2Rk= .700	
E1 =	1.20	E2 = 1.50	



FIGURE 5.104

04 FRACTIONAL FLOW CURVE OF WATER FOR BASE CASE MPF-05



FIGURE 5.105 WATER FLOOD PHASE CUT AND OIL RECOVERY HISTORIES FOR BASE CASE MPF-05





FIGURE 5.107 RUN 145 AQUEOUS CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-05







FIGURE 5.110 RUN 145 TOTAL CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-05



FIGURE 5.111 RUN 145 TOTAL MOBILITY AND RELATIVE PRESSURE DROP PROFILES AT 0.5 P.V. FOR BASE CASE MPF-05



FIGURE 5.112 RUN 145 INTERFACIAL TENSION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-05



1 . A . A

2

FIGURE 5.113 RUN 145 AQUEOUS CONCENTRATION HISTORIES FOR BASE CASE MPF-05









FIGURE 5.117 RUN 145 PHASE CUT AND OIL RECOVERY HISTORIES FOR BASE CASE MPF-05

a ser as es







RUN NO : MPF-06

C3MAX0=	. 20000	C3MAX1 =	. 15000
C3MAX2=	. 20000		





1 SURFACTANT CONCENTRATION ON THE PHASE ENVELOPE AS A FUNCTION OF SALINITY FOR BASE CASE MPF-06







FIGURE 5.123 FRACTIONAL FLOW CURVE OF WATER FOR BASE CASE MPF-06

	٢	1PF -06				
F1=0.00 A2	2=0.00 F	73=300.0	Fi4=0.1	00	A5=0.00	
MUW=.85 MU	JØ=20.00 (C1=.470	C2=.51	00	C3=.030	
C3MAXO=	.20 C	C3MAX1=.1	.6 1	СЗМАХ	2=.20	
C2PR=.99 C2	PL=.01		CSEL=	. 60	CSEU=1.4	40



FIGURE 5.124

MICROEMULSION VISCOSITY AS A FUNCTION OF SALINITY FOR BASE CASE MPF-06

C1 = .470	C2=.500 C3	3=.030	
C3MAX0=.20	C3MAX1=.15	СЗМАХ	2=.20
C2PR=.99 C2PL=.01	C	SEL= .60	CSEU=1.40



FIGURE 5.125 MICROEMULSION VOLUME FRACTION AS A FUNCTION OF SALINITY FOR BASE CASE MPF-06





C1=.470	C2=.500 C3=.	030
C3MAX0=.20	C3MAX1=.16	C3MAX2=.20
C2PR=.99 C2PL=.01	CSEL	= .60 CSEU=1.40



FIGURE 5.127

j

SOLUBILIZATION RATIOS AS A FUNCTION OF SALINITY FOR BASE CASE MPF-06





MPF-05	C1=.470	22=.500	C3=.030
G11=13.1270	G12=-14.000	G13=	. 0220
G21=13.1270	G22=-14.000	G23=	. 0220
C3MAX0=,20	C3MAX1=.16	СЗМАХ	(2=.20
C2PR=.99	C2PL=.01 (CSEL= .60	CSEU=1.40



MPF-06

CSER= .1035 N NaCl C3MAX0=.2 C3MAX1=.16 C3MAX2=.2 C2PR=0.99



FIGURE 5.130 TERNARY DIAGRAM FOR BASE CASE MPF-05 AT 0.6 WT% NaCl



CSER= .5865 N NaCl C3MAXO=.2 C3MAX1=.16 C3MAX2=.2 C2PR=0.99



MPF-06

CSER= .3450 N NaCl C3MAXO=.2 C3MAX1=.16 C3MAX2=.2 C2PR=0.99 C2PL=0.01



÷3 .


MPF-05



MPF-05



Salinity:	0.26	N NaCl			
C3MAX0=: 2		C3MAX1=.	16	C3MAX2=.2	• •
C2PR=0.99				C2PL=0.	01







FIGURE 5.137 SIMULATED POLYMER VISCOSITIES VERSUS SHEAR RATE FOR BASE CASE MPF-06



FIGURE 5.138 COMPARISON OF SIMULATED AND EXPERIMENTAL WATER FLOOD HISTORY (e_1 =1.0, e_2 =1.0)









e1=2.5



FIGURE 5.143 WATER FLOOD TOTAL CONCENTRATION HISTORIES FOR BASE CASE MPF-06



FIGURE 5.144 WATER FLOOD PHASE CUT AND OIL RECOVERY HISTORY FOR BASE CASE MPF-06









には、「「「「「

... :.



FIGURE 5.149 RUN 133 TOTAL CONCENTRATION PROFILES AT 0.5 P.V. FOR BASE CASE MPF-06















Experimental Oil Recovery



· ·

 ${\mathfrak e}_i /$





MPF-06	C1=.470	C2=.500	C3=.030
G11=13.1270	G12=-14.000) G13=	0221
G21=13.1270	G22=-14.000) G23:	0435
C3MAX0=.20	C3MAX1=.16	S СЗМАХ	X2=.20
C2PR=.99	C2PL=.01	CSEL= .60	CSEU=1.40



FIGURE 5.160

INTERFACIAL TENSION AS A FUNCTION OF SOLUBILIZATION RATIOS FOR RUN 220

MPF-06	C1=.470 C	2=.500	C3=.030
G11=13.1270	G12=-14,000	G13=	.0221
G21=13.1270	G22=-14.000	G23=	.0435
C3MAX0=.20	C3MAX1=.16	СЗМАХ	2=.20
C2PR=.99	C2PL=.01 C	SEL= .60	CSEU=1.40



FIGURE 5.161

INTERFACIAL TENSION AS A FUNCTION OF SALINITY FOR RUN 220



FIGURE 5.162 RESIDUAL SATURATION AS A FUNCTION OF CAPILLARY NUMBER



FIGURE 5.163 RUN 220 TOTAL CONCENTRATION AND OIL RECOVERY HISTORIES



* * *

CHAPTER VI

SENSITIVITY STUDY

6.1 Introduction

The purpose of a sensitivity study is to identify and determine the effect of the most important parameters affection the oil recovery of the process. It is necessary that the most sensitive parameters be eliminated before the design of an actual process. The sensitivity study can be accomplished by systematically varying the input parameters, one at a time, from the base case run, within the range of practical interest. If the oil recovery is not affected or is only slightly affected by the changes, this parameter is considered to be insensitive; otherwise, it is sensitive.

Because simulation runs can be accomplished in a relatively short time and at less cost, computer simulations rather than laboratory experiments were utilized to perform this sensitivity study. A high-speed computer can generate simulated results in a matter of seconds or minutes whereas the comparable laboratory experiment may require days or even weeks to run. However, the simulator is only a mathematical model and the quality of the simulation depends on the numerical model and the solution techniques used. Before using the simulator to design an actual process, history matching studies must be conducted in order to determine the

reliability of the simulator.

In general, the lower the interfacial tension and the better the mobility control during a micellar/polymer process, the higher the oil recovery will be. The surfactant loss, dispersion, phase behavior, slug viscosity and slug salinity, all directly affect the amount of oil recovered. Of these, the single most important factor related the oil recovery is probably the amount of surfactant which is available for the oil recovery.

Three of the many important factors in the design of a micellar/polymer flood are the use of an electrolyte gradient, the type of slug (microemulsion versus aqueous) and mobility control. Each of the above design factors will be affected by the type of reservoir rock, reservoir brine, type of oil, type of surfactant, alcohol, and polymer, the amount of surfactant and polymer loss, dispersion and ion exchange.

A sensitivity study was conducted by Wang^{61,62} using an improved version of the simulator of Pope and Nelson⁶⁰. His study gives a general idea of the most sensitive parameters affecting oil recovery.

In this study, three design factors (electrolyte gradient, microemulsion versus aqueous slug, and mobility control) were specifically studied in connection with the history matches previously discussed. The results of this sensitivity study are presented in the following sections. Since this is not a complete study, more studies are suggested and should be continued with emphasis on the more important parameters identified.

6.2 Electrolyte Gradient

The electrolyte gradient (salinity gradient) is affected by the cationic composition of the reservoir brine, preflood, surfactant slug, polymer slug, chase brine, cation exchange with the reservoir rock, dispersion, etc. High salinity usually causes a higher surfactant and polymer retention and lower polymer viscosity. As a result, less oil is recovered. A preflood is sometimes used to condition the reservoir to the desired salinity for the following surfactant slug. Sacrificial agents may be included to reduce the loss of surfactant. Prefloods are not always effective and if not properly designed may even be detrimental to good oil recovery. Nor are prefloods always necessary. The salinity of the polymer drive is the most important salinity because it tends to dominate and control the final surfactant environment.

In a study of Holm's (base case QPH) and Rathmell's (base case QPR) laboratory designs for the Bell Creek field scale project, with similar core properties, oil, surfactant and polymer, Holm's microemulsion slug achieved about 87% oil recovery (run 29) compared with about 75% oil recovery (run 151) for Rathmell's aqueous slug. However, using the simulator, about 89% oil recovery (run 158) was achieved for Rathmell's experiment by lowering the salinity in polymer slug to one third of that in the surfactant slug. This salinity gradient was roughly equivalent to that in Holm's experiment. Due to the fact that phase behavior and surfactant and polymer absorption were made independent of salinity, the salinity reduction in the buffer bank only affected the polymer viscosity, which increases with decreasing salinity. This alone increased oil recovery by 14% (75% to 89%). If the amount of surfactant and polymer absorption had been reduced as the salinity decreased, even higher simulated oil recovery might have resulted.

During history matching of MPF-05, run 179 showed an oil recovery of 80%. After decreasing the salinity in polymer drives to one-half of that in the surfactant slug (i.e., from optimal salinity of 0.129 N NaCl to 0.065 N NaCl), the oil recovery dropped to only 58% (run 180). This is contrary to the result of the previous example. The basic difference is that a constant Type II (-) phase environment is assumed for the former example and salinity-dependent phase environment is assumed in the latter example. Low salinity (away from optimal salinity) in the polymer drive for the latter increased the phase envelope and interfacial tension which resulted in decreased oil recovery. This negative effect combined with positive factors such as the increase in polymer viscosity and the decrease in the absorption determines the final oil recovery. To determine the net effect of the salinity gradient on the oil recovery requires an understanding of the interaction of all of these effects. However, a salinity higher than optimal in the preflush and lower than optimal in the drive will usually produce higher oil recovery. More simulations would be required to determine if there is a polymer drive
salinity between the limits investigated for which this would be true in this specific case (MPF-05). Such simulations should be used to help design future experiments.

6.3 Sensitivity Study of Microemulsion Versus Aqueous Slugs

Some researchers prefer the injection of a large slug of low concentration aqueous solution whereas others prefer the injection of a small highly concentrated slug of microemulsion. Wang⁶¹ showed in his sensitivity study that the computer simulation results showed no significant advantages of the design over the other under his model case conditions as long as the total amount of surfactant injected remained constant. Similar findings were reported in the previous section for case QPH and QPR. Four additional runs (i.e., 173, 174, 188 and 189) were made to further verify this result (Table 6.1). Basically, these are similar to the simulation base case run MPF-06 but without polymer inaccessible pore volume.

Run 173 (a small slug, high surfactant concentration microemulsion run) produced 66% of the oil after correction for the oil injected in the slug. Run 174 (a large slug, low surfactant concentration, aqueous injection run) produced 62% of the oil. In a small, high concentration, aqueous injection slug case (run 188), 61% of the oil was produced. However, as high as 77% of the oil was recovered with a large slug, low surfactant concentration, microemulsion slug (run 189).

In the above four cases, the total amount of surfactant

injected and the total surfactant retention (both input and output) were identical. A large slug, low concentration, microemulsion slug produced the highest oil recovery, whereas a small slug, high concentration, aqueous injection produced the lowest oil recovery. The injected slug viscosity varied from 19 cp. to 57 cp. High slug viscosity did not correlate with high oil recovery. However, two factors could be the cause for this lack of correlation. First, the slug viscosity changes immediately after it is injected due to composition changes as it disperses and its phase behavior changes. Secondly, and even more important, 1-D results (both simulated and actual core floods) are insensitive to mobility control compared to an unconfined reservoir process. Thus, these as well as the results discussed below should not be used in connection with field scale behavior. This type of study is useful for interpreting or designing linear core floods. Even for them, however, gravity, fingering, and heterogeneity can sometimes be significant, depending on the core, mobility ratios, flooding rate, etc. In such cases, 2-D simulation should be used.

When the interfacial tension profiles at 0.5 P.V. were compared for both cases (Figures 6.1 through 6.4), it was found that the interfacial tension between water and microemulsion was about identical, but low interfacial tension between oil and microemulsion was achieved in run 189. This may explain why more oil was produced in run 189.

6.4 Sensitivity Study of Mobility Control

Mobility control is important to both polymer flooding and micellar/polymer flooding processes. There are two mobility ratios of importance. The first is between the oil bank and the surfactant slug and the second between the surfactant slug and the following polymer drive. Many variables are associated with the mobility ratios, either directly or indirectly, such as the viscosities of the oil, water, slug and drive, the polymer inaccessible pore volume, permeability reduction, non-Newtonian behavior, surfactant-polymer interaction, and dispersion. These should be investigated for their effects on the oil recovery.

In order to reduce the cost of the polymer buffer bank, a graded polymer bank has been suggested ¹⁴⁵⁻¹⁴⁷. Base case MPF-05 was a constant salinity (at optimal), aqueous surfactant slug simulation run with four slugs of polymer drive. The concentration in the polymer slugs was graded back to reduce the polymer utilization while still maintaining good oil recovery.

Run 181 which used 0.5 P.V. of 2250 ppm polymer produced 82% oil recovery compared with 79.5% oil recovery for the four graded polymer slug design of run 179. The total amount of polymer injected was identical. In other studies (Table 6.2, continuous injection of 1900 ppm polymer (run 185) produced 80.3% oil recovery while the amount of polymer injected was 2.4 times greater than that in the previous cases. For continuous injection of 800 ppm polymer (run 184), the total amount of polymer injected was equal to that of run 179 and

run 181, and the oil recovery dropped to 74%. This suggests that not only is the amount of polymer injected important but also the design of the polymer slug concentrations. As indicated above, more polymer in the buffer bank may not necessarily increase the oil recovery while the graded bank design, if not superior to the single polymer bank design, gives good oil recovery provided that the polymer slugs are carefully designed. A preliminary screening study of each combination of polymer slug or slugs using the simulator was suggested in order to obtain good oil recovery using a minimal amount of polymer.

6.5 Other Sensitivity Studies

During the history matching studies of the experiments conducted in this laboratory, numerous simulation runs were required to adequately match the experimental data. In some cases, since several input parameters were changed simultaneously, these may not represent an ideal sensitivity study. The results of these studies, however, are of assistance in determining the changes in the simulation resulting from changing the input parameters.

6.5.1 Base Case MPF-02

For this particular simulation run, the initial brine and surfactant slug salinities were at 0.189 N NaCl, which is optimal. The injected surfactant slug was 0.0825 P.V. of a microemulsion slug. The polymer (1000 ppm) slug was continuously injected at a salinity 0.086 N NaCl. The simulation results of this base case run (run 48)

are presented in Figures 5.75 through 5.85.

1) Injection Composition Effect

The injected composition of base case run 48 and runs 61 and 62 are presented in Table 6.3. Higher oil recovery was associated with higher oil content slug even after correction for the oil injected. Run 61 (35% oil in slug) resulted in 74.2% oil recovery compared with 79.1% and 82.0% oil recoveries in run 62 (59% of oil in slug) and run 48 (49% of oil in slug), respectively. The slug viscosity was about the same in all cases since oil and water viscosities were similar (0.83 cp. for water and 0.85 cp. for oil). The reason for the higher oil recovery (about 7.7% between runs 61 and 62) is not understood.

2) Phase Behavior

It was observed that a higher phase envelope produced less oil (Table 6.3). For run 65, the oil recovery reached 92.6% (corrected for injected oil) with C_{3MAX0} , C_{3MAX1} , C_{3MAX2} equal to 0.15, 0.05 and 0.15, respectively. Only 62.0% of the oil was produced (corrected for oil injected) when C_{3MAX0} , C_{3MAX1} and C_{3MAX2} were 0.25, 0.15 and 0.25 (run 64). The oil recovery for the base case 48 was 79.1% with C_{3MAX0} , C_{3MAX1} and C_{3MAX1} and 0.2, respectively.

Relocating the plait point at 15% oil concentration did not produce a significant difference in oil recovery, as shown on Table 6.3 (run 48 versus run 66).

6.5.2 Base Case MPF-05

Run 145, base case MPF-05, was a constant (optimal) salinity, six-component, aqueous slug injection run with four graded polymer slugs. Oscillations of the oil cut were a problem for this set of simulation runs with a time step of 0.001 P.V. Decreasing the time step to 0.0001 P.V. reduced the oscillation significantly (Figures 5.116 and 5.119).

The simulated oil cut was too low in the front but too high in the rear of the oil bank on the simulation curve as shown on Figure 5.116. A change in the Type III phase behavior boundaries (i.e., C_{SEL} and C_{SEU}) resulted in a higher simulated oil cut at the oil bank front (Figure 6.6).

In run 156, the lowest effective salinity for Type III, C_{SEL} , was raised from 0.103 N NaCl to 0.14 N NaCl, which was above the optimal salinity (0.129 N NaCl). In other words, all slug salinities and the initial salinity were lower than C_{SEL} , and a Type II(-) phase environment was assumed throughout the process. It was believed that a particular value for C_{SEL} might exist which will produce the exact oil bank front desired. However, it was doubtful that Type II(-) was actually the phase environment encountered during the process. It was more realistic that Type II(+), instead of Type II(-), would be encountered due to the divalent ions being picked up by ion exchange. In an investigation of a Type II(+) phase environment (run 157), decreasing the highest effective salinity of Type III phase behavior from 0.1551 N NaCl to 0.12 N NaCl (below the optimal salinity 0.129N)

did not show an improved match (Figure 6.10). The low oil cut front was not understood.

In another study on the effect of relative permeability, the exponents e_1 and e_2 of the water and oil permeability equations were changed from 1.2 and 1.5 to 1.0 and 2.5, respectively. The oil break-through moved from 0.08 P.V. to 0.2 P.V., which was close to that of 0.018 P.V. reported by Hedges and Glinsmann (Figure 6.13). 0il recovery was also lowered about 8% (Figure 6.14). Nevertheless, this could partly explain the difference between the oil breakthrough time of Hedges and Glinsmann's experiment compared with that of MPF-05.

6.5.3 Base Case MPF-06

Base case run of MPF-06 (run 133) was a six-component, Type III phase environment, microemulsion slug run with a salinity gradient. Oil recovery was 65% (corrected for oil injected) for a 0.64 P.V. surfactant slug injection. The alcohol and surfactant were combined as the surfactant pseudo-component in determination of the phase compositions and interfacial tensions.

Several changes in the input parameters were made in order to obtain a good match with the laboratory result.

1) Slug Viscosity

Run 74 with a slug viscosity of 37.8 cp. produced 86.23% oil while run 71 with a slug viscosity of 22.74 cp. produced 83.4% oil (Figures 6.16 and 6.18). A difference in the oil bank was also observed. With the lower viscosity slug (run 71), the oil bank was shorter than the oil bank produced by the higher viscosity slug. An oil peak appeared at the oil bank trailing edge in the lower viscosity slug case.

2) Oil Viscosity

Oil viscosities of 25 cp. and 15 cp. were tested in addition to 20 cp. (Figures 6.20 and 6.22). Essentially no change in oil recovery was observed.

Table 6.1

SUMMARY OF SIMULATION RESULTS WITH DIFFERENT SURFAC-TANT SLUG DESIGNS FOR RUNS 173, 174, 188 AND 189

Run No.	Surfactant Composition (v%)	Slug Size (P.V.)	Amount of Surfactant Injected $(C_{3T}V_{ps})$	Slug Viscosity (cp.)	Final Oil Recovery (%)
173	C _{1I} =0.42 Water C _{2I} =0.42 Oil C _{2I} =0.16 Surfactant	0.04	0.0064	56.7	66.3 *
174	C _{1I} =0.94 Water C _{3I} =0.06 Surfactant	0.1067	0.0064	18.8	62:0
188	C _{1I} =0.94 Water C _{3I} =0.16 Surfactant	0.04	0.0064	48.7	61.1
189	C _{1I} =0.47 Water C _{2I} =0.47 Oil C _{3I} =0.06 Surfactant	0.1067	0.0064	27.8	77*

* corrected for the amount of injected oil

Table 6.2

SUMMARY OF THE SIMULATED OIL RECOVERY WITH DIFFERENT BUFFER BANK DESIGN FOR RUNS 179, 181, 184 AND 185

Run No.	P Concentration (ppm)	olymer E Size (P.V.)	Buffer Bank Total Polymer Injected (C ₄₁ V _{ps})	Final Oil Recovery (%)
179	1900	0.19	0.1061*	79.5
	1200	0.20		
	700	0.40		
	300	0.60		
181	2250	0.50	0.1125	82.0
184	800	1.40	0.1120	74.0
185	1900	1.40	0.2660	80.3

 \star polymer concentration in wt%

.

Table 6.3

LIST OF SOME OF THE INPUT PARAMETERS AND SIMULATED OIL RECOVERIES FOR RUNS, 48, 61, 62, 64, 65 AND 66

Input Parameters	Pun No							
Full dire cer s	48	61	62	64	65	66		
C _{3MAX0}	0.2	0.2	0.2	0.25	0.15	0.2		
C _{3MAX1}	0.08	0.08	0.08	0.15	0.05	0.08		
C _{3MAX2}	0.2	0.2	0.2	0.25	0.15	0.2		
C _{2PLC}	0.0	0.0	0.0	0.0	0.0	0.15		
C _{2PRC}	1.0	1.0	1.0	1.0	1.0	0.85		
c [*] ₁₁	0.45	0.59	0.35	0.45	0.45	0.45		
c [*] ₂₁	0.49	0.35	0.59	0.49	0.49	0.49		
C _{3I}	0.06	0.06	0.06	0.06	0.06	0.06		
0il Recovery (%)	y 90.32	82.27	95.53	73.22	103.80	90.45		
0il Recovery (%) (corrected for injected	y ed							
oil)	79.06	74.23	81.97	61.96	92.54	79.19		

* of injected slug water,oil and surfactant concentration





FIGURE 6.2 RUN 173 INTERFACIAL TENSION PROFILES AT 0.5 P.V.









































CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

- Several improvements were made in an existing 1-D micellar/ polymer simulator. These include physical property models for polymer, alcohol, dispersion, and inaccessible pore volume. The calculation of pressure drop was also added and used in the history matching part of this study.
- 2. Several oil recovery corefloods were performed for history matching purposes. Significant additions to the data collected in similar experiments by Glinsmann and Hedges included polymer concentration, cation concentrations, and pressure drop. Also, tritium was used as a tracer to measure dispersivity and residual oil saturation. Physical property data measured included phase behavior, viscosity, and IFT.
- 3. These experiments plus several in the literature were matched with the simulator. Various physical property data were compared with simulation input. These included polymer viscosity, microemulsion viscosity, interfacial tension, phase behavior, relative permeability to oil and water, and capillary desaturation curves. Data on other properties were not available.

- 4. Additional physical property and coreflood data will be needed before the simulator can be adequately tested. A better description of the phase behavior (especially the effects of calcium, polymer, and alcohol) is needed. The precise location of the plait point made a big difference in one case studied.
- 5. The early breakthrough of oil and surfactant and the pressure drop all indicated a problem with fingering or gravity in all but one of the corefloods. The gravity effect should be studied with Hong's 2-D simulator. The simulator should be used to help design future experiments and more attention given to these factors.
- 6. More work is needed on some of the physical property models such as inaccessible pore volume. The description of polymer viscosity seems to be adequate. However, in some cases a different viscosity had to be input to match the coreflood pressure drop. This could be due to several effects, such as the increase in calcium which occurred, which strongly affects polyacrylamide viscosity. More study of this difference is needed.
- 7. The same relative permeability parameters determined by matching the waterfloods gave an adequate match of the oil bank cut and breakthrough for the micellar floods. Collection of waterflood data is desirable and useful and should be reported with such micellar floods if history matching is contemplated.

- More extensive data should be collected to enable a more defi-8. nitive test of the simulator. Specifically, a more complete compositional analysis of the produced fluids should be done. Sulfonate and alcohol in particular should always be measured, in each phase if possible. More extensive pressure drop data (closer spacing of taps) would also be desirable. More extensive physical property data are also needed in some cases. In particular, in addition to the pseudo-ternary and volume fraction diagrams, dilution diagrams would be very useful. Since collection of these data are extremely time consuming, concentration on a particular formulation such as used here in experiment MPF-06 is probably the most feasible approach. This enables us to take advantage of some very well established quantities, such as the IFT correlation shown in Figure 4.10. Also, the data collected on low tension relative permeability, trapping, and dispersion by Delshad 140 and Mac Allister 139 and on rheology by Jones¹²⁴ can then be used more or less directly. Some additional physical property modelling will be required to incorporate these items.
- 9. The use of Hirasaki's ¹⁴⁴ cation exchange model was limited to just one case. Many more calculations are needed and a better determination of the appropriate input parameters is needed. This model should be used to help design the amount of calcium which should be used in the physical property measurements.
- 10. The results of Ohno¹⁵⁰ and Engelsen¹⁴⁹ should be combined with those of this study to produce a better simulator and a more complete physical property and history matching picture. The improved numerical techniques used by Ohno (various semi-discrete approaches) should help reduce the occasional problem with oscillations which is encountered during some history matching simulations since the time-step is automatically reduced as needed. The improved microemulsion viscosity model of Engelsen should be further tested and improved. More comparisons with experimental viscosity data are needed. The dilution model of Engelsen should be tested and improved as needed.
- 11. A limited sensitivity study was done in connection with the history matching work. Since many runs are almost always needed to match a given flood, this is an efficient and desirable effort to combine with the history matching and should be continued and expanded. Results of this study continue to show low sensitivity to the type of slug (aqueous versus oleic), slug size (at constant amount of injected surfactant), and polymer grading (at constant amount of injected polymer) for these homogeneous 1-D simulations. However, more attention to the coupling of these with mobility control factors is needed, for example, the effect of polymer-surfactant interaction. The latter is another item not yet properly modelled in the simulator. These same variables need to be studied in 2-D (as being done

by Hong^{70,79} and Wang^{84,85}). It has been firmly established that salinity gradient almost always makes a big difference even in 1-D, yet more studies of this very important factor are needed to fully evaluate how it is coupled with other variables, for example, cation exchange, polymer type, surfactant type, and so on. Sensitivity studies of these and other factors such as alcohol effects can now be done more completely and precisely because of the various improvements made in the simulator.

12. Several comparisons between the dispersion produced by truncation error and that due to physical dispersion using a large enough number of grid blocks to make the truncation error negligible were made. Also, the use of a negative input dispersivity was tested and compared with the above. These comparisons suggest that the equivalence of numerical and physical dispersion in 1-D is reasonably close under the limited conditions studied and assuming that all phase dispersivities were equal. But more comparisons of this type are needed, especially under three phase flow conditions. Also, since the just completed studies of Delshad and Mac Allister show that the phase dispersivities vary over two orders of magnitude even at a fixed velocity for a given rock depending on phase type, phase saturation, and IFT, these effects should be incorporated and this type of comparison repeated under more exacting conditions.

- 13. This study has demonstrated the feasibility of conducting core flood experiments and matching them with a compositional simulator using a reasonable number of physical property data as the basis for selecting the many model parameters required. Although much remains to be done, the utility of using such a simulator has been demonstrated both by the generally reasonable overall agreement of the matches with the experimental corefloods and equally so by the numerous minor to moderate discrepancies between the two. The latter must be studied and more data on them collected before a completely adequate test of the simulator can be made.
- 14. Corefloods need to be performed and matched which cover a wider range of variables than was feasible in this study. Examples include different rock types, surfactant types, temperatures, core lengths, core geometry, and so on.

NOMENCLATURE

NOMENCLATURE

a _{ij}	=	adsorption parameters
А	=	area of cross section
A _{ij}	=	binodal curve parameters
A _{p1} , A _{p2} , A _{p3}	=	polymer viscosity parameters
b _p	=	permeability reduction parameter
^b 3, ^b 4	=	adsorption parameters
C _{ij}	=	concentration of component i in phase j
c _i	=	overall concentration of component i in mobile
		phases
ĉ _i	=	concentration of component i in rock phase,
		expressed in the same units as C _i
°,	=	overall concentration of component i in mobile
		and rock phases
C _{SE}	=	effective ionic strength
C _{SEL}	=	lowest effective salinity for Type III phase
		behavior
C _{SEM}	=	effective ionic strength for polymer viscosity
		equation
C _{SEU}	=	highest effective salinity for Type III phase
		behavior
C _{SOP}	=	optimal salinity

C _{3MAXO}	=	height of binodal curve at C _{SE} = O
C _{3MAX1}	=	height of binodal curve at C _{SE} = 1
C _{3MAX2}	=	height of binodal curve at C _{SE} = 2
D	=	molecular diffusion coefficient, (cm ² /sec)
e ₁ , e ₂	=	relative permeability exponents
E _R	=	recovery efficiency, fraction of initial oil
		recovered
fj	=	fractional flow of phase j, $j = 1, 2, 3$
F _{DV}	=	$\Delta t_D / \Delta x_D$
G _{ij}		interfacial tension parameters
k	=	absolute permeability
k'	= .	parameter used in eq. (3.12)
k _{rj}	=	relative permeability of phase j
k ^o rj	=	end point relative permeability of phase j
K _{ij}	=	physical dispersion coefficient, (cm ² /sec)
κ ₈₆ , κ ₉₆ , κ	=	mass action exchange constants
L	=	length of system
n _c	=	number of components
n _i	=	mass flux of component i, mass/area/time
n _p	=	number of phases
n'	=	power-law exponent
Ν	П	number of grid blocks
Р	=	pressure, psia

Pe	=	Peclet Number
Pa	= .	parameter used in Meter's equation
q	=	volumetric injection rate
Q _v	=	cation exchange capacity of clays, (meg/ml)
ri	=	total reaction rate of component i, mass/volume/
		time
R _k	=	permeability reduction factor
R _{k,max}	=	maximal value of R _k
^R rf	=	residual resistance factor
S	=	saturation, volume fraction
S _{or}	=	residual oil saturation
s _p	=	salinity dependent parameter for polymer
		solution viscosity
s _{wr}	=	residual water saturation
t	=	time
t _D	=	$\int_0^t q dt/LA\phi$ = cumulative injection or production
		in pore volume
T _{ij}	=	desaturation parameters
^u j	=	volumetric flux of phase j
U _T	=	total volumetric flux
V	=	frontal velocity
w _i	=	mass concentration of component i, mass of i/
		volume

W _{ij}	=	mass fraction of component i in phase j,
		mass/mass
ŵi	=	mass concentration of component i in rock phase,
		mass of i/volume
x	=	space coordinate
× _D	н	dimensionless distance in x-direction, x/L
× _{D,10}	=	fractional distance at 10% concentration
× _{D,90}	=	fractional distance at 90% concentration
α	=	dispersivity, (cm)
α _D	=	normalized dispersivity, (α/L)
(a _D) _{eff}	=	normalized effective dispersivity, (cm/L)
(a _D) _{phy}	=	normalized physical dispersivity, (cm/L)
αj	=	viscosity parameter
β	=	contribution factor of calcium to sodium,
		physical dispersion parameter
β ^C	=	ion exchange coefficient for clays for Hirasaki's
		model, (meg/ml) ⁻¹
β ^s	=	ion exchange coefficient for surfactant for
		Hirasaki's model, (meg/ml) ⁻¹
γ	=	interfacial tension, (dyne/cm)
Ŷ	=	shear rate, (sec ⁻¹)
Υ ₁₂	=	shear rate at which viscosity equals to $\mu_0^{}/2$
Ŷc	= ,	equivalent shear rate, (sec ⁻¹)

=	shear rate at which viscosity equals ($\mu_0^{}+\mu_\infty^{})/2$
=	$(t_{D}-1)/(t_{D})^{\frac{1}{2}}$
=	λ when effluent contains 10% tracer concentration
=.	λ when effluent contains 90% tracer concentration
=	total relative mobility, (cp. ⁻¹)
=	viscosity of phase j, (cp.)
=	apparent viscosity, (cp.)
=	viscosity at zero shear rate
=	polymer viscosity at zero shear rate (cp.)
=	viscosity of the solvent
=	$(\mu-\mu_s)/\mu_s$
=	viscosity at infinite shear rate
=	density
=	density of pure component i
Ξ	porosity
н	effective porosity $(\phi-\phi_{inacc})/\phi$
=	inaccessible pore volume, fraction of $\boldsymbol{\varphi}$
=	difference operator

SUBSCRIPTS

i = component number
1 = water
2 = oil

3	3 =	chemical (surfactant)
4	↓ =	polymer
5	5 =	total nonsorbing anions
6	5 =	calcium (or tracer)
7	' =	alcohol
8	} =	calcium/surfactant complex
g) =	sodium
j	=	phase number
1	. =	aqueous (water-rich)
2	2 =	oleic (oil-rich)
3	; =	microemulsion (oil/water/surfactant)
с	=	chemical
I	=	initial value
m	8	microemulsion
М	=	invariant point concentration
0	=	oil
w	п	water

APPEDICES

APPENDIX A

DERIVATION OF GOVERNING EQUATIONS WITH TRUNCATION ERROR ESTIMATION

GENERAL DESCRIPTION OF THE SIMULATOR AND THE MATHEMATICAL MODEL

This section mainly discusses the nature of the compositional simulator and the development of the mathematical model.

The original Pope and Nelson simulator⁶⁰ was a onedimensional, compositional simulator which solved the governing equations using an explicit finite-difference technique. The basic assumptions made were:

- the system is one-dimensional and homogeneous in permeability and porosity,
- 2) local thermodynamic equilibrium exists everywhere,
- the total mixture volume does not change upon mixing individual components,
- 4) gravity and capillary pressure are negligible,
- 5) fluid properties are a function of composition only,
- 6) Darcy's law applies, and

A.1

 physical dispersion can be adequately approximated by numerical dispersion by selecting the appropriate grid size and time step.

Additional assumptions were required to model various properties such as interfacial tension and viscosities, which are discussed whenever needed. In the current simulator, the physical

dispersion term has been modeled using a three-point central difference formula as mentioned in Chapter III.

A.1.1. Derivation of General Governing Equation Without Dispersion 148

To derive the governing equation, a mass balance for a small element of volume (of total porous medium) $\Delta x \Delta y \Delta z$ must be done. By the law of conservation of mass,

Accumulation = Mass in - Mass out + Generation terms.

For the one-dimensional case,

Assume no chemical reaction, i.e. $r_i = 0$, and divide eq. (A.1) through by $\Delta x \Delta y \Delta z \Delta t$,

$$\frac{(w_i|_{t+\Delta t} - w_i|_t)_{xyz}}{\Delta t} = \frac{(n_i|_{xyz} - n_i|_{x+\Delta x,y,z})_t}{\Delta x}$$
(A.2)

At the limit of eq. (A.2) as $\triangle x$ and $\triangle t$ approach zero,

$$\frac{\partial w_i}{\partial t} + \frac{\partial n_i}{\partial x} = 0$$
 (A.3)

where,
$$i = 1, 2, 3, ..., n_c$$

By averaging over a small volume of porous medium and taking the limit through this volume assuming that Darcy's law is valid, the mass flux n_i in a porous medium with diffusion and convection terms can be expressed as eq. (A.4):

$$n_{i} = \sum_{j} (\rho_{j} u_{j} w_{ij} - \phi S_{j} K_{ij} \rho_{j} - \frac{\partial W_{ij}}{\partial x})$$
(A.4)

where

$$u_{j} = - \frac{k k_{rj}}{\mu_{j}} \left(\frac{\partial P_{j}}{\partial x} + g \sin \theta \right)$$
 (A.5)

$$K_{ij} = D_{ij} + \alpha_j v_j^{\beta_j}$$
(A.6)

$$v_j = \frac{u_j}{\phi S_j}$$

The mass concentration w_i is the sum of the mass in the flowing fluid and the mass adsorbed on the rock surface, thus,

$$w_{i} = \phi_{j} \sum_{i} (\rho_{j} S_{j} w_{ij}) + (1 - \phi) \widehat{w}_{i}$$
(A.7)

Substitute eq's. (A.7) and (A.4) into eq. (A.3),

$$\frac{\partial}{\partial t} \left(\phi \sum_{j} (S_{j} w_{ij}) + (1 - \phi) \widehat{w}_{i} \right) + \frac{\partial}{\partial x} \left(\sum_{j} (\rho_{j} u_{j} w_{ij} - \phi S_{j} K_{ij} \rho_{j} - \frac{\partial}{\partial x} \right) = 0$$
(A.8)

With no dispersion (i.e. $K_{ij} = 0$), by the previous assumptions (1) and (3), eq. (A.8) can be simplified as,

$$\Phi \xrightarrow{\partial}_{\partial t} \left(\sum_{j} S_{j} C_{ij} + \frac{(1 - \phi)}{\rho_{i}} \widehat{w}_{i} \right) + \frac{\partial}{\partial x} \sum_{j} u_{j} C_{ij} = 0 \quad (A.9)$$

Define:

$$\hat{\vec{C}}_{i} \equiv \frac{1 - \phi}{\phi \rho_{i}^{0}} \hat{w}_{i}$$
(A.10)

$$f_{j} \equiv \frac{\lambda j}{\sum_{j \neq j}^{\lambda} j}$$
(A.11)

$$U_{\rm T} \equiv \sum_{j} u_{j} \qquad (A.12)$$

$$C_{i} = \sum_{j} S_{j}C_{ij} \qquad (A.13)$$

eq. (A.9) becomes,

$$\frac{\partial}{\partial t} (C_{i} + \hat{C}_{i}) + \frac{\partial}{\phi \partial x} \sum_{i} u_{j} \hat{c}_{ij} = 0$$
 (A.14)

Using $u_j = U_T f_j$, eq. (A.14) can be written as,

$$\frac{\partial}{\partial t} (C_i + \hat{C}_i) + \frac{U_T^2}{\phi^2 x} \sum_{j} f_j C_{ij} = 0$$
 (A.15)

3:52

Defining dimensionless groups of time and space,

$$x_{D} \equiv \frac{x}{L}$$
, and $t_{D} \equiv \int_{0}^{t} \frac{U_{T}}{\phi L} dt$, (pore volume injected)

Further set $\hat{C}_i = C_i + \hat{C}_i$, thus, eq. (A.14) becomes the equation of Pope and Nelson⁶⁰,

$$\frac{\partial}{\partial t_{D}} (C_{i}) + \frac{\partial}{\partial x_{D}} (\sum_{j} f_{j}C_{ij}) = 0$$
 (A.16)

After correcting the porosity for the volume of the adsorbed surfactant,

$$\hat{c}_{i} = (1 - \hat{c}_{3})c_{i} + \hat{c}_{i}$$

A.1.2 Special Case of General Equation With Dispersion

To study the physical dispersion effect on the oil recovery in micellar/polymer flooding, a governing equation involving a physical dispersion term must be derived.

To model the dispersion, the term of $\phi S_j K_{ij} \rho_j \frac{\partial W_{ij}}{\partial x}$ in eq. (A.4) must be retained. If diffusion is insignificant and the parameter $\beta_j = 1.0$, then, $K_{ij} = \alpha_j v_j$. Also, by definition $v_j = u_j / \phi S_j$ and $w_{ij} = c_{ij} \rho_i^0 / \rho_j$. The mass flux n_i can be expressed as, $\sum_j U_T (f_j C_{ij} - \alpha_j f_j (\partial C_{ij} / \partial x))$. The new governing equations in dimensionless form become,

$$\frac{\partial}{\partial t_{D}}(\hat{C}_{i}) + \sum_{j} \left\{ \frac{\partial}{\partial x_{D}} (f_{j}C_{ij}) - \alpha_{Dj} \frac{\partial}{\partial x_{D}} (f_{j} \frac{\partial C_{ij}}{\partial x_{D}}) \right\} = 0 \text{ (A.17)}$$
where $\alpha_{Dj} = \frac{\alpha_{j}}{L}$

This is the same as eq. (3.2) except for the inaccessible pore volume term $\phi_{i,eff}$.

Since,

$$\frac{\partial^2}{\partial x_D^2} (f_j C_{ij}) = \frac{\partial}{\partial x_D} (C_{ij} \frac{\partial f_j}{\partial x_D} + f_j \frac{\partial C_{ij}}{\partial x_D})$$
(A.18)

the last term in eq. (A.17) can be replaced, and the equation rearranged giving,

$$\frac{\partial}{\partial t_{D}}(\hat{C}_{i}) + \sum_{j} \left\{ \frac{\partial}{\partial x_{D}}(f_{j}C_{ij}) - \frac{\partial}{\partial x_{D}}(c_{ij}) - \frac{\partial}{\partial x_{D}}(c_{ij}) - \frac{\partial}{\partial x_{D}}(c_{ij}) \right\} = 0 \quad (A.19)$$

Instead of solving eq. (A.19), Pope and Nelson solved eq. (A.16) in their simulator. They used the numerical truncation error to represent the real physical dispersion expressed as, $-\alpha_{D}(\partial^{2}(f_{j}C_{ij})/\partial x_{D}^{2} - \partial(C_{ij}\partial f_{j}/\partial x_{D})/\partial x_{D}) \text{ in eq. (A.19). As will be shown in Section A.2, a truncation error on the order of <math display="block"> -(\Delta x_{D}/2)(\partial^{2}(\sum_{j}f_{j}C_{ij})/\partial x_{D}^{2}) \text{ results in solving eq. (A.16) by explicit finite difference technique providing <math>\Delta t_{D}^{<<\Delta x_{D}}$. By setting $\alpha_{Dj}=\Delta x_{D}/2$, the truncation error becomes $\alpha_{Dj}^{2}(f_{j}C_{ij})/\partial x_{D}^{2}$ which is identical to the first dispersion term in eq. (A.19). This implies that the difference between the numerical dispersion produced by the current simulator and the model derived from the P.D.E. eq. (A.19) is the term of $\alpha_{Dj}\frac{\partial}{\partial x_{D}}(C_{ij}\partial f_{j}/\partial x_{D})$. In another words, the use of the numerical dispersion in eq. (A.16) to represent the physical dispersion in eq. (A.19) is only true when $\alpha_{Dj}\frac{\partial}{\partial x_{D}}(C_{ij}\partial f_{j}/\partial x_{D})$ is insignificant. For this reason, the numerical technique has been modified to more accurately solve eq. (A.19).

OF THE GOVERNING EQUATION

A.2

Numerical diffusion (truncation error) is always introduced in solving a partial differential equation by a numerical finitedifference approximation.

Lantz⁹¹ discussed the quantitative evaluation of numerical diffusion. His technique provides a guideline for simulation users to choose a suitable block size and time step combination in their reservoir simulator to minimize the effect of numerical diffusion. For a single-component and single-phase system, Lantz estimated that the truncation error of the convection-diffusion equation, i.e. $\partial C/\partial t = D(\partial^2 C/\partial x) - \partial C/\partial x$, is on the order of $(\Delta x - \Delta t)/2$, when an explicit, first order finite difference approximation is used.

In this section, the truncation error for the governing equations of a multi-component, multi-phase system without physical dispersion will be analyzed. It is important to know the relationship between the real physical dispersion and the numerical truncation error involved in the numerical approximation. If the numerical dispersion represents the physical dispersion, it can be used to replace the physical dispersion and simplify the calculations. Otherwise, it is necessary to either adjust the numerical dispersion to approximate the physical dispersion or introduce a real physical

dispersion term. In the latter case, the numerical dispersion must be eliminated or at least reduced to a significance level low enough to avoid a possible interference effect.

The governing equation can be written in a discrete form using forward-difference in time and backward-difference in space, then the Taylor's expansion technique can be applied to replace the derivatives. The governing equation previously derived (Section A.1) has the form of:

$$\frac{\partial}{\partial t_{D}}(\tilde{c}_{i}) + \frac{\partial(\sum_{j} f_{j} c_{ij})}{\partial x_{D}} = 0$$
 (A.16)

Writing this equation in discrete form,

$$\frac{(\tilde{c}_{i})_{t_{D}}+\Delta t_{D}}{t_{D}} + \frac{(\sum_{j} f_{j}c_{ij})_{x_{D}} - (\sum_{j} f_{j}c_{j})_{x_{D}}-\Delta x_{D}}{\Delta x_{D}} = 0$$
(A.20)

By Taylor series expansion,

$$\frac{(\tilde{C}_{i})_{t_{D}} + \Delta t_{D}}{\Delta t_{D}} = \frac{(\tilde{C}_{i})_{t_{D}}}{\partial t_{D}} + \frac{\Delta t_{D}}{2} - \frac{\partial^{2}(\tilde{C}_{i})}{\partial t_{D}^{2}} + \frac{(\Delta t_{D})^{2}}{\frac{\partial^{3}(\tilde{C}_{i})}{\partial t_{D}^{3}} + \dots$$
(A.21)

and

$$\frac{\left(\sum_{j} f_{j}C_{ij}\right)_{x_{D}} - \left(\sum_{j} f_{j}C_{ij}\right)_{x_{D}} - \Delta x_{D}}{\Delta x_{D}} = \frac{\partial\left(\sum_{j} f_{j}C_{ij}\right)}{\partial x_{D}} - \frac{\partial\left(\sum_{j} f_{j}C_{ij}\right)}{\partial x_{D}} - \frac{\partial\left(\sum_{j} f_{j}C_{ij}\right)}{\partial x_{D}} - \frac{\partial\left(\sum_{j} f_{j}C_{ij}\right)}{\partial x_{D}} + \frac{(\Delta x_{D})^{2}}{6} - \frac{\partial^{3}\left(\sum_{j} f_{j}C_{ij}\right)}{\partial x_{D}^{3}} + \dots (A.22)$$

Substituting eq's. (A.21), (A.22) into eq. (A.20) with a secondorder approximation,

$$\frac{\partial (\hat{C}_{i})}{\partial t_{D}} + \frac{\Delta t_{D}}{2} - \frac{\partial^{2} (\hat{C}_{i})}{\partial t_{D}^{2}} + \frac{\partial (\sum_{j} f_{j} \hat{C}_{ij})}{\partial x_{D}} - \frac{\Delta x_{D}}{2} - \frac{\partial^{2} (\sum_{j} f_{j} \hat{C}_{ij})}{\partial x_{D}^{2}} = 0 \quad (A.23)$$

It is apparent that two additional terms, i.e. $\frac{D}{2}(\partial^2(C_i)/\partial t_D^2)$ and $-\frac{\Delta x_D}{2}(\partial^2(\sum_j f_j C_{ij})/\partial x_D^2)$, have been introduced compared with eq. (A.16). By differentiating eq. (A.16) with respect to time,

$$\frac{\partial^{2}(\hat{C}_{i})}{\partial t_{D}^{2}} + \frac{\partial^{2}(\sum_{j} f_{j}C_{ij})}{\partial x_{D} \partial t_{D}} = 0 , \quad \text{or}$$
$$\frac{\partial^{2}(\hat{C}_{i})}{\partial t_{D}^{2}} = -\frac{\partial^{2}(\sum_{j} f_{j}C_{ij})}{\partial x_{D} \partial t_{D}}$$

(A.24)

Substituting eq. (A.24) back into eq. (A.23),

$$\frac{\partial(\hat{C}_{i})}{\partial t_{D}} + \frac{\Delta t_{D}}{2} \left(- \frac{\frac{\partial^{2} \left(\sum f_{j} C_{ij} \right)}{j + \partial x_{D} \partial t_{D}} \right) +}{\left(- \frac{\partial(\sum f_{j} C_{ij})}{j + \partial x_{D}} - \frac{\Delta x_{D}}{2} - \frac{\partial^{2} \left(\sum f_{j} C_{ij} \right)}{\partial x_{D}^{2}} \right) = 0 \quad (A.25)$$

Generally, the error due to the cross-derivative expression (the second term of eq. (A.25)) is small compared with the fourth term; thus it can be neglected 87,91 . Certainly, if $\Delta t << \Delta x$, this cross-derivative term is negligible and eq. (A.25) reduces to,

$$\frac{\partial(\hat{c}_{i})}{\partial t_{D}} + \frac{\partial(\sum_{j} f_{j} c_{ij})}{\partial x_{D}} - \frac{\Delta x_{D}}{2} - \frac{\partial^{2}(\sum_{j} f_{j} c_{ij})}{\partial x_{D}^{2}} = 0$$
 (A.26)

By comparing eq's. (A.16) and (A.26) the last term of eq.(A.26) can be summed to represent the error due to numerical dispersion. If $\alpha_{Dj} = \Delta x_D/2$, the difference between the apparent dispersion in eq's. (A.26) and (A.19) is the term $\alpha_{Dj} = \frac{\partial}{\partial x_D} (C_{ij} = \frac{\partial f_j}{\partial x_D})$.

APPENDIX B

•

COMPUTER PROGRAM LISTING

```
THIS IS A ONE-DIMENSIONAL MICELLAR/POLYMER FLOODING SIMULATOR.
С
    AT MOST THREE (AQUECUS, CLEIC, AND MICR CEMULSION) PHASES ARE
¢
С
    CONSIDERED.
    MAJOP PHYSICAL FEATURES IN THIS SIMULATOR ARE AS FOLLOWS :
С
      PHASE BEHAVIOR
С
С
      INTERFACIAL TENSION
С
      TRAPPING FUNCTION
С
      VISCOSITY
      PELATIVE PERMEABILITY
С
С
      ADSCRPTTCN
      DISPERSION
С
      INACCESIBLE PAPE VOLUME
С
С
      ALCOHOL EFFECT
      CATION EXCHANGE AND SURFACTANT COMPLEX
С
C
C *
     C
С
   DEFINITION OF COMPONENT AND PHASE NUMBERS
С
      I = COMPONENT NUMBER
С
С
          1 = WATER
С
          2 = CIL
          3 = SUPFACTANT
С
          4 = POLYMER
С
С
          5 = TOTAL NONSORBING ANIONS
С
          6 = CALCIUM
С
          7 = ALCOHOL
С
          8 = CALCIUM-SURFACTANT COMPLEX
С
          9 = SCDIUM
С
     J = PHASE NUMBER
С
          1 = AQUEOUS(WATER-RICH)
С
          2 = OLEIC(OIL-RICH)
С
          3 = MICROEMULSION(MOST SURFACTANT RICH PHASE)
C
C *
    ***********
C
   EXPLANATION OF INPUT DATA
С
С
С
      AC31, AD32 = SURFACTANT ADSCRPTION PARAMETERS
С
               = SALINITY DEPENDENCE SURFACTANT ADSORPTION PARAMETER
      AD32
               = POLYMER ADSOPPTION PAPAMETERS
С
      A40.840
               = ABSOLUTE PERMEABILITY EDAPCY3
С
      ABPERM
С
      AL1.AL2.AL3 = ALCOHOL PARTITIONING COEFFICIENTS
      ALPHA1 - ALPHAF = PHASE VISCOSITY PARAMETERS
С
С
      AP1 - AP3 = POLYMER-RICH PHASE VISCOSITY PARAMETERS
С
      BETA1.BETA2.BETA3 = DILUTION EFFECT PAPAMETERS FOR CATIONS.
C
                         SUPFACTANT AND ALCOHOL
               = PEPMEABILITY REDUCTION PAPAMETER
С
      BRK
               = IMJECTION CONCENTRATIONS OF SUPECATANT AND ALCOHOL
С
      039,070
               = NORMALIZED FACTOR FOR SURFACTANT CONCENTRATION IN
С
      C33N
С
                  MICROEMULSION PHASE
      CTAN
С
               = NORMALIZED FACTOR FOR TOTAL SURFACTANT CONCENTRATION
С
      C 4 4 M
               = NOPMALIZED FACTOR FOR TOTAL PULYMEP CONCENTRATION
               = MORMALIZED FACTOR FOR TOTAL CALCIUM CONCENTRATION
С
      CE4N
               = NOPMALIZED FACTOR FOR TOTAL ALCOHOL CONCENTRATION
С
      C7AM
С
      CSELI, CSEUI = LOWER AND UPPER SALINITY LIMITS AT INITIAL RESERVOIR
С
                   COMBITION
               = CONCENTRATION OF COMPONENT I IN N-TH INJECTED SLUS
С
      CINCT, N)
               = LOWEST EFFECTIVE SALIMITY FOR TYPE III PHASE BEHAVIOP
С
      CSEL
               = HIGHEST EFFECTIVE SALINITY FOR TYPE III PHASE BEHAVIOR
С
      CSFU
```

С = CUT OFF SALINITY FOR THE SALINITY EFFECT ON POLYMER CSF1 = OIL CONCENTRATION AT PLAIT FOINT FOR TYPE II(+) С C2PLC С C2PRC = OIL CONCENTRATION AT PLAIT POINT FOR TYPE II(-) С C3MAX0+C3MAX1+C3MAX2 = MAXIMUM HEIGHT OF BINODAL CURVE AT THE С NGRMALIZED SALINITY OF D. 1. AND 2 С C511,C611 = INITIAL CONCENTRATIONS OF ANIONS AND CALCIUM IN С AGUEOUS PHASE С DISP = DIMENSIONLESS LONGITUDINAL DISPERSIVITY C DCSE = SALINITY LIMIT WHILE PLAIT POINTS ARE AT THE CORNERS DTMAX С = MAXIMUM TIME STEP SIZE ALLOWED IN SEMI-DISCRETE METHOD = RELATIVE ERROR TOLERANCE FOR SEMI-DISCRETE METHODS C ERR С E1,E2 = RELATIVE PERMEABILITY EXPONENT FOR WATER AND OIL С IN WATER-OIL SYSTEM С EPHI3, EPHI4 = EFFECTIVE PORDSITY FOR SURFACTANT AND POLYPER EPSME С = SURFACTANT CONCENTRATION AT WHICH MICROEMULSION C IS DEFINED Ĉ EPSMOB = TOLERANCE FOR MOBILITY ITERATION С EPSTIE = TOLERANCE FOR TIELINE ITERATION = THE RATIO OF TIME STEP SIZE OVER SPATIAL GRID SIZE С FFDV = SHEAR RATE AT WHICH VISCOSITY EGOALS ONE HALF OF C GAMHF С NO SHEAR VISCOSITY С G11 - G13 = INTERFACIAL TENSION FARAMETERS FOR TYPE II(+) С G21 - G23 = INTERFACIAL TENSION FAFAMETERS FOR TYPE II(-) С HINC = INCREMENT FOR PRINTING/PLCTING HISTORIES ICONT С = FLAG FOR CONTINUING THE CALCULATION AS THE MAXIMUM NUMBER OF ITERATION ON MOBILITY IS EXCEEDED С = NUPBER OF GRID BLCKS С TCT С ICTL, ICTU = PRESSURE IS MEASURED BETWEEN ICTL-TH AND ICTU-TH BLOCK С ID = SITE I.D. FOR THE RELEASE CF PLOTS = OPTION FOR PRINTING HISTORY, (0) NO, (1) YES С IHPRNT С IHPLOT = OPTION FOR PLOTING HISTORY, (0) NO, (1) YES С = OPTION FOR READING AND PLOTING LABORATORY DATA ILAB С IPRAX = MAXIMUM NUMBER OF ITERATION ON MOBILITY С IPPLOT = OPTION FOR PLOTING PROFILES, (0) NO, (1) YES С IPPRNT = OPTION FOR PRINTING PROFILES, (0) NO, (1) YES С IPRES = OPTICN FOR CALCULATING RELATIVE PRESSURE DROP (0), С OR TOTAL MOBILITY (1) = OPTION FOR PRINTING LAST ITERATION IF MOBILITY C IPRNT С ITERATION IS NOT CONVERGENT С IPERM = PARAMETER TO SPECIFY THREE PHASE FLOW MODEL С ISEM = PARAMETER TO SPECIFY 0.D.E. INTEGRATOR C ISOLV = PARAMETER TO SPECIFY THE NUMERICAL SOLUTION TECHNIQUE = NUMBER OF COMPONENTS TO BE CONSIDERED С NCOMP Ċ NSLUG = NUMBER OF SLUGS INJECTED C = PARAMETER TO SPECIFY PREDICTCR-CORRECTOR METHOD ME TH С = PARAMETER TO SPECIFY THE ITERATION SCHEME FOR A MITER Ċ PREDICTOR-CORRECTOR METHOD С = POROSITY PHT С POWN = SHEAR RATE DEPENDENCE FARAMETER FOR POLYMER VISCOSITY P1RW,P2RW = ENDPOINT RELATIVE PERMEABILITY TO WATER AND CIL IN С C WATER/OIL SYSTEM С P1RC.P2RC = ENC POINT RELATIVE PERMEABILITY TO AQUEOUS AND OLEIC С PHASE UNDER THE CONDITION OF INFINITE CAPILLRY NUMBER C Q٧ = CATION EXCHANGE CAPACITY EMEG/ML PORE VOLUME] = PARAMETER FOR THE CALCULATION OF EFFECTIVE SALINITY С RCSE С = MAXIMUM VALUE OF PERMEABILITY REDUCTION FACTOR RKMAX С SSLOPE = SALINITY DEPENDENCE FARAMETER FOR POLYMER VISCOSITY С \$1.52 = INITIAL SATURATION OF WATER AND OIL SIRH, S2RH = RESIDUAL SATURATION OF WATER AND OIL IN WATER/OIL С С SYSTEM С TITLE = INFOMATION FOR YOURSELF (DOES NOT AFFECT COMPUTATION) = DESATURATION PARAMETERS FOR AQUEOUS PHASE C T11,T12

```
= DESATURATION PARAPETERS FOR CLIC PHASE
C
     T21,T22
     HT
               = SUPERFICIAL (DARCY) VELOCITY OF TOTAL PHASE
C
С
                 (USED ONLY FOR SHEAR RATE EFFECT ON POLYMER)
               = CUMULATIVE AMOUNT OF INJECTED FLUID AFTER THE
     VINCN)
С
С
                 COMPLETION OF N-TH SLUG INJECTION
C
     VIS1,VIS2 = VISCOSITY OF WATER AND OIL
     VT.
               = TOTAL AMOUNT OF INJECTED FLUID EPV]
С
C
     XEND
               = SHOULD BE SMALL NUMBER SUCH AS 0.0001 (USED IN DGEAR)
     XIFTW
               = LOGARITHM OF INTERFACIAL TENSION BETWEEN WATER AND OIL
С
     XK96, XK86, XKHAT = MASS ACTION EXCHANGE CONSTANTS
C
С
     XKC
               = EQUILIBRIUM CONSTANT USED IN THE CALCULATION OF
C
                 COMPLEX
               = SELECTIVITY COEFFICIENT FOR MICELLES
С
     XKS
С
     YBIAS
               = CUT OFF VALUE FOR ESTIMATED ERROR TO AVOID EXCESSIVELY
С
                 SMALL TIME STEP (USED IN RK12 AND RK1)
С
С
C
   EXPLANATION OF OPTION PARAMETERS
С
C
     NUMERICAL SOLUTION TECHNIQUE
C
       ISOLV = 0 FOR FULLY-DISCRETE FORWARD EULER METHOD
С
С
             = 1 FOR SEMI-DISCRETE METHOD
C
С
     ORDINARY DIFFERENTIAL EQUATION INTEGRATOR
С
     (REQUIRED IF ISOLV=1)
       ISEM = 1 FOR RK12 (RUNGE-KUTTA-FEHLBERG ALGORITHM)
C
             = 2 FOR RK1 (RUNGE-KUTTA ALGCRITHM)
C
             = 3 FCR DGEAR (ADAMS* OR GEAR*S METHOD)
С
C
С
     PREDICTOR-CORRECTOR PETHOD
      (REQUIRED IF ISOLV=1 AND ISEM=3)
C
       METH = 1 FCR ADAMS* METHODS
C
             = 2 FCR GEAR'S METHODS
С
C
     ITERATION SCHEME FOR PREDICTOR+CCRRECTOR METHOD
С
С
      (REQUIRED IF ISOLV=1 AND ISEM=3)
                  FOR FUNCTIONAL (FIXED POINT) ITERATION
С
       MITER = 0
                  FOR A CHORD METHOD WITH THE JACOBIAN SUPPLIED BY
C
             = 1
                  THE USERS
С
                  FOR A CHORD METHOD WITH THE JACOBIAN CALCULATED
C
             = 2
С
                  INTERNALLY BY FINITE CIFFERENCES
                  FOR A CHORD METHOD WITH THE JACOBIAN REPLACED BY
C
             = 3
                  A DIAGONAL APPROXIMATION BASED ON A DIRECTIONAL
С
                  DERIVATIVE
С
С
С
     THREE PHASE FLOW MODEL
       IPERM = 0 FOR POPE'S MODEL
С
С
             = 1
                  FOR HIRASAKI'S MCDEL
                  FOR MODIFIED HIRASAKI'S MODEL (NOT COMPLETED YET)
C
             = 2
             = 3 FOR LAKE'S MODEL
С
C
      FOR SITE I.D. TO SPECIFY WHERE THE PLOTS SHOULD BE RELEASED.
С
     CONSULT TAURUS USER'S REFERENCE
C
C
   C##
C
  EXFLANATION OF VARIABLES IN COMMON ELCCKS OR FORMAL PARAMETERS
С
   SUBSCRIPTS ARE USED AS FOLLOWS :
C
        I = COMPONENT NUMBER
C
С
         J = PHASE NUMBER
```

K = BLOCK NUMBER

С

...

C			
C	A11+A12	Ξ	BINODAL CURVE PARAMETERS USED WHEN CSE.GT.CSEOP
С	A21, A22	=	BINODAL CURVE PARAMETERS USED WHEN CSE-LE-CSEOP
C	A 3D	=	SURFACTANT ADSORPTION PARAMETER (=AD31+AD32+CSF)
Ċ	A3DS(K)	=	OLD VALUE OF A3D NEEDED FOR TRREVERSTRUCTY
č	81.82.83	=	RINDAL CURVE DARAMETERS (FIVED TO BE MINUS UNITY
ř	DIFFEFUU	-	THEORE CONTENTIATED TO BE MINUS ONIT
	C(T (K)	_	
L A	LCI#J#KJ	Ξ	CONCENTRATION OF COMPONENT I IN PHASE J AT K-TH BLOCK
C	C(1949K)	=	IUTAL CUNCENTRATION OF COMPONENT I IN MOBILE PHASE OR
C			OVERALL CONCENTRATION OF COMPONENT I IN BOTH MOBILE
C			AND ROCK PHASE
C	CSE(K)	=	EFFECTIVE SALINITY
C	CSEOP	=	OPTINAL SALINITY
С	C3PH	Ξ	SURFACTANT CONCENTRATION IN MOST SURFACTANT RICH PHASE
Ċ	CAPH	Ξ	POLYMER CONCENTRATION IN MOST POLYMER RICH PHASE
č	C3ADSS (K)	=	VOLUME OF SURFACTANT ADSORBED PER UNIT PORE VOLUME
ř	CAADSSEKS	-	CONFENTATION OF DOLYMED IN DOLY DHASE
r r	CLADSCIN	Ξ.	CONCENTRATION OF FOUTHER IN NOCK PHASE
	COLDECINI	_	CONCENTRATION OF COMPLEX IN DOCK PHADE
C .	LSAUSS(K)	Ξ	CONCENTRATION OF COMPLEX IN NOCK PHASE
C	COHAISCRI	=	CUNCENTRATION OF COUNTER ION OF ADSORBED SURFACTANT
C	C5MAX,C6MA	X	= MAXIMUM CONCENTRATION OF ANION AND CALCIUM IN THE
C			PAST (USED TO NORMALIZE CONCENTRATION FOR PLOT)
C	DC3	Ξ	SMALL INCREMENT USED IN IONCNG
С	ER	Ξ	CUMULATIVE OIL PRODUCTION
C	DVP	Ξ	TIPE STEP SIZE EPV]
ř	DISP(J)	=	DIMENSIONLESS LONGITUDINAL DISPERSIVITY
ř	DTOLD	-	TINE STEP STEP AT THE LAST STEP (FOR SENI-DISCRETE)
r	FELLEXY	_	EPACTTONAL FLOU
~	E1 - E7	_	TRECTIONNE TEOM
	r1 - r3	-	DISTRIBUTION CORVE PARAMETER (FIXED TO BE UNIT
C			INSIDE INE SIMULATURY
C	IADS	Ξ	SWITCH USED TO DEAL WITH IRREVERSIBLE SURFACTANT
C			ADSORPTICN WHEN RK1 OR RK12 IS USED
С	ICT1	Ŧ	ICT+1
С	ICT2	Ξ	ICT+2
С	IEVA	Ξ	NUMBER OF FUNCTION EVALUATION OF SEMI-DISCRETE METHOD
с	IH	Ξ	COUNTER USED TO PUT TITLES IN HISTORY PRINT
Ċ	IPASS	=	SWITCH USED TO CONVERT C(I+4+K) TO 1-D ARRAY IN SOLVE1
ř	TPV	=	CUNULATIVE NUMBER OF TIME STEP
ř	TONFAD	_	TNOTCATOR FOR SHEAR RATE FEFECT ON DOLYMER
	K.KK	-	DICCK NUMBER
L C		_	NUNDER DE EDUATIONS ANCONDATOTY
L A	NCH	-	NUMBER OF ENGLISHED TIME STED OLDE OF FEETION
C	NKEJ	Ξ	NUMBER OF PREDICTED TIPE STEP SIZE REJECTION
Ç	NPHASE(K)	Ξ	NUMBER OF PHASES AT THE BLUCK
С			(SET TO BE 4 FOR THE LEFT NODE OF TYPE III)
C			(SET TO BE 5 FOR THE RIGHT NODE OF TYPE III)
С	NSTOP	Ξ	INDICATOR WHETHER THE JOB IS COMPLETED
С	P(I)	2	CUMULATIVE PRODUCTION
с	PERH(J.K)	Ξ	RELATIVE PERMEABILITY
Ĉ	PHT(K)	=	TOTAL RELATIVE HOBILITY
ř	PHTLU	=	TOTAL RELATIVE MUBILITY AT INITIAL CONDITION
ř	PRESCEN	-	NORMALIZED DRESSURE DRCP (=PHT11/PHT(K))
ř	DDEMAY	_	MAXIMUM DRESSURE DROP
		-	HANTHON FREGOURE DROF Total dregende odog (chr de dregen)
ι •	FKESUR	=	IVIAL PRESSURE UNUP ISUM OF PRESSNIT CONCLEY
C	P8	Ξ	LUMULATIVE PRODUCTION OF SURFACTANT COMPLEX
C	RTEMAX	=	MAXIMUM LUCAL TRUNCATION ERROR (RELATIVE) ESTIMATED
С	S(J,K)	Ξ	SATURATION
С	SN(J,K)	=	SATURATION IN REDUCED SATURATION SPACE
С	SRED(J,K)	Ξ	RESIDUAL SATURATION
С	S1R - S3R	Ξ	RESIDUAL SATURATION (ICENTICAL TO SRED(J,K))
с	T31 - T32	=	DESATURATION PARAMETER FOR MICROEMULSION
C			(USED ONLY IN POPE'S RELATIVE PERHEABILITY MODEL)
-			the second s

```
(SET TO ZERO INSIGE THE SIMULATOR)
С
C
     VP
              = CURRENT TIME (CUMULATIVE INJECTION)
     VPI
C
              = TIPE WHEN THE INJECTED SLUG IS CHANGED NEXT
              = VISCOSITY
C
     VIS
С
     XICT
              = GRID SIZE (INVERSE OF ICT)
     XIFT1(K)
             = LOG OF IFT BETWEEN AQUEOUS AND MICRCEMULSION PHASE
C
             = LOG OF IFT BETWEEN MICRCEMULSION AND OLEIC PHASE
С
     XIFT2(K)
             = MIN(XIFT1,XIFT2)
C
     KIFT3(K)
С
     ZE(I)
              = TOTAL AMOUNT INITIALLY EXISTED
Ĉ
     ZI(I)
              = TOTAL AHOUNT INJECTED
C
C+++
       **************
     PROGRAM MAIN(INPUT,OUTPUT,PLOTR)
С
  THIS HAIN PROGRAM DRIVES ALL SUBPROGRAMS.
  DEPENDING ON ISOLV, CONTINUITY EQUATIONS ARE SOLVED EITHER WITH
С
 FULLY-DISCRETE OR SEMI-DISCRETE METHOD.
С
      ISOLV = 0 FOR FULLY-DISCRETE METHOD
С
С
           = 1 FOR SEMI-DISCRETE METHOD
C----
     С
     COMMON/MAIN/ISOLV.NSTOP.ID
     CONHON/REST/IERROR, IH, IK, II, VPP, KK, IFLAG, ISLUG
С
     CALL INPUT
     IF(ISOLV.EQ.0)GO TO 10
  20 CALL SOLVE1
     CALL OUTPUT
     IF(IERROR.E0.1) GO TO 30
     IF(NSTOP.NE.1)G0 TO 20
     GO TO 30
  10 CALL SOLVE
     CALL OUTPUT
     IF(IERROR.EQ.1) GO TO 30
     IF(NSTOP.NE.1)GO TO 10
  30 CONTINUE
     STOP
     END
     SUBROUTINE INPUT
C
     С
     THIS SUBROUTINE READS AND PRINT INPUT DATA.
С
     SOME PARAMETERS ARE CALCULATED AND INITIALIZED.
С
     THE INITIAL CONDITION OF CORE DATA ARE SET IN THIS SUBROUTINE
C
C
C
     С
С
     COMMON /MAIN/ ISOLV.NSTOP.ID
     COMMON /NORM/ C33N, C34N, C44N, C64N, C74N
     COMMON /PLOT4/ LINTYP(10),FFPP(504,4),YN(43,4),ILAB
     COMMON /PRINT/ VPRINT, HINC, PINC, IMFRAT, IMPLCT, IPPRAT, IPPLOT, IPRAT
     COMMON /TITLE/ TITLE(24)
     COMMON /NO/ ICT,ICT1,ICT2,XICT,NCOMP,NF
     COMMON/SYSTEM/UT+ABPERN+PHI+EPHI3+EPHI4+CISPJ(4)
     COMMON /SEMID1/ DTMAX, ERR, YBIAS, PCT, IPASS
     COMMON /SEMID3/ NEG, ISEM, XEND, METH, MITER
     COMMON /IN/ VIN(10),CIN(7,10)
     COMMON /SOL/ C(7,4,42),S(3,42),FF(3,42),NPHASE(42),EPSHE
     COMMON /CSE/ CSE(42),CSA(42),CSEL,CSEU,RCSE,CSEOP,DCSE,CSELI,CSEUI
     COMMON /PHASE/ F1+F2+F3+B1+B2+B3+C2PLC+C2PRC
     COHMON /A/ A11, A12, A21, A22
```

COMMON / PRODIN/ ER, P(7), P8, ZI(7), ZE(7), S2 COHMON /ADSURP/ CJADSS(40),C4ADSS(40),C6ADSS(40),C6HATS(40) COMMON / CALC/ C6J0(40) COMMON /PERM/ IPERM, PIRW, P2RW, E1, E2, E3, P1RC, P2RC COMMON /PERMC/ PERM(3:40);SRED(3:40);SN(3:40);VIS(3:40);LPERM(40) COMMON /IFT/ G11,G12,G13,G21,G22,G23 COMMON /XIFT/ XIFT1(42),XIFT2(42),XIFT3(42),XIFTW CONHON /TRAP/ T11+T12+T21+T22+T31+T32+S1RW+S2RW+PHT(40)+EPSMCB+IC0 INT, IPHAX COMMON /ALPHA/ ALPHA1.ALPHA2.ALPHA3.ALPHA4.ALPHA5.ALPHA6 COMMON /CSEVIS/ VIS1.VIS2.AP1.AP2.P3.SSLOPE COMMON /SHEVIS/ ISHEAR, GAMHE, POWA, CSE1, RKMAX, BRK COMMON /CHEMAD/ C3PH, A3D, B3D, AD31, AC32, A3DS(40) COMMON /POLYAD/ C4PH+A4D+B4D COMMON /PRESS/ PHTLU,PRESUM,ICTL,ICTU,PRES(40) COMMON /ABVIS/ IPRES, ABVISH, ABVISF, ABHAX, ABVMAX CONHON /COMPLX/ XKC+XKS+QV COMMON /ION/ FEDVP.FEDV.DC3.K COMMON /INJECT/ DVPP, DVP, VP. VT. VPI COMMON /DIL/ BETA1,BETA2,BETA3 COMMON /ALC/ AA, BB,CC COMMON / TAB/ ISK.BT2.S25.BT3.S11.S21 COMMON /REST/ IERROR, IH, IK, II, VPF, KK, IFLAG, ISLUG COMMON /TRY/ A,B,G,F,IFX,ALPHA,BETA,XR,XL,EPSTIE COMMON /PRFPL/ PFPL(10),NPF;NFG NPF=1 NF=0 II=0 THEA IK=9 ISK=0 ISLUG=1 IERROR=0 IFLAG=1 DC3=1.0E-9 VP=0.0 ABVMAX=0.0 INPUT TITLE - SLOUTION AND PRINTING FLAGS READ 240, (TITLE(I), I=1,7) PRINT 250, (TITLE(I), I=1,6) READ 260, ISOLV, IPERM, IPRES, ID, HINC, PINC READ 262, ISEM, DTHAX, ERR, YBIAS, PCT READ 270, IPRNT, IHPRNT, IHPLOT, IPFRNT, IPPLOT, ILAB READ 270. NN.NFG READ 290, (PFPL(N),N=1,NN) PRINT 290, (PFPL(N),N=1,NN) READ 290. C33N+C34N+C44N+C64N+C74N INPUT INITIAL CONDITIONS AND SYSTEP FARAPETERS READ 280, VT, FFDV, NCOMP, ICT, ICTL, ICTU READ 290, UT+ABPERM+PHI+EPHI3+EPHI4+DISP READ 290, C511, C611, S1, S2, S1RH, S2RL INPUT INTERFACIAL TENSION AND DESATURATION PARAPETERS READ 290, XIFTW READ 290, G11,G12,G13,G21,G22,G23

С

C C

C C

С

C r

C

C C

READ 290, T11, T12, T21, T22, T31, T32 C С INPUT PHASE VISCOSITY FARAMETERS С READ 290, ALPHA1, ALPHA2, ALPHA3, ALPHA4, ALPHA5, ALPHA6 Ĉ INPUT VISCOSITY AND FOLYMER PHASE-VISCOSITY PARAMETERS C С READ 290, VIS1, VIS2, AP1, AP2, AP3, SSLOPE С INPUT SHEAR RATE, PERM. REDUCTION AND SALINITY DEP. VISC. С С READ 300, ISHEAR, GAMHE, POWN, CSE1, RKNAX, BRK С INPUT END POINT PERMEABILITIES AND PHASE PARAMETERS C C READ 290, PIRW, P2RW, P3RW, E1, E2, E3 READ 310, ICONT, IPMAX, PIRC, P2RC, EPSHE, EPSHOB C INPUT BINODAL CURVE PARAMETERS C С READ 290, B1, B2, B3, C3MAX0, C3MAX1, C3MAX2 READ 290, C2PLC, C2PRC, CSELI, CSEUI, CCSE, EPSTIE C INPUT ADSORPTION AND ICNEXCHANGE PARAFETERS С С READ 290, A40,840,AD31,AD32,B30 READ 290, XKC, XKS, QV, RCSE C С INPUT DILUTION EFFECT PARAMETERS С READ 290, C30, C70, BETA1, BETA2, BETA3 С ALCOHOL PARTITION COEFFICIENTS С С READ 290, AA, BB, CC С TEST FOR INPUT С С IF (UT.GT.0.0) GO TO 10 PRINT 230 STOP **10 CONTINUE** С С - - PERMEABILITY AFTER CHEM. SLUG FASSED С D0 20 LL=1.ICT 20 LPERM(LL)=0 C С С C С CALCULATE NEW SALINITY LIMITS BASED ON DILUTION EFFECT C C60=C61I+S1 C50=C51I*S1 C69=C60/(C50-C60) EXP3=EXP(BETA3+C70) CSEL=(CSELI+BETA1+C69+BETA2+C30)+EXP3 CSEU=(CSEUI+BETA1+C69+BETA2+C30)+E>P3 CSEOP=0.5+(CSEU+CSEL) С

CALCULATE BINCDIAL- AND DISTRIBUTION CUVE PARAMETERS С C F3=1.0 F2=F3 F1=F2 AA0=((2.+C3MAX0)/(1.-C3MAX0))++2 AA1=((2.+C3MAX1)/(1.-C3MAX1))++2 AA2=((2.*C3MAX2)/(1.-C3MAX2))**2 A21=AA0 A22=(AA1-AA0)/CSEOP A11=2.*AA1-AA2 A12=(AA2-AA1)/CSEOP A32=(A21-A11+A22+CSEL-A12+CSEU)/(CSEL-CSEU) A31=-A32+CSEL+A21+A22+CSEL C С C PRINT 330 PRINT 340, ISOLV, IPERM, IPRES, ID, HINC, PINC PRINT 342, ISEM, DTHAX, ERR, YBIAS, PCT PRINT 350, IPRNT, IHPRNT, IHPLOT, IPPRNT, IPPLOT, ILAB PRINT 360, C33N, C34N, C44N, C64N, C74N PRINT 370, VT, FFDV, NCOMP, ICT, ICTL, ICTU PRINT 380, UT, ABPERM, PHI, EPHI3, EPHI4, DISP PRINT 390, C511, C611, S1, S2, S1RW, S2RW PRINT 400, XIFTW PRINT 410, 611,612,613,621,622,623 PRINT 420, T11, T12, T21, T22, T31, T32 PRINT 430, ALPHA1, ALPHA2, ALPHA3, ALFHA4, ALPHA5, ALPHA6 PRINT 440, VIS1, VIS2, AP1, AP2, AP3, SSLOPE PRINT 450, ISHEAR, GAMHE, POWN, CSE1, RKMAX, BRK PRINT 460, PIRW, P2RW, P3RW, E1, E2, E3 PRINT 470, ICONT, IPMAX, PIRC, P2RC, EFSFE, EPSMOB PRINT 480, 81,82,83,C3MAX0,C3MAX1,C3MAX2 PRINT 490, C2PLC,C2PRC,CSELI,CSELI,DCSE,EPSTIE PRINT 500, A4D, B4D, AD31, AD32, B3D PRINT 510, XKC, XKS, QV, RCSE PRINT 520, C30,C70,BETA1,BETA2,BETA3 PRINT 530, AA,BB,CC PRINT 540 PRINT 550. A11.A12.A21.A22.A31.A32 PRINT 560, CSEL, CSEU, CSEOP С INITIALIZING PRINTING FLAGS C C VPRINT=0.01 VPP=PINC С ICT1=ICT+1 NEG=ICT+NCOMP ICT2=ICT+2 С С С INITIAL REL.PERM., MOBILITY AND FRACTIONAL FLOW С С S1 I=S1 S21=S2 SR=(S1-S1RW)/(1.0-S1RW-S2RW) IF (SR.LT.0.0) SR=0.0 IF (SR.GT.1.0) SR=1.0 PERM1=P1RW+SR++E1

```
PERM2=P2RW+(1.0-SR)++E2
      PHTLU=PERM1/VIS1+PERM2/VIS2
      00 30 K=1,ICT
   30 PHT(K)=PHTLU
      FF1=PERM1/VIS1/PHTLU
      FF2=PERM2/VIS2/PHTLU
С
С
      PRINT INITIAL CONDITIONS
С
      PRINT 570
      PRINT 580, S1, S2, PERM1, PERM2, VIS1, VIS2
      PRINT 590, ICTL, ICTU
      PRINT 600, S1RW,S2RW,P1RW,P2RW,FF1,FF2
С
      SET UP TIME INCREMENT
С
С
      DVP=FFDV/FLOAT(ICT)
С
      INITIAL SALINITY
С
C
      DO 40 K=1.ICT
         CSE(K)=C511-C611+C611+RCSE
   40 CSA(K)=CSE(K)
С
      INITIAL ADSCRPTICN
C
С
      D0 50 K=1,ICT
         C6HATS(K)=0.0
         C4ADSS(K)=0.0
         C3ADSS(K)=0.0
   50 A3DS(K)=AD31+AD32+CSE(K)
С
С
      INITIAL INTERFACIAL TENTION
С
      DO 70 K=1.ICT
         XIFT1(K)=XIFTW
   70 XIFT2(K)=XIFTW
С
      INITIAL ADSORPTION OF CALCIUM
С
C
      IF (C61I.LE.0.0) GO TO 90
      C9=C51I-C61I
      R96=XKC+QV+C9++2/C61I
      IF (QV.LT..000001) GO TO 80
      C6IAD=.5+(2.+QV+R96-SQRT(4.+QV+R96+R96++2))
   80 CONTINUE
      GO TO 100
   90 C6IAD=0.0
  100 CONTINUE
С
      DO 130 K=1+ICT1
С
С
      INITIALLY NUMBER OF PHASES
С
         NPHASE(K)=2
         IF (S1.LE.0.99999) GO TO 110
         NPHASE(K)=1
  110
         CONTINUE
С
      CONCENTRATION OF CALCIUM ON ROCK AND IN MOBILE PHASE
С
С
      IF (K.GT.ICT) GO TO 105
```

```
CEADSS(K)=CEIAD
      C6J0(K)=C61I
  105 CONTINUE
С
С
      INITIAL CONCENTRATIONS
С
         DO 120 I=1,7
         D0 120 J=1+4
  120
         C(I,J,K)=0.0
         C(1,1,K)=1.0
         C(2+2+K)=1+0
         C(5,1,K)=C51I
         C(6,1,K)=C61I
С
C
      INITIAL SATURATIONS AND OVERALL CONCENTRATIONS
Ċ
         S(1,K)=S1
         S(2+K)=S2
         S(3,K)=1.0-S1-S2
         C(2,4,K)=S2
         C(1,4,K)=S1
         C(5,4,K)=C51I*S1
         C(6,4,K)=C61I+S1
С
      INITIAL PERMEABILITIES
С
С
         PERM(1+K)=PERM1
         PERM(2,K)=PERM2
         PERM(3+K)=0.0
С
С
      INITIAL FRACTIONAL FLOW
С
         FF(1,K)=FF1
         FF(2,K)=FF2
         FF(3.K)=0.0
C
      PHASE DISPERTICN (DISPERTION COEFFICIENT)
С
С
         DISPJ(1)=DISP
         DISPJ(2)=DISP
         DISPJ(3)=DISP
         DISPJ(4)=DISP
  130 CONTINUE
      DO 140 I=1,7
С
C
      INITIAL CONCITION AND CUMALATIVE PRODUCTION
С
      IN PRODUCER
С
      DO 140 J=1.4
         C(I,J,ICT2)=0.0
  140 CONTINUE
      C(1,1,ICT2)=1.0
      C(2,2,ICT2)=1.0
      C(5,1,ICT2)=C51I
      C(6,1,ICT2)=C61I
      S(1,ICT2)=FF(1,1)
      S(2,ICT2)=FF(2,1)
      S(3,ICT2)=0.0
      C(1,4,ICT2)=S(1,ICT2)
      C(2,4,ICT2)=S(2,ICT2)
      C(5,4,ICT2)=S(1,ICT2)+C51I
      C(6,4,ICT2)=S(1,ICT2)+C61I
```

```
С
    DO 150 I=1.7
 150 P(I)=0.0
С
С
    С
    READ 320. NSLUG
С
    DO 160 N=1,NSLUG
       READ 610. VIN(N). (CIN(I.N). I=1.7)
 160 CONTINUE
С
С
    START INJECTION
С
    DO 170 I=1.NCOMP
    DO 170 J=1+3
 170 C(I,J,ICT1)=0.0
    DO 180 I=1,NCOMP
 180 C(I+1,ICT1)=CIN(I+1)
    C(2,2,ICT1)=0.0
    FF(1+ICT1)=1.0
    FF(2,ICT1)=0.0
    FF(3,ICT1)=0.0
    VPI=VIN(1)
    PRINT 620, VPI,(C(I,1,ICT1),I=1,NCCMP)
C
С
    +++++++++ CUMULATIVE AMOUNT OF EACH COMPONENT INJECTED +++
С
    DO 190 I=1,7
 190 ZI(I)=0.0
    ZZ=0.0
    DO 220 N=1,NSLUG
       VINJ=VIN(N)
       IF (N.NE.NSLUG) GO TO 200
       IF (VT.LT.VIN(N)) VINJ=VT
 200
       CONTINUE
       Z=VINJ-ZZ
       ZZ=VINJ
       DO 210 I=1.NCOMP
 210
       ZI(I)=CIN(I_{1}N)+Z+ZI(I)
 220 CONTINUE
С
    С
С
    ZE(1)=S1
    ZE(2)=S2
    ZE(5)=S1+C51I
    ZE(6)=S1+C61I+C6IAD
    ZE(3)=0.0
    ZE(4)=0.0
    ZE(7)=0.0
С
    С
С
    IF (ILAB.EQ.1) CALL LABDATA
C
    RETURN
С
    С
C
 230 FORMAT (//,10%,27HUT CAN NOT BE ZERO IN INPUT,/)
 240 FORMAT (2410/2410/3410)
```

250 FORMAT (1H1+15X+2410+/15X+2410+/15X+2410) 260 FORMAT (413,2F10.0) 262 FORMAT (13,4F10.0) 270 FORMAT (613) 280 FORMAT (2F10.0,5I3) 290 FORMAT (7F10.0) 300 FORMAT (13.6F10.0) 310 FORMAT (213,6F10.0) 320 FORMAT (I2) 330 FORMAT (/,5X,12HINPUT VALUES,/,4X,8(2H++)) 340 FORMAT (1X,T5,7H ISOLV=,14,T24,7H IPERM=,14,T43,7H IPRES=,14,T59,7 ID=,I4,T85,7H HINC=,F9.4,T101,7H PINC=,F9.4,/) 1H 342 FORMAT(1X, T5, 7h ISEM=, 14, T25, 7H DTMAX=, F9.4, T45, 7H FRP=+F9.6. T65.7H YBIAS=.F9.5.T85.7H PCT=.F9.4/) 1 350 FORMAT (1X+T5+7H IPRNT=+14+T24+7HI+PRNT=+14+T43+7HIHPLOT=+14+T59+7 1HIPPRNT=,14,T75,7HIPPLOT=,14,T91,7F ILAB=,14,/) 360 FORMAT (1X, T5, 7H C33N=, F9.4, T25, 7H C34N=, F9.4, T45, 7H C44N=, F9.4 1, T65, 7H C64N=, F9. 4, T85, 7H C74N=, F9.4, /) 370 FORMAT (1X, T5, 7H VT=,F9.4,T25,7+ FFDV=,F9.4,T43,7H NCOMP=, I4, T 159.7H ICT=, I4, T75, 7H ICTL=, I4, T51, 7H ICTU=, I4, /) 380 FORMAT (1X, 15, 7H UT=,F9.4,T25,7+ABPERM=,F9.4,T45,7H PHI=, F9.4 1,765,7H EPHI3=,F9.4,785,7H EPHI4=,F9.4,7105,7H DISP=,F9.4,/) 390 FORMAT (1X, T5, 7H C511=, F9.4, T25, 7F C611=, F9.4, T45, 7H S1=+F10+ S2=+F9+4+T85+7H S1R4=+F9+4+T105+7H S2RW=+F5+4+/) 14, T65, 7H 400 FORMAT (1X, T5, 7H XIFTW=, F9.4,/) 410 FORMAT (1X, T5, 7H G11=, F9.4, T25, 7H G12=,F9.4,T45,7H G13=+F9-4 G21=,F9.4,T85,7H G22=,F9.4,T105,7H G23=,F9.4,/) 1, T65, 7H 420 FORMAT (1X, T5, 7H T11=, F9.4, T25, 7H T12=,F9.4,T45,7H T21=.F9.4 T22=,F9.4,T85,7H T31=,F9.4,T105,7H T33=,F9.4,/) 1.T65.7H 430 FORMAT (1X,T5,7HALPHA1=,F9.4,T25,7HALPHA2=,F9.4,T45,7HALPHA3=,F9.4 1.T65,7HALPHA4=,F9.4,T85,7HALPHA5=,F9.4,T105,7HALPHA6=,F9.4,/) 440 FORMAT (1X+T5,7H VIS1=+F9+4+T25+7+ VIS2=+F9+4+T45+7H AP1=, F9.4 AP2=,F9.4,T85,7H AP3=, F9.4, T105, 7HSSLOPE=, F9.4./) 1, T65, 7H 450 FORMAT (1X,T5,7HISHEAR=,I4,T25,7+ CAMHF=,F9.4,T45,7H POWN=,F9.4,T 165,7H CSE1=,F9.4,T85,7H RKMAx=,F9.4,T105,7H BRK=,F9.4,/) 460 FORMAT (1X,T5,7H P1RW=,F9.4,T25,7H P2RW=,F9.4,T45,7H P3RW=,F9.4 1,T65,7H E1=+F9+4+T85+7H E2=+F9+4+T105+7H E3=+F9+4+/) 470 FORMAT (1X, T5, 7H ICONT=, 14, T25, 7H IPMAX=, 14, T45, 7H PIRC=, F9, 4, T65 1,7H P2RC=,F9.4,T85,7H EPSME=,E9.3,T105,7HEPSM0B=,E9.3,/) 480 FORMAT (1X, T5, 7H 81=,F9.4,T25,7+ B2=,F9.4,T45,7H 83=,F9.4 1,T65,7HC3MAX0=,F9.4,T85,7HC3MAX1=,F9.4,T105,7HC3MAX2=,F9.4,/) 490 FORMAT (1X,T5,7H C2PLC=,F9.4,T25,7H C2PRC=,F9.4,T45,7H CSELI=,F9.4 1,T65,7H CSEUI=,F9.4,T85,7H DCSE=,F9.4,T105,7HEPSTIE=,E9.3,/) 500 FORMAT (1×,T5,7H A4D=,F9.4,T25,7H B4D=,F9.4,T45,7H AD31=,F9.4 1, T65, 7H AD32=, F9.4, T85, 7H B3D=, F9.4, T105,/) XKC=,F9.4,T25,7H 510 FORMAT (1X, T5, 7H XKS= .F9.4. T45.7H QV=.F9.4 1, T65, 7H RCSE=, F9. 4,/) 520 FORMAT (1X+T5+7H C30=+F9+4+T25+7H C70=,F9.4.T45.7H BETA1=,F9.4 1, T65, 7H BETA2=, F9. 4, T85, 7H BETA3=, F9.4, /) 530 FORMAT (1X, T5, 7H AA=+F9.4+T25+7+ BB= + F9 . 4 . T45 . 7H CC=+F9-4 1,/) 540 FORMAT (////,5X,21HCALCULATED FRCM INPUT,/,4X,12(2H**),//) 550 FORMAT (1X,T5,7H A11=,F9.4,T25,7H A12=,F9.4,T45,7H A21=,F9.4 1,T65,7H A22=,F9.4,T85,7H A31=,F9.4,T105,7H A32=,F9.4,/) 560 FORMAT (1X+T5+7H CSEL=+F9+4+T25+7H CSEU=+F9+4+T45+7H CSEOP=+F9+4 1./) 570 FORMAT (1H1) 580 FORMAT (//,5X,18HINITIAL CONDITIONS,/,4X,11(2H++),//,5X,32HWATER S :,F8.4,/,5).32HOIL SATURATION 1ATURATION :.F8.4./.5X.32HWATER PHASE RELATIVE PERM. :.E8.4./.5X.32H0 2 **3IL PHASE RELATIVE PERM.** :+F8.4./.5X.32HWATER VISCOSITY :,F8.4,/,5X,32HUIL VISCOSITY 4 :,F8.4./)
```
590 FORMAT (5X, 30HPRESSURE DROP RECORDED BETWEEN, 13, 4H AND, 13)
 GOC FORMAT (/+5X+32HRESIDUAL WATER SATURATION
                                                  :+F8.4./.5X.32HRESI
                               :,F8.4./,EX.32HEND POINT REL. PERM. FOR
    1DUAL OIL SATURATION
    2 WATER :.F8.4./.5X.32HEND POINT REL. PERM. FOR OIL
                                                        :,F8.4,/,5X,3
    32HWATER FRACTIONAL FLOW
                                     :,F8.4,/,5X,32HOIL FRACTIONAL FLO
    44
                  :.F8.4)
 610 FORMAT (6F10.0)
 620 FORMAT (////.3X.11HINJECTION :.4X.4HVPI=.F6.4.4X.4HC11=.F6.4.4X.4H
    1C21=,F6.4,4X,4HC31=,F6.4,4X,4HC41=,F6.4,4X,4HC51=,F6.4,4X,4HC61=,F
    26.4,4X,4HC71=,F6.4,///)
С
     END
     SUBROUTINE LABDATA
C
С
     ---- LABDATA
С
С
     PURPOSE:
C
     THIS SUBROUTINE READS AND FRINTS EXPERIMENTAL EFFLUENT
С
C
     DATA FOR TOTAL OIL CONCENTRATION TCTAL SURFACTANT CON-
С
     CENTRATION AND OIL RECOVERY
С
С
     С
     COMMON /PLCT3/ YH1(504.7).YH2(504.7).YH3(504.7).YH4(504.10).XDH(50
    14,10),XDD(504,4)
     COMMON /PLOT4/ LINTYP(10),FFPP(504,4),YN(43,4),ILAB
     COMMON /ARVIS/ IPRES, AEVISH, ABVISF, ABMAX, ABVMAX
     CONMON /HISP/ FREMAX, IPT, NPO, NPS, NFR, NPL
С
     ++++++ TNPUT EXFERIMENTAL DATA POINTS FOR PLOTTING ++++
С
С
С
     READING , C2 , C3/C3I , OIL RECOVERY
C
     PRINT 70
     PRINT 80
     READ 100, NPO
     DO 10 I=1,NP0
  10 READ 120, XDH(1,8), YH4(1,8)
     READ 100, NPS
     DO 20 I=1,NPS
  20 READ 120, XDH( 1,9), YH4(1,9)
     READ 100. NPR
     DO 30 I=1,NPR
  30 READ 120, XDH(I+10), YH4(I+10)
     PRINT 110. NPO.NPS.NPR
     PRINT 130
     DO 40 I=1.NPO
  40 PRINT 150, XDH(I,8),YH4(I,8),XCH(I,9),YH4(I,9),XDH(I,10),YH4(I,10)
С
     READING PRESSURE DATA
С
С
     IF (IPRES.NE.1) GO TO 60
     PRINT 90
     READ 100, NPL
     PRINT 110, NPL
     PRINT 140
     DO 50 I=1,NPL
        READ 120, XDD(1,3), FFPP(1,3), XDD(1,4), FFPP(1,4)
        PRINT 150, XDD(1,3), FFPP(1,3), XDD(1,4), FFPP(1,4)
   50 CONTINUE
   60 CONTINUE
```

```
C
С
      С
      RETURN
C
   70 FORMAT (///,10X,37HEXPERIMENTAL DATA POINTS FCR PLCTTING,//)
  BO FORMAT (10X,40HDATA POINTS FOR . C2 , C3/C3I . OIL REC.,/)
  90 FORMAT (///,10X,29HDATA POINTS FCR PRESSURE DATA,/)
  100 FORMAT (I3)
  110 FORMAT (/,10X,22HNUMBER OF DATA FOINTS=,315,/)
  120 FORMAT (6F10.0)
  130 FORMAT (/,10X, T18, 2HXD, T28, 2HC2, T38, 2HXD, T46, 6HC3/C31, T58, 2HXD, T68
     1,2HER,/)
  140 FORMAT (/,10X, T18, 2HXD, T26, 6HABVISF, T38, 2HXD, T46, 6HABVISF, /)
  150 FORMAT (11X,6(3X,F7.4))
С
     END
     SUBROUTINE CUTPUT
С
С
     C
     PURPOSE:
С
С
C
     DEPENDING ON HOW MANY FOREVOLUMES ARE INJECTED. THIS
С
     SUBROUITNE CALLS THE SUBROUTINES LISTED BELOW:
        HISPRNT : PRINT PRODUCTION AT GIVEN TIME INCREMENT
С
С
                   (FINC+DVP). THE SUBROLTINE IS NOT CALLED
С
                   IF IHPRNT=0
         HISPLOT : PLOT PRODUCTION DATA AT GIVEN TIME INCR-
С
С
                   EPENT (HINC+DVP), THE SUBROUTINE IS NOT
С
                   CALLED IF IHPLOT=0
С
         PREPRNT : PRINT PROFILE (AT EVERY GRID BLOCK) FOR
С
                   TIME GIVEN BY PINC
С
                   THE SUBROUTINE IS NCT CALLED IF IPPRNT=0
С
         PRFPLOT : PLOT PROFILE AT EVERY PINC
С
                   THE SUBROUITNE IS NOT CALLED IF IPPLOT=0
С
         MATBAL
                 : CALULATES MATERIAL BALANCE ERROR AT THE
                  TERMINATION OF INJECTION
С
С
         TABOUT
                : TABLE LISTING OF SOME OF THE MOST IMPORT-
С
                   ANT VARIABELS
C
С
         THE SUBROUTINE ALSO SAVE DATA FCR HISTORY PRINTING
С
         AND PLOTTING
C
С
С
С
     COMMON /PLOT2/ NPT(10),FFP(504,2),YM(43,4),XD2(43,4),YMN(43,4),SAL
     1(504,3)
     CONMON /PLOT3/ YH1(504,7), YH2(504,7), YH3(504,7), YH4(504,10), XDH(50
     14,10),XDD(504,4)
     COMMON /PLOT4/ LINTYP(10), FFPP(504,4), YN(43,4), ILAB
     COMMON /HAIN/ ISOLV.NSTOP.ID
     COMMON /NORM/ C33N, C34N, C44N, C64N, C74N
     COMMON /PRINT/ VPRINT, HINC, PINC, IHFRNT, IHPLCT, IPPRNT, IPPLOT, IPRNT
     COMMON /REST/ IERROR, IH, IK, II, VPP, KK, IFLAG, ISLUG
     CONMON /HISP/ FREMAX, IPT, NPD, NPS, NFR, NPL
      COMMON /NO/ ICT+ICT1+ICT2+XICT+NCOFP+NF
      COMMON /SOL/ C(7,4,42),S(3,42),FF(3,42),NPHASE(42),EPSHE
      COMMON /CSE/ CSE(42),CSA(42),CSEL,CSEU,RCSE,CSEOP,DCSE,CSELI,CSEUI
      COMMON /PRODIN/ ER, P(7), P8, ZI(7), ZE(7), S2
      COMMON /PRESS/ PHTLU, PRESUM, ICTL, ICTU, PRES(40)
```

```
COMMON /ABVIS/ IPRES, ABVISH, ABVISF, ABMAX, ABVMAX
     COMMON /INJECT/ DVPP+DVP+VP+VT+VFI
     COMMON /TAB/ ISK+BT2,S25,BT3,S11,S21
     COMMON /PRFPL/ PFPL(10),NPF,NFG
     DATA IPT/0/
     DATA PREMAX/1.0/
C
     С
С
     IF (ABS(VT-VP).LT.1.0E-10) GO TO 10
     IF ((VPRINT-VP).GT.1.DE-8) GC TO 95
     IF(ISOLV.NE.1)VPRINT=VPRINT+HINC+DVP
     IF(ISOLV.EQ.1)VPRINT=VPRINT+D.01
  10 IPT=IPT+1
С
     С
С
     IF (S(2,ICT2).LT.0.0001) GO TO 30
     IF (ISK.GT.D) GO TO 20
     ISK=1
     BT2=VP
  20 IF ((VP-DVP).LT.0.5) GO TO 30
     IF (ISK.GT.1) 60 TC 30
     ISK=2
     $25=$(2,ICT2)
  30 CONTINUE
     IF (S(3,ICT2).LT.0.0001) GO TO 40
     IF (ISK.GT.2) GO TO 40
     ISK=3
     BT3=VP
  40 CONTINUE
С
С
     Ċ
     DO 50 I=1+NCOMP
        YH1(IPT,I)=C(I,1,ICT2)
        YH2(IPT,I)=C(I,2,ICT2)
        YH3(IPT,I)=C(I,3,ICT2)
        YH4(IPT,I)=C(I,4,ICT2)
  50 XDH(IPT+I)=VP
     XOD(IPT.1)=VP
     XDD(IPT,2)=XDD(IPT,1)
     YH4(IPT,1)=ER
     YH3(IPT,3)=C(3,3,ICT2)/C33N
     YH4(IPT,3)=C(3,4,ICT2)/C34N
     YH4(IPT,4)=C(4,4,ICT2)/C44N
     YH4( IPT, 6)=C(6,4,ICT2) /C64N
     YH4(IPT,7)=C(7,4,ICT2)/C74N
С
     FFP(IPT,1)=FF(1,1)
     FFP(IPT,2)=1.0-FF(2,1)
С
     SAL(IPT,1)=CSE(ICT2)
     SAL(IPT,2)=CSEL
     SAL(IPT.3)=CSEU
С
     FFPP(IPT,1)=PRESUM
     FFPP(IPT,2)=0.0
     IF (PREMAX.LT.FRESUM) PREMAX=PRESUM
     IF (IPRES.EQ.3) GO TC 60
     FFPP(IPT+1)=ABVISH
     FFPP(IPT,2)=ABVISF
```

```
ABMAX=AMAX1 (ABVISH, ABVISF)
    IF (ABMAX.GT.ABVMAX) ABVMAX=ABMAX
  60 CONTINUE
С
С
    С
    IF (IMPRNT.NE.1) GO TO 70
    CALL HISPRNT
С
  70 IF (VP.LT.VT) GO TO 80
С
    C
С
    NSTOP=1
    CALL MATBAL
    CALL TABOUT
C
C
    C
    IF (IMPLOT.EQ.0) GO TO 80
    CALL HISPLOT
  80 CONTINUE
Ĉ
С
    C
  90 IF (IERROR.EQ.1) GO TO 100
    IF (NSTOP.NE.1.AND.ABS(VP-PFPL(NFF)).GT.1.0E-8) GO TO 120
С
    NPF=NPF+1
    VPP=VPP+PINC
    IF (IPPRNT.NE.1) GO TO 110
 100 CALL PREPRNT
С
    C
С
    PRINT 130, NPF, PFPL(NPF), VP
 110 IF (IERROR.EQ.1) GO TO 120
    IF (IPPLOT.EQ.0) GO TO 120
С
    CALL PREPLOT
C
 120 CONTINUE
C
    RETURN
С
 130 FORMAT (//,5X,13,2F12.5,//)
С
    END
    SUBROUTINE HISPRNT
С
С
    HISPRNT ------
С
С
    PURPOSE:
С
С
    THIS SUBROUTINE PRINT HISTORY WITH INCREMENTS
    HINC+DVP
С
    HISTORY WILL BE PRINTED IF IHPRNT=1
С
С
C
     _____
С
    COMMON /HISP/ FREMAX, IPT, NPO, NFS, NFR, NPL
    COMMON /REST/ IERROR, IH, IK, II, VPP, KK, IFLAG, ISLUG
```

```
COMMON /NO/ ICT.ICT1.ICT2.XICT.NCOPP.NF
     COMMON /PRESS/ PHTLU, PRESUN, ICTL, ICTU, PRES(40)
     COMMON /SOL/ C(7+4+42)+S(3+42)+FF(3+42)+NPHASE(42)+EPSHE
     COMMON /CSE/ CSE(42),CSA(42),CSEL,CSEU,RCSE,CSEOP,DCSE,CSELI,CSEUI
     COMMON /PRODIN/ ER,P(7),P8,ZI(7),ZE(7),S2
     COMMON /TRAP/ T11, T12, T21, T22, T31, T32, S1RW, S2RW, PHT(40), EPSMOB, ICO
    INT, IPMAX
     COMMON /INJECT/ DVPP, DVP, VP, VT, VPI
     COMMON /TAB/ ISK, BT2, S25, BT3, S11, S21
С
     С
С
     TH=TH+1
     II=II+1
     IF (IH.EQ. 7. AND. IK.NE. 1) GO TO 10
     IF (II.GT.1.ANC.IK.NE.1) GO TC 40
     IF (IK.EQ.1) GC TO 20
   10 PRINT 70
   20 PRINT 80, VP, (P(I), I=1,7), ER, P8, FHT(1), PRESUM, CSE(ICT2)
     IH=0
     IK=0
     D0 30 J=1,3
  30 PRINT 90, J.(C(I,J,ICT2),I=1,7),S(J,ICT2),FF(J,1)
     PRINT 110, (C(I+4+ICT2)+I=1+7)
     GO TO 60
   40 PRINT 100, NP, (P(I), I=1,7), ER, P8, PHT(1), PRESUM, CSE(ICT2)
     DO 50 J=1,3
  50 PRINT 90, J,(C(I,J,ICT2),I=1,7),S(J,ICT2),FF(J,1)
     PRINT 110, (C(I:4,ICT2)+I=1,7)
  60 CONTINUE
C
С
     С
     RETURN
С
  70 FORMAT (1H1)
   80 FORMAT (3X,2HVP,7X,2HP1,5X,2HP2,5X,2HP3,5X,2HP4,5X,2HP5,5X,2HP6,5X
    1, 2HP7, 10X, 2HER, 10X, 2HP8, 9X, 8HTOT. MC8., 5X, 8HPRESSURE, 5X, 3HCSE, /1X, F
     25.3,3X,7(1X,F6.4),5X,F6.4,8X,F6.4,EX,F6.4,7X,F6.4,5X,F6.4,//,5X,5H
     3PHASE, 6X, 27HCONCENTRATION OF CONFONENTS, 17X, 10 HSATURATION, 3X, 13HFR
     4ACTION FLOW,/11X,2HC1,5X,2HC2,5X,2HC3,5X,2HC4,5X,2HC5,5X,2HC6,5X,2
    5HC7+10X+1HS+12X+2HFF)
  90 FORMAT (6X,13,7(1X,F6.4),5X,F6.4,8%,F6.4)
  100 FORMAT (//,1X,F5.3,3X,7(1X,F6.4),5X,F6.4,8X,F6.4,6X,F6.4,7X,F6.4,5
     1X,F6.4,/)
  110 FORMAT (6X, 3H 4,7(1X, F6.4),2(5X, FE.4))
С
     END
     SUBROUTINE HISPLOT
С
С
     С
С
     PURPOSE:
C
С
     THIS SUBROUTINE PLOT HISTORY AFTER THE LAST TIMESTEP
     WITH INCREMENTS : HINC+DVP
С
     HISTORY IS PLOTTED IF IHPLOT>0
С
С
     OPTIONS FOR PLOTTING ARE :
                   : ONLY PRINTER PLOT
C
          IHPLOT=1
                  : ONLY ZETA PLOT
С
         IHPLOT=2
         IHPLOT=3 : BOTH PRINTER AND ZETA PLOT
С
C
```

С ****** C COMMON /AXLABL/ XLABEL(3), YLABEL(3), NXCHAR, NYCHAR, LABSID COMMON /AXTYP/ IXA, IYA CONHON /BORDER/ IBORDR COMMON /FXDSCL/ XF,YF,XD,YD,IX,IY COMMON /LEGEND/ LEGEND, FACTL, YLEGNE(3,10) COMMON /LINHOD/ LINHOD(10) COMMON /PLTSIZ/ TEMP(2),XL,YL COMMON /SYMBZT/ ISYMZT(10) COMMON /TITL/ NTITLE, ITITL(5,5) COMMON /Y2AXIS/ Y2AXIS IY2AXT, Y2FSTV . Y2DELV. IY2AXF, Y2LNZ .NY2CHR, Y2 1LABL(3), IYAXNO(10) С COMMON /PLOT2/ NPT(10) +FFP(504+2) + YM(43+4) + XD2(43+4) + YMN(43+4) + SAL 1(504,3) COMMON /PLOT3/ YH1(504,7),YH2(504,7),YH3(504,7),YH4(504,10),XDH(50 14,10),XDD(504,4) COMMON /PLOT4/ LINTYP(10) +FFPP(504+4) + YN(43+4) + ILAB С COMMON /TITLE/ TITLE(24) COMMON /MAIN/ ISOLV, NSTOP, ID COMMON /PRINT/ VPRINT, HINC, PINC, IHFRNT, IHPLOT, IPPRNT, IPPLOT, IPRNT COMMON /HISP/ FREMAX, IPT, NPO, NPS, NFR, NPL COMMON /ABVIS/ IPRES,ABVISH,ABVISF,ABMAX,ABVMAX COMMON /INJECT/ DVPP, DVP, VP, VT, VPI COMMON /PRFPL/ PLPF(10),NPF,NFG С LOGICAL LEGEND, Y2AXIS C С C NVFCT=7 NMAX3=504 DO 10 I=1.7 LINTYP(I)=3 10 NPT(I)=IPT IF (IHPLOT.EQ.2) GO TO 30 C PRINTER PLOT С С TPLT=1 XLABEL(1)=10HP.V. INJEC XLABEL(2)=3HTED YLABEL(1)=10H YLABEL(2)=10HC ONCENTRAT YLABEL(3)=10HIONS NXCHAR=13 NYCHAR=30 ITITL(1,2)=10H ITITL(2,2)=10H ITITL(1,5)=10H HISTORI ITITL(2,5)=10HES UP TO ENCODE (7,160, ITITL(3,5)) VP ITITL(4,5)=10HPV. INJECT ITITL(5,5)=2HED CALL PLOTZ2 (XDH, YH1, IPLT, NVECT, NPT, NMAX3, LINTYP) CALL PLOTZ2 (XDH, YH2, IPLT, NVECT, NPT, NHAX3, LINTYP) CALL PLOTZ2 (XDH, YH3, IPLT, NVECT, NPT, NMAX3, LINTYP) CALL PLOTZ2 (XDH, YH4, IPLT, NVECT, NPT, NMAX3, LINTYP) С NVECT=2

YLABEL(1)=10HPFASE CUT YLABEL(2)=10HOR OIL REC YLABEL(3)=10HOVERY CALL PLOTZ2 (XDH, FFP, IPLT, NVECT, NPT, NMAX3, LINTYP) C YLABEL(1)=10H YLABEL(2)=10HREL PRESS YLABEL(3)=10HDROP ITITL(1,1)=10H ITITL(2,1)=10H ITITL(3,1)=10H ITITL(4,1)=10H NVECT=1 IF (IPRES.NE.1) GO TO 20 NVECT=2 YLABEL(1)=10HAPPARENT YLABEL(2)=10HVISCOSITY YLABEL(3)=10H ECP] IF (ILAB.NE.1) GO TO 20 NVECT=4 20 CONTINUE CALL PLOTZ2 (XDD, FFPP, IPLT, NVECT, NFT, NKAX3, LINTYP) 30 IF (IHPLOT.LT.2) GO TO 150 С С ZETA PLOT C C CALL PLOTS (0,0,5LPLOTR) NTITLE=5 IPLT=2 DO 40 L=1,10 40 LINMOD(L)=2 С SCALE PARAMETERS С C IX=2IY=2 XL=5. YL=4. XD=0.3 YD=0.25 XF=0. YF=0. С С SECOND Y-SCALE PARAMETERS С Y2AXIS=.TRUE. IY2AXT=1 Y2FSTV=0.0 Y2DELV=0.25 IY2AXF=2 Y2LNZ=4.0 NY2CHR=0 С С Y2LABL(1)=10H С Y2LABL(2)=10H С Y2LABL(3)=10H С DO 50 L=1.10 50 IYAXNO(L)=1 C С BORDER AND LEGEND PARAMETER

С IBORDR=1 LEGEND=.TRUE. С DO 60 I=1+10 60 LINTYP(I)=10 XLABEL(1)=10HP.V. INJEC XLABEL(2)=3HTED ITITL(1,3)=10H HISTORI ITITL(2,3)=10HES UP TO ENCODE (7+160, ITITL(3,3)) VP ITITL(4,3)=10HPV. INJECT ITITL(5,3)=2HED С Ċ PLOTTING TOTAL CONCENTRATIONS AND CIL RECOVERY YL=5.0 Y2LNZ=5.0 NVECT=6 ITITL(2,1)=10H FIGUR ITITL(3+1)=10HE 3.1. NFG=NFG+1 ENCODE (2,170,ITITL(4,1))NFG ITITL(1+5)=10H TOT. CO ITITL(2,5)=10HNC. OR OIL ITITL(3,5)=10H. REC. VS. ITITL(4,5)=10H PV. INJEC ITITL(5,5)=3HTED YLEGND(1,1)=10H OIL RECOV YLEGND(2+1)=10HERY ESIMUL YLEGND(3,1)=10HATED] YLEGND(1,2)=10H TOTAL OIL YLEGND(2,2)=10H CONC. ESI YLEGND(3,2)=10HMULATED] YLEGND(1+3)=10H TOT. SURF YLEGND(2,3)=10+ CONC. ESI YLEGND(3,3)=10HM. 1/0.03] YLEGND(1,4)=10H TOTAL POL YLEGND(2,4)=10HYMER CONC. YLEGND(3,4)=10HESIMULATED С YLEGND(1,5)=10H YLEGND(2,5)=10+ YLEGND(3,5)=8H C YLEGND(1,5)=10H TOT. CAL. YLEGND(2.5)=10H CONC. ESI YLEGND(3,5)=10+M. 1/0.08] YLEGND(1,6)=10H TOT. ALC. YLEGND(2,6)=10H CONC. ESI YLEGND(3,6)=10HM. 1/0.043 С IF (ILAB.NE.1) GO TO 120 С NVECT=9 YLEGND(1,7)=10H TOT. OIL YLEGND(2,7)=10HCONC. ELAB YLEGND(3,7)=6H DATA] YLEGND(1,8)=10H SURF. CON YLEGND(2,8)=10HC. ELAB-DA YLEGND(3,8)=10+TA/0.03] YLEGND(1,9)=10H OIL RECOV

and a second real damage of the

```
YLEGND(2,9)=10HERY ELAB D
      YLEGND(3,9)=4HATA]
С
      ISYMZT(7)=5
      ISYMZT(8)=1
      ISYMZT(9)=0
      NPT(7) = NPO
      NPT(8)=NPS
      NPT(9)=NPR
С
      NPPP=NPT(1)
      D0 70 I=1,NPPP
     DO 70 J=5+6
  70 YH4(I,J)=YH4(I,J+1)
      DO 80 I=1,NPO
         YH4(I,7)=YH4(I,8)
  80 XDH(I+7)=XDH(I+8)
      DO 90 I=1,NPS
         YH4(I,8)=YH4(I,9)
  90 XDH(I,8)=XDH(I,9)
      DO 100 I=1,NPR
         YH4(I,9)=YH4(I,10)
  100 XDH(I,9)=XDH(I,10)
      DO 110 I=7,9
         LINTYP(I)=-1
  110 CONTINUE
  120 CONTINUE
С
      ISYMZT(1)=0
      ISYMZT(2)=12
      ISYMZT(3)=1
      ISYMZT(4)=4
С
С
      ISYMZT(5)=7
С
      ISYMZT(5)=2
     ISYMZT(6)=10
      YLABEL(1)=10H TOT. CON
                        OR
      YLABEL(2)=10HC.
      YLABEL(3)=10H OIL REC.
С
     CALL PLOTZ2 (XDH, YH4, IPLT, NVECT, NPT, NMAX3, LINTYP)
С
С
     POLTTING FRACTIONAL FLCW
С
     NNP=NPT(1)
     DO 130 I=1,NNP
  130 XDH(I+7)=XDH(I+1)
      NPT(7) = NPT(1)
     LINTYP(7)=10
С
      YL=5.0
      Y2LNZ=YL
      NVECT=2
      NFG=NFG+1
      ENCODE (2,170, ITITL(4,1) )NFG
      ITITL(1+5)=10H
                        FRACT
      ITITL(2,5)=10HIONAL FLOW
      ITITL(3,5)=10H VS. PV.
      ITITL(4,5)=10H INJECTED
      ITITL(5,5)=10H
      YLEGND(1,1)=10H FRACTIONA
```

YLEGND(2,1)=10HL FLOW AQU VLEGND(3.1)=10HEOUS PHASE YLEGND(1,2)=10H FRACTIONA YLEGND(2,2)=10HL FLCW CLE YLEGND(3,2)=8HIC PHASE C С YLEGND(1,3)=10H FRAC. FLO С YLEGND(2,3)=10HW AQUE. PH С YLEGND(3,3)=9HASE ELAB] С YLEGND(1.4)=10H FRAC. FLO С YLEGND(2,4)=10HW OIL PHAS С YLEGND(3,4)=7HE [LAB] C ISYMZT(1)=1ISYMZT(2)=2 YLABEL(1)=10H FRAC YLABEL(2)=10HTIONAL FLO YLABEL(3)=10HW C CALL PLOTZ2 (XDH, FFP, IPLT, NVECT, NPT, NMAX3, LINTYP) C C C PLOTTING SALINITY AND SALINITY LIMITS NVECT=3 NFG=NFG+1 ENCODE (2,170, ITITL(4,1))NFG ITITL(1,5)=10HSALINITY A ITITL(2,5)=10HND SALINIT ITITL(3,5)=10HY LIMITS ITITL(4,5)=10HVS. PV. I ITITL(5,5)=7HNJECTED YLEGND(1,1)=10H SALINITY YLEGND(2,1)=10H YLEGND(3,1)=10+ YLEGND(1,2)=10H LOWER SAL YLEGND(2,2)=10+INITY LIMI YLEGND(3+2)=1HT YLEGND(1,3)=10H UPPER SAL YLEGND(2,3)=10HINITY LIMI YLEGND(3,3)=1HT ISYMZT(1)=1ISYMZT(2)=4ISYMZT(3)=5 SALIN YLABEL(1)=10H YLABEL(2)=10HITY EMEQ. YLABEL(3)=4H/ML] С CALL PLOTZ2 (XCH, SAL, IPLT, NVECT, NPT, NMAX3, LINTYP) C GO TO 333 C--PLOTTING CONCENTRATIONS IN AGUEOUS PHASE С С NVECT=7 NFG=NFG+1 ENCODE (2,170, ITITL(4,1)) NFG ITITL(1,5)=10 HAQUEOUS PH ITITL(2,5)=10HASE CONCEN ITITL(3,5)=8HTRATICNS ITITL(4.5)=10HVS. PV. I ITITL(5,5)=7HNJECTED YLEGND(1+1)=10H WATER CON

```
VLEGND(2,1)=10+CENTRATION
      YLEGND(3,1)=10⊦
      YLEGND(1,2)=10H OIL CONCE
      YLEGND(2,2)=10FNTRATION
      YLEGND(3,2)=10+
      YLEGND(1,3)=10H NORM. SUR
      YLEGND(2,3)=10HF. CONC. E
      YLEGND(3.3)=10+SIM 1/.01]
      YLEGND(1,4)=10H POLYFER C
      YLEGND(2,4)=10+ONCENTRATI
      YLEGND(3,4)=2HCN
      YLEGND(1.5)=10H ANIONIC C
      YLEGND(2,5)=10 HONCENTRATI
      YLEGND(3,5)=2HCN
      YLEGND(1,6)=10H CALCIUM C
      YLEGND(2,6)=10HONCENTRATI
      YLEGND(3+6)=2HCN
      YLEGND(1,7)=10H ALCOHOL C
      VLEGND(2,7)=10HONCENTRATI
      YLEGND(3,7)=2HCN
      ISYMZT(1)=1
      ISYMZT(2)=0
      ISYMZT(3)=5
      ISYMZT(4)=4
      ISYMZT(5)=6
      ISYMZT(6)=7.
      ISYMZT(7)=2
      YLABEL(1)=10H
                          AQUE
      YLABEL(2)=10HOUS PHASE
      YLABEL(3)=5HCCNC.
      CALL PLOTZ2 (XDH, YH1, IPLT, NVECT, NPT, NMAX3, LINTYP)
С
      PLOTTING CONCENTRATIONS IN OLEIC PHASE
С
      NFG=NFG+1
      ENCODE (2,170,ITITL(4,1) )NFG
      ITITL(1,5)=10H OLEIC FH
      YLABEL(1)=10H
                            0L
      YLABEL(2)=10HEIC PHASE
      CALL PLOTZ2 (XDH, YH2, IPLT, NVECT, NPT, NHAX3, LINTYP)
С
       PLOTTING CONCENTRATIONS IN M.E. PHASE
С
      NFG=NFG+1
      ENCODE (2,170, ITITL(4,1) ) NFG
      ITITL(1.5)=10H MICRO. PH
      YLABEL(1)=10H
                         MICR
      YLABEL(2)=10HO. PHASE C
      YLABEL(3)=4HONC.
      CALL PLOTZ2 (XDH, YH3, IPLT, NVECT, NPT, NHAX3, LINTYP)
С
      PLOTTING PRESSURE DROP OR APPARENT VISCOSITY
C
      NVECT=1
      IX=2
      IY=0
      NFG=NFG+1
      ENCODE (2,170, ITITL(4,1) )NFG
      ITITL(1,5)=10H PRESSUR
```

С

С

С

С

С

С

```
ITITL(2,5)=10HE DROP ENO
      ITITL(3,5)=10HRM3 VS.
      ITITL(4+5)=10HFV. INJECT
      ITITL(5,5)=2HED
      YLEGND(1,1)=10H NORMALIZE
      YLEGND(2,1)=10HD PRESSURE
      YLEGND(3,1)=5H DROP
      YLABEL(1)=10H
                        RELAT
      YLABEL(2)=10HIVE PRESS
      YLABEL(3)=8HURE DROP
      IF (PREMAX.LE.5.0) IY=2
      IY2AXF=IY
      IF (PREMAX.LE.5.0) YD=1.0
      Y2DELV=Y0
C
      IF (IPRES.NE.1) GO TO 140
С
     NVECT=4
      ITITL(1,5)=10H
                        APPARE
      ITITL(2,5)=10HNT VISC. E
      ITITL(3,5)=10HCP] VS.
      ITITL(4,5)=10HPV. INJECT
      ITITL(5,5)=2HED
      YLEGND(1.1)=10H APPARENT
      YLEGND(2,1)=10HVISCOSITY
      YLEGND(3,1)=10HAT 0.5 VP
      YLEGND(1,2)=10H APPARENT
      YLEGND(2,2)=10+VISCOSITY
      YLEGND(3,2)=10HAT 1.0 PV
      YLEGND(1,3)=10H APP. VISC
      YLEGND(2.3)=10H. AT 0.5 P
      YLEGND(3,3)=7HV ELAB]
      YLEGND(1,4)=10H APP. VISC
      YLEGND(2,4)=10+. AT 1.0 P
      YLEGND(3,4)=7HV [LAB]
     ISYMZT(1)=14
      ISYMZT(2)=7
     ISYMZT(3)=1
     ISYMZT(4)=0
      YLABEL(1)=10H
                       APPARE
      YLABEL(2)=10HNT VISCCS
     YLABEL(3)=10HITY [CP]
      NPT(3) = NPL
      NPT(4) = NPL
     LINTYP(3) = -1
     LINTYP(4) = -1
     IY=2
     IY2AXF=IY
      IYMAX=INT(ABVMAX/10.0)
      YSC=FLOAT(IYMAX+1)+10.0
      YD=YSC/YL
      Y2DELV=YD
 140 CONTINUE
     CALL PLOTZ2 (XDD, FFPP, IPLT, NVECT, NFT, NMAX3, LINTYP)
С
  333 CONTINUE
      CALL PLOT (XDUM, YDUM, 999)
      CALL RELEASE (ID)
С
  150 CONTINUE
      RETURN
С
```

```
160 FORMAT (3X, F4.2)
 170 FORMAT (12)
С
     END
     SUBROUTINE PREPRNT
С
С
     ---- PRFPRNT -----
С
С
     PURPOSE:
С
С
     THIS SUBROUTINE PRINTS PROFILE FOR EVERY PINC INCREMENT
     PROFILE WILL BE PRINTED IF IPPRNT=1
C
С
С
     C
     COMMON /MAIN/ ISOLV.NSTOP.ID
     COMMON /PRINT/ VPRINT, HINC, PINC, IHFRNT, IHPLOT, IPPRNT, IPPLOT, IPRNT
     COHMON /IFTP/ GRA1(41), GRA2(41)
     COMMON /REST/ IERRCR, IH, IK, II, VPP, KK, IFLAG, ISLUG
     COMMON /NO/ ICT.ICT1.ICT2.XICT.NCOMP.NF
     COMMON /SOL/ C(7,4,42),S(3,42),FF(3,42),NPHASE(42),EPSME
     COMMON /CSE/ CSE(42),CSA(42),CSEL,CSEU,RCSE,CSEOP,DCSE,CSELI,CSEUI
     COMMON /ADSORP/ C3ADSS(40) +C4ADSS(40) +C6ADSS(40) +C6HATS(40)
     COMMON /CALC/ C6J0(40)
     COMMON /XIFT/ XIFT1(42),XIFJ2(42),XIFT3(42),XIFTW
     COMMON /TRAP/ T11.T12.T21.T22.T31.T32.S1RW.S2RW.PHT(40).EPSMOB.ICO
     1NT, IPMAX
     COMMON /PRESS/ PHTLU, PRESUM, ICTL, ICTU, PRES(40)
     COMMON /PERMC/ PERM(3.40), SRED(3.40), SN(3,40), VIS(3,40), LPERM(40)
     COMMON /INJECT/ DVPP, DVP, VP, VT, VPI
С
     С
С
     XICT=1./FLOAT(ICT)
     II=0
     00 60 K=1,ICT
        II=II+1
        KD=XICT * FLOAT(ICT-K+1)
        IF (NPHASE(K).NE.1) GO TO 20
        GRA1(K)=0.0
        GRA2(K)=0.0
        IF (II.LE. 7. AND.K.GT.1) GO TO 10
        PRINT 70, VP
        PRINT 80, XD, (C(I,1,K),I=1,7),S(1,K),SRED(1,K),FF(1,K),VIS(1,K)
        , PERH(1,K),C3ADSS(K),GRA1(K),GRA2(K)
     1
        II=1
        GO TO 40
        PRINT 90, XD,(C(I,1,K),I=1,7),S(1,K),SRED(1,K),FF(1,K),VIS(1,K)
  10
         PERM(1,K),C3ADSS(K),GRA1(K),CRA2(K)
    1
        GO TO 40
  20
        GRA1(K)=10.0++XIFT1(K)
        GRA2(K)=10.0++XIFT2(K)
        IF (II.LE.7.AND.K.GT.1) GO TO 30
        PRINT 70. VF
        PRINT 100, XD,(C(I,1,K),I=1,7),S(1,K),SRED(1,K),FF(1,K),VIS(1,K
        ),PERM(1,K),C3ADSS(K),GRA1(K),GPA2(K)
     1
        II=1
        GO TO 40
   30
        PRINT 90, XD, (C(I,1,K), I=1,7), S(1,K), SRED(1,K), FF(1,K), VIS(1,K)
        *PERH(1,K),C3ADSS(K),GRA1(K),GRA2(K)
    1
   40
        00 50 J=2+3
        PRINT 110, J, (C(I,J,K),I=1,7),S(J,K),SRED(J,K),FF(J,K),VIS(J,K)
  50
```

```
1
        , PERM(J.K)
        J=4
        PRINT 110, J, (C(I,J,K), I=1,7)
        PRINT 120, C6HATS(K),C6ADSS(K),C6J0(K),PHT(K),PRES(K),CSE(K)
  60 CONTINUE
     II=0
С
     С
C
     RETURN
C
  70 FORMAT (1H1,/.1X.T35,4(2H++),2X,14HPROFILES AT .F4.2,23H INJECT
    1ED POREVOLUMES+2X+4(2H++))
  RO FORMAT (//,2X,2HXD,1X,5HPHASE,10%,27HCONCENTRATION OF COMPONENTS,1
    15X,10HSATURATICN,51X,5HGAMNA,/11X,2HC1,5X,2HC2,5X,2HC3,5X,2HC4,5X,
    22HC5+5X+2HC6+5X+2HC7+7X+1HS+7X+2+SR+6X+2HFF+7X+3HVIS+7X+4HPERM+6X+
    35HC3ADS,7X,3HWME,8X,3HOME,/1X,F5.3,2X,1H1,7(1X,F6.4),1X,F6.4,2(1X,
    4F7.4),1X,3F10.5,2(1X,F10.5))
  90 FORMAT (//,1X,F5.3,2X,1H1,7(1X,F6.4),1X,F6.4,2(1X,F7.4),1X,3F10.5,
    12(1X,F10.5))
 100 FORMAT (//,2X,2HXD,1X,5HPHASE,10X,27HCONCENTRATION OF COMPONENTS,1
     15X,10HSATURATICN,51X,5HGAMNA,/11X,2HC1,5X,2HC2,5X,2HC3,5X,2HC4,5X,
    22HC5,5X,2HC6,5X,2HC7,7X,1HS,7X,2HSF,6X,2HFF,7X,3HVIS,7X,4HPERM,6X,
    35HC3ADS,7X,3HWME,8X,3HOME,/1X,F5.3,2X,1H1,7(1X,F6.4),1X,F6.4,2(1X,
     4F7.4),1X,3F10.5,2(1X,F10.5))
  110 FORMAT (6X,13,7(1X,F6.4),1X,F6.4,2(1X,F7.4),1X,2F10.5)
 120 FORMAT (1X+6HC6HAT=+E10+4+1X+7HC6ADSS=+E10+4+1X+5HC6J0=+E10+4+1X+
    110HT0T. MOB.=,E10.4,2X,9HPRESSURE=,E10.4,2X,21HEFFECTIVE SALINITY=
       +E10.4)
    2
С
     END
     SUBROUTINE PREPLCT
С
С
     ---- PRFPLOT -------
С
     PURPOSE:
С
С
     THIS SUBROUTINE PLOT PROFILE FOR EVERY PINC INCREMENT
С
     PROFILE WILL BE PLOTTED IF IPPLOT>0
С
     OPTIONS FOR PLOTTING:
С
         IPPLOT=1 : CNLY PRINTER PLCT
С
                  : ONLY ZETA PLOT
С
         IPPLOT=2
         IPPLOT=3 : BOTH PRINTER AND ZETA PLOT
С
С
     C
С
     COMMON /AXLABL/ XLABEL(3), YLABEL(3), NXCHAR, NYCHAR, LABSID
     COMMON /AXTYP/ IXA, IYA
     COMMON /BORDER/ IBORDR
     COMMON /FXDSCL/ XF,YF,XD,YD,IX,IY
     COMMON /LEGEND/ LEGEND, FACTL, YLEGNE(3,10)
     COMMON /LINMOD/ LINMOD(10)
     COMMON /PLTSIZ/ TEMP(2),XL,YL
     COMMON /SYMBZT/ ISYMZT(10)
     COMMON /TITL/ NTITLE, ITITL(5,5)
     COMMON /Y2AXIS/ Y2AXIS, IY2AXT, Y2FSTV, Y2DELV, IY2AXF, Y2LNZ, NY2CHR, Y2
     1LABL(3), IYAXNO(10)
С
     COMMON /PLOT1/ Y1(43,8),Y2(43,8),Y3(43,8),Y4(43,8),XD1(43,8),NPTS(
     18) •Y5(43+6)
     COMMON /PLOT2/ NPT(10),FFP(504,2),YM(43,4),XD2(43,4),YMN(43,4),SAL
     1(504+3)
```

```
COMMON /PLOT3/ YH1 (504+7) + YH2 (504,7) + YH3 (504,7) + YH4 (504,10) + XDH (50
     14,10),XDD(504,4)
     COMMON /PLOTA/ LINTYP(10),FFPP(5C4,4),YN(43,4),ILAB
C
     COMMON /NORM/ C33N, C34N, C44N, C64N, C74N
     COHMON /IFLP/ GRA1(42), GRA2(42)
     COMMON /PERMC/ PERM(3,40), SRED(3,40), SN(3,40), VIS(3,40), LPERM(40)
     COMMON /TITLE/ TITLE(24)
     COMMON /MAIN/ ISOLV, NSTOP, ID
     COMMON /PRINT/ VPRINT, HINC, PINC, IMPRNT, IMPLOT, IPPRNT, IPPLOT, IPRNT
     COMMON /NO/ ICT+ICT1+ICT2+XICT+NCOMP+NF
     COMMON /SOL/ C(7,4,42),S(3,42),FF(3,42),NPHASE(42),EPSHE
     COMMON /TRAP/ T11, T12, T21, T22, T31, T32, S1RW, S2RW, PHT(40), EPSMOB, ICO
     INT.IPMAX
     COMMON /PRESS/ PHTLU, PRESUN, ICTL, ICTU, PRES(40)
     COMMON /ABVIS/ IPRES, ABVISH, ABVISF, ABNAX, ABVMAX
     COMMON /INJECT/ DVPP.DVP.VP.VT.VPI
     COMMON /PRFPL/ PFPL(10),NPF,NFG
С
     LOGICAL LEGEND.Y2AXIS
С
С
      r
     DO 10 K=1.ICT
        XD1(K,8)=XICT+FLOAT(ICT-K+1)
        YM(K,1)=PHT(K)
        YM(K,2)=GRA1(K)
        YM(K,3)=GRA2(K)
        YM(K,4)=PRES(K)
        Y5(K+1)=S(1+K)
        Y5(K,2)=SRED(1,K)
        Y5(K,3)=1.0-S(2,K)
        Y5(K,4)=1.0-SRED(2,K)
        Y5(K,5)=1.0-S(2,K)-SRED(3,K)
        Y1(K.8)=S(1.K)
        Y2(K+8)=S(2+K)
   10 Y3(K,8)=S(3,K)
     DO 20 I=1.7
     DO 20 K=1,ICT
        XD1(K,I)=XD1(K,8)
        Y1(K,I) = C(I,1,K)
        Y2(K+I)=C(I+2+K)
        Y4(K,I)=C(I,4,K)
        Y4(K,1)=0.0
   20 Y3(K,I)=C(I,3,K)
     DO 30 K=1.ICT
        Y1(K,3)=C(3,1,K)
        Y2(K,3)=C(3,2,K)
        Y3(K,3)=C(3,3,K)/C33N
        Y4(K,3)=C(3,4,K)/C34N
      Y4 (K,6)=C(6,4,K)/C64N
   30 CONTINUE
С
     TEST FOR PRINTER AND/OR ZETA PLOT
С
£
      IF (IPPLOT.EQ.2) GO TO 40
     IPLT=1
      GO TO 50
   40 IPLT=2
   50 CONTINUE
C
      С
```

		INITIALIZING PLOTTER PARAMETERS
C		IX=0 IY=0 NVECT=8 D0 60 I=1.8 LINTYP(I)=3 TSYM2T(I)=1
	60	NPTS(I)=ICT NMAX2=43 IF (IPLT.EQ.2) IX=2 IF (IPLT.EQ.2) IY=2 IF (IPLT.EQ.2) CALL PLCTS (0,0,5LPLCTR) XL=5.0 YL=5.0 YD=0.25 YE=0
		YF=0.0 VF=0.0 LABTYP=0 NDEC=1
		SECOND Y-SCALE PARAMETERS
L		Y2AXIS=.TRUE. IY2AXT=1 Y2FSTV=0.C Y2DELV=YD IY2AXF=2 Y2LN7=5
_	70	DO 70 L=1+10 IYAXNO(L)=1
		BORDER AND LEGEND PARAMETERS
		IBORDR=1 LEGEND=.TRUE. FACTL=0.7
ſ		NXCHAR=20 NYCHAR=30 XLABEL(1)=10H FRACTIONA XLABEL(2)=10HL DISTANCE NTITLE=5 ITITL(1,1)=10H ITITL(2,1)=10H FIGURE ITITL(3,1)=10H 3.1. IF (IPLT.EQ.2) NFG=NFG+1 ENCODE (2,150,ITITL(4,1))NFG ITITL(1,3)=10H P ITITL(2,3)=10HROFILES AT ENCODE (7,160,ITITL(3,3))VP ITITL(4,3)=4HP.V. ITITL(5,3)=10H
		IF (VP_GT.1.2.AND.VP.LT.1.3) GO TO 3333
		LINHOD(2)=2 LINHOD(4)=2

. .

C LINMOD(5)=2IF (VP.LE.0.499999.0R.VP.GT.0.5000(1) 60 TO 120 С С 3333 CONTINUE С PLOTTING TOTAL CONCENTRATION С NVECT=7 IF (IPLT.EQ.2) NFG=NFG+1 ENCODE (2+140+ITITL(4+1)) NFG ITITL(1,5)=10H TOTAL CO ITITL(2,5)=10HNCENTRATIO ITITL(3,5)=10HN VS. FRA ITITL(4,5)=10HCTIONAL DI ITITL(5,5)=6HSTANCE YLEGND(1,1)=10H TOTAL WAT YLEGND(2.1)=10HER CONCENT YLEGND(3,1)=6HRATION YLEGND(1,2)=10H TOTAL OIL YLEGND(2,2)=10H CONCENTRA YLEGND(3,2)=4HTION YLEGND(1,3)=10H TOT. SURF YLEGND(2,3)=10H. CONC. E YLEGND(3,3)=10H1/0.03] YLEGND(1,4)=10H TOTAL POL YLEGND(2,4)=10HYMER CONCE YLEGND(3,4)=8HNTRATION YLEGND(1,5)=10H TOTAL ANI YLEGND(2,5)=10HONIC CONCE YLEGND(3,5)=8HNTRATION YLEGND(1,6)=10H TOT. CALC YLEGND(2.6)=10H. CONC. E1 YLEGND(3,6)=10H/0.08] YLEGND(1,7)=10H TOT. ALC. YLEGND(2,7)=10H CONC. E1/ YLEGND(3,7)=10H0.0375] ISYMZT(1)=1ISYMZT(2)=0 ISYMZT(3)=5 ISYHZT(4)=4 ISYMZT(5)=6 ISYMZT(6)=7ISYMZT(7)=14 YLABEL(1)=10H TOTA YLABEL(2)=10HL CONCENTR YLABEL(3)=6HATIONS Ċ CALL PLOTZ2 (XD1,Y4, IPLT, NVECT, NFTS, NMAX2, LINTYP) С IF (VP.GT.0.51) GO TO 120 C PLOTTING SATURATION AND RESIDUAL SATURATION С NVECT=5 IF (IPLT.EQ.2) NFG=NFG+1 ENCODE (2+150+ITITL(4+1))NFG ITITL(1,5)=10HSATURATION ITITL(2,5)=10H AND RES. ITITL(3,5)=10HSATURATICN ITITL(4,5)=10H VS. FRAC ITITL(5,5)=10H. DISTANCE YLEGND(1,1)=10H SATURATIO YLEGND(2.1)=10HN OF AQUEO

```
YLEGND(3,1)=8HUS PHASE
YLEGND(1,2)=10H RES. SAT.
YLEGND(2+2)=10H OF AQUEOU
YLEGND(3,2)=7HS PHASE
YLEGND(1.3)=10+ SATURATIO
YLEGND(2,3)=10HN OF OLEIC
YLEGND(3,3)=6H PHASE
YLEGND(1,4)=10H RES. SAT.
YLEGND(2,4)=10H OF OLEIC
YLEGND(3,4)=5HPHASE
YLEGND(1,5)=10H RES. SAT.
YLEGND(2,5)=10H OF MICRO.
YLEGND(3,5)=6H PHASE
ISYMZT(1)=5
ISYMZT(2)=7
ISYMZT(3)=1
ISYMZT(4)=14
ISYMZT(5)=4
                SATURAT
YLABEL(1)=10H
YLABEL(2)=10HION OR R
YLABEL(3)=BHES. SAT.
LINMOD(2)=4
LINMOD(4)=4
LINMOD(5)=4
CALL PLOTZ2.(XD1,Y5,IPLT,NVECT,NFTS,NMAX2,LINTYP)
NVECT=7
IF (IPLT.EQ.2) NEG=NEG+1
ENCODE (2,150, ITITL(4,1) )NFG
ITITL(1,5)=10HAQUEOUS PH
ITITL(2,5)=10HASE CONCEN
ITITL(3,5)=10HTRATION VS
ITITL(4,5)=10H FRACTIONA
ITITL(5,5)=10HL DISTANCE
YLEGND(1,1)=10H WATER CON
YLEGND(2,1)=10HCENTRATICN
YLEGND(3,1)=10H
YLEGND(1,2)=10H OIL CONCE
YLEGND (2,2)=10HNTRATION
YLEGND(3,2)=10H
YLEGND(1,3)=10H SURF. CON
YLEGND(2,3)=10HC. [1/0.01
YLEGND(3,3)=10H]
YLEGND(1,4)=10H POLYMER C
YLEGND(2+4)=10FONCENTRATI
YLEGND(3,4)=2HCN
YLEGND(1,5)=10H ANIONIC C
YLEGND(2,5)=10FONCENTRATI
YLEGND(3,5)=2HON
YLEGND(1,6)=10H CALCIUM C
YLEGND(2,6)=10FONCENTRATI
YLEGND(3.6)=2HON
YLEGND(1,7)=10H ALCOHOL C
YLEGND(2,7)=10FONCENTRATI
YLEGND(3,7)=2HCN
ISYMZT(1)=1
```

С

C C C

С

С

С

```
ISYMZT(2)=0
     ISYMZT(3)=5
     ISYMZT(4)=4
     ISYMZT(5)=6
     ISYMZT(6)=7
      ISYMZT(7)=2
     YLABEL(1)=10H
                        AQUE
     YLABEL(2)=10HOUS PHASE
     YLABEL(3)=5HCONC.
C
     LINMOD(2)=2
     LINMOD(4)=2
     LINHOD (5)=2
С
     CALL PLOTZ2 (XD1, Y1, IPLT, NVECT, NFTS, NMAX2, LINTYP)
C
С
     PLOTTING OLEIC PHASE CONCENTRATIONS
С
     IF (IPLT.EQ.2) NFG=NFG+1
     ENCODE (2,150,ITITL(4,1) )NFG
     ITITL(1,5)=10HOLEIC PHAS
     ITITL(2,5)=10HE CONCENTR
     ITITL(3,5)=10HATION VS.
     ITITL(4,5)=10H FRACTIONA
     ITITL(5,5)=10HL DISTANCE
С
     YLABEL(1)=10H
                          0L
     YLABEL(2)=10HEIC PHASE
С
     CALL PLOTZ2 (XD1,Y2,IPLT,NVECT,NFTS,MMAX2,LINTYP)
С
     PLOTTING MICROEMULSION PHASE CONCENTRATIONS
С
С
     IF (IPLT+EQ+2) NFG=NFG+1
     ENCODE (2,150, ITITL(4,1) ) NFG
     ITITL(1,5)=10HM.E. PHASE
     ITITL(2,5)=10H CONCENTRA
     ITITL(3,5)=10HTION VS.
     ITITL(4,5)=10H FRACTIONA
     ITITL(5,5)=10HL DISTANCE
С
     YLABEL(1)=10H
                        MICR
     YLABEL(2)=10H0. PHASE C
     YLABEL (3)=4HONC.
C
     CALL PLOTZ2 (XD1+Y3+IPLT+NVECT+NFTS+NMAX2+LINTYP)
С
     GO TO 120
С
      С
С
     PLOTTING REL. PRESURE DROP OR APPARENT VISCOSITY
C
     ITITL(1,2)=10H
     ITITL(2,2)=10H
     NVECT=2
     ICON1=0
     DO 80 I=1.ICT
        YMN(I,1)=YM(I,1)
        YMN(I+2)=YH(I+4)
        IF (YM(I,2).GT.0.2) GO TO 80
        IF (YM(I,2).LT.1.0E-8) GO TO 80
        ICON1=ICON1+1
```

```
YN(ICON1.1)=YM(I.2)
         XD2(ICON1,1)=XD1(I,2)
   80 CONTINUE
      ICON2=0
      D0 90 I=1+ICT
         IF (YM(1,3).GT.0.2) GO TO 90
         IF (YM(I,3).LT.1.0E-8) GO TO 50
         ICON2=ICON2+1
         YN(ICON2,2)=YH(I,3)
         XD2(ICON2,2)=XD1(I,3)
   90 CONTINUE
     NPTS(1)=ICT
     NPTS(2)=ICT
      YLABEL(1)=10HTOTAL MOBI
      YLABEL(2)=10HL. OR REL
      VLABEL(3)=10HPRES DROP
      IF (IPRES.NE.1) GO TO 110
     DO 100 I=1,ICT
 100 YMN(I+1)=1.0/PHT(I)
     NVECT=1
      YLABEL(1)=10HAPPARENT
      YLABEL(2)=10HV ISCOSITY
      YLABEL(3)=10H [CP]
  110 CONTINUE
     IX=2
      IY=0
     CALL PLOTZ2 (XD1.YMN, IPLT, NVECT, NPTS, NMAX2, LINTYP)
С
C
     PLOTTING INTERFACIAL TENSION
С
     NVECT=2
     IF (ICON1.EQ.0) NVECT=NVECT-1
      IF (ICON2.EG.0) NVECT=NVECT-1
     NPTS(1)=ICON1
     NPTS(2)=ICON2
     YLABEL(1)=10H
                       INTER
     YLABEL(2)=10HFACIAL TEN
     YLABEL(3)=10HSIONS
     CALL PLOTZ2 (XD2, YN, IPLT, NVECT, NFTS, NMAX2, LINTYP)
С
 120 CONTINUE
 334 CONTINUE
     IF (IPLT.EQ.2) CALL PLOT (XDUM,YDUM,999)
      IF (IPLT.EQ.2) CALL RELEASE (ID)
С
С
     WANT ADDITIONAL ZETA PLOT (IPPLOT=3)
С
     IF (IPLT.E0.2) GO TO 130
     IF (IPPLOT.EQ.3) GO TO 40
 130 CONTINUE
С
     RETURN
С
 140 FORMAT (I2)
 150 FORMAT (12)
 160 FORMAT (3X+F4.2)
C
     END
     SUBROUTINE TABOUT
С
С
      _____
С
     THIS SUBROUTINE PRINTS A SUMMERY TABLE AFTER THE LAST
```

```
С
     TIMESTEP
С
      C
     REAL IS
     COMMON /TITLE/ TITLE(24)
     COMMON/SYSTEM/UT, ABPERM, PHI, EPHI3, EPHI4, CISPJ(4)
     COMMON /NO/ ICT.ICT1.ICT2.XICT.NCOPP.NF
     COMMON /IN/ VIN(10), CIN(7,10)
     COMMON /TRAP/ T11, T12, T21, T22, T31, T32, S1RW, S2RW, PHT(40), EPSHOB, ICO
     INT . IPHAX
     COMMON /CSEVIS/ VIS1, VIS2, AP1, AP2, AP3, SSLOPE
     COMMON /CSE/ CSE(42),CSA(42),CSEL,CSEU,RCSE,CSEOP,DCSE,CSELI,CSEUI
     COMMON /PRCDIN/ ER,P(7),P8,ZI(7),ZE(7),S2
     COMMON / PERM/ IPERM, P1RW, P2RW, E1, E2, E3, P1RC, P2RC
     COMMON /PERMC/ PERM(3,40), SRED(3,40), SN(3,40), VIS(3,40), LPERM(40)
     COMMON /INJECT/ DVPP, DVP, VP, VT, VFI
     COMMON /REST/ IERROR, IH, IK, II, VPP, KK, IFLAG, ISLUG
     COMMON /TAB/ ISK.BT2.S25.BT3.S11.S21
     COMMON /MAT/ E(7).RE(7).PR(7).ADS(7).CPCB(7)
C
     INJ. + ADS. + RET. + OF SURFACTANT
С
C
     R3=ADS(3)+CMOB(3)
С
      RETENTION OF FOLYMER
C
С
     R4 = ADS(4) + CMOB(4)
C
      PRINT TABLE
С
C
     PRINT 30
     PRINT 40
     PRINT 50
     PRINT 60, (TITLE(I), I=1,7)
     PRINT 70
     PRINT 80, PHI, ABPERM
     PRINT 90. S11.S1RW.P1RW.VIS1.S2I.S2RW.P2RW.VIS2
     PRINT 100
     DO 20 N=1. ISLUG
         IF (N.NE.1) GO TO 10
        PRINT 110, VIN(1), (CIN(I,1), I=1, NCCMP)
        GO TO 20
  10
        NN=N-1
         PRINT 120, NN,VIN(N),(CIN(I,N),I=1,NCCMP)
   20 CONTINUE
     PRINT 130, BT2, S25, ER, VP
     PRINT 140, BT3,CSEL,CSEOP,CSEU
     PRINT 150, ZI(3),ZI(4),ADS(3),ADS(4),CMCB(3),CMOB(4),R3,R4,P(3),P(
     14)
     PRINT 160, (E(I),I=1,7),(RE(I),I=1,7)
     PRINT 40
C
     RETURN
С
C
      C
   30 FORMAT (1H1)
   40 FORMAT (/.1X.135(1HS))
                                  SUMMARY TABLE + + ++//)
   50 FORMAT (//+1X+T45+41H+ + +
   60 FORMAT (5X,2A10,T39,2A10,T73,3A10)
   70 FORMAT (//,5X,19HROCK FROPERTIES
                                        :,/,4X,50(1H*))
   80 FORMAT (5X.9HPV
                          : +T39 +9HPCRCSITY=+1X+F6+4+1X+7HEFRAC+ ]+T73+12
```

1HABS.PERM. :, F6.4,1X,7HEDARCY],//) 90 FORMAT (5X+21HINITIAL CONDITIONS :+/+4X+50(1++)+/+5X+11+W A T E R 1 : • 1X • 13HINITIAL SAT •: • F5 • 3 • T39 • 21 + RESIDUAL SAT • : • F5 • 3 • T73 • 219HEND POINT REL PERM: +F6.4+1X+3+EC]+T107+5HVISC:+F7.4+1X+4H[CP]+/ 3,5X,11H0 I L : 1X 13HINITIAL SAT .: F5. 3, T39, 21HRESIDUAL SAT. :+F5.3+T73+19HEND POINT REL PREM: +F6.4+1X+3HED]+T107+5HVISC:+ 5F7.4,1X,4HECP],//) 100 FORMAT (5X, 39HINJECTION SEQUENCE AND CONCENTRATIONS :,/,4X,50(1H+) 1./.T25.9HSLUG SIZE.T39.3HCI1.T49.3HCI2.T59.3HCI3.T69.3HCI4.T79.3HC 215,T89,3HC16,T99,3HC17) : +T23+8(4X+F6+4)) 110 FORMAT (5X,18HCHENICAL SLUG 120 FORMAT (5X,14HFOLYPER SLUG #,12,1X,1H:,T23,8(4X,F6.4)) 130 FORMAT (//,5X,35HOIL CONCENTRATION AND OIL RECOVERY ,10HCEFFLUENT] 1,/,4X,50(1H+),/,5X,16HCIL B.T. :,F6.4,T39,19HOIL CUT AT 0.5 2PV :,F6.4,T73,14H0IL RECOVERY :,F6.4,T107,5HVPI :,F6.4) 140 FORMAT (//,5X,44HPHASE BEHAVIOR - SURFACTANT CONCENTRATION :,/,4X 1,50(1H+),/,5X,16HSURFACTANT 8.T.:,F6.4,T39,6HCSEL :,F6.4,T73,6HCSE 20P: +F6.4.T107.6HCSEU : +F6.4) 150 FORMAT (//,5X,11HRETENTION :,/,4X,50(1H*),/,10X,12HSURFACTANT :,2X 1,18HINJECTED: C3I* VPI=,F7.5,1X,10HEML/ML.PVJ+T73,10HPOLYMER :,11H 2INJECTED =+F7.5,1X,10HEWT% + PV]+/+T25,8HADSORBED+9X,1H=+F7.5,1X+ 310HE ML/ML. PV], T83, 11HADSORBED =, F7.5, 1X, 10HE WTX + PV], /, T25, 7HTRA 4PPED,10X,1H=,F7.5,1X,10HEML/ML.PV],T83,11HTRAPPED =,F7.5,1X,10HE 5WT% + PV],/,T25,8HRETAINED,9X,1H=,F7.5,1X,10HENL/HL.PV],T83,11HRET 6AINED =,F7.5,1X,10HEHT% + PV3,/,T25,8HPRODUCED,9X,1H=,F7.5,1X,10H 7EML/ML.PV3,TR3,11HPRODUCED =,F7.5,1X,10HEWTX + PV3) 160 FORMAT (//,5X,30HMATERIAL BALANCE ERRCRS EREL.J,/,4X,50(1++),/,T29 1, 2HE1, T43, 2HE2, T57, 2HE3, T71, 2HE4, T85, 2HE5, T99, 2HE6, T113, 2HE7, /, 5X, 212HABS. ERROR : +T21+7(4X+E10+4)+/+EX+12HREL. ERROR : +T21+7(4X+E10+ 34)./) С END SUBROUTINE SOLVE С С _____ С SUBROUTINE SOLA - UPDATED 03/05/81 DILUTION EFFECT INCLUDED IN THE CALCULATION OF SALINITY (CSE) С SALINITY FOR CALCULATION OF POLYMER VISCOSITY (CSA) DOES С С NOT INCLUDE ANY DILUTION EFFECT С С COMMON /NO/ ICT, ICT1, ICT2, XICT, NCGPP, NF COMMON /IN/ VIN(10),CIN(7,10) COMMON /TRAP/ T11, T12, T21, T22, T31, T32, S1RW, S2RW, PHT(40), EPSMOB, ICO **INT, IPHAX** COMMON/SYSTEM/UT, ABPERM, PHI, EPHI3, EPHI4, DISPJ(4) COMMON /SOL/ C(7,4,42),S(3,42),FF(3,42),NPHASE(42),EPSME COMMON /CSE/ CSE(42),CSA(42),CSEL,CSEU,RCSE,CSEOP,DCSE,CSELI,CSEUI COMMON /ADSCRP/ C3ADSS(40),C4ADSS(40),C6ADSS(40),C6HATS(40) COMMON /PRODIN/ ER, P(7), P8, ZI(7), ZE(7), S2 COMMON /CALC/ C6J0(40) COMMON /XIFT/ XIFT1(42),XIFT2(42),XIFT3(42),XIFTW COMMON /CHEMAD/ C3PH,A30,B30,AC31,AC32,A3DS(40) COMMON /POLYAD/ C4PH+A4D+B4D COMMON /ION/ FFDVP+FFDV+DC3+K COMMON /INJECT/ DVPP, DVP, VP, VT, VFI COMMON /COMPLX/ XKC+XKS+QV COMMON /PRESS/ PHTLU, PRESUM, ICTL, ICTU, PRES(40) COMMON /ABVIS/ IPRES,ABVISH,ABVISF,ABMAX,ABVMAX COMMON /DIL/ BETA1, BETA2, BETA3 COMMON /REST/ IERROR, IH, IK, II, VPP, KK, IFLAG, ISLUG COMMON /TAB/ ISK, BT2, S25, BT3, S11, S21

```
INSKIP=0
С
С
     С
     FFDVP=FFDV
     DVPP=DVP
     VOVP=VP
     VP=VP+DVP
     IF ((VP-VPI).LT.0.0) GC TO 10
     VDVP=VPI
     INSKIP=1
     GO TO 20
  10 IF ((VP-VT).LT.0.0) GC TO 30
     VDVP=VT
  20 DVPP=DVP+VDVP-VP
     VP=VDVP
     FFDVP=FFDV+CVPP/DVP
  30 CONTINUE
C
     С
C
     DO 40 I=1,NCOMF
     D0 40 J=1,3
  40 P(I)=FF(J,1)+C(I,J,1)+DVPP+P(I)
     ER=P(2)/S2
C
     ++++++ TEST FOR CHANGING BOUNDARY CONDITIONS IN INJECTOR ++
С
C
     IF (INSKIP.EQ.0) GC TO 60
С
С
     NEW INJECTION
С
     ISLUG=ISLUG+1
     VPI=VIN(ISLUG)
     D0 50 I=1.NCOMF
  50 C(I+1+ICT1)=CIN(I+ISLUG)
     PRINT 300, VPI,(C(I+1+ICT1)+I=1+NCCMP)
  60 CONTINUE
С
     С
С
     D0 70 K=1.ICT
       X=1.-C3ADSS(K)
       C(1,4,K)=C(1,4,K)*X
       C(2,4,K)=C(2,4,K)+X
       C(3,4,K)=C(3,4,K)+X+C3ADSS(K)
       C(7+4+K)=C(7+4+K)+X
  70 CONTINUE
     DO 170 KK=1+ICT
        K=ICT+1-KK
        DO 100 I=1 + NCOMP
          GFUN=0.0
          FFUN=GFUN
          00 90 J=1.3
             IF (K.EQ.1) GO TO 80
С
     MATERIAL TRANSPORT BY DISPERSION
Ċ
С
             FFUN=FFUN+DISPJ(J)*(FF(J_9K+1)*(C(I_9J_9K+1)-C(I_9J_9K))-FF(J_9)
             K) * (C(I, J, K) - C(I, J, K-1))) * FLOAT(ICT)
    1
             GO TO 90
             FFUN=FFUN+DISFJ(J)*(FF(J,2)*(C(I,J,2)-C(I,J,1))-FF(J,1)*(
  80
```

1 C(I+J+1)-C(I+J+2)))*FLOAT(ICT) C MATERIAL TRANSPORT BY CONVECTION C С 90 GFUN=GFUN-(FF(J,K+1)+C(I,J,K+1)-FF(J,K)+C(I,J,K)) EPHI1=1.0 С INACCESSIBLE PORE VOLUMES TO SURFACTANT AND/OR POLYMER С С IF (I.EQ.3) EPHI1=EPHI3 IF (I.EQ.4) EPHI1=EPHI4 C(I+4+K)=C(I+4+K)=FFDVP*(GFUA=FFUA)/EPHI1 IF (C(I,4,K).LT.0.0) C(I,4,K)=0.0 100 CONTINUE С ++++++ CALCULATION OF ACTUAL AND EFFECTIVE SALINITY ++++++ С С С ION EXCHANGE С 110 IF (QV.GE.1.0E-4) CALL IONCNG CSA(K)=(C(5,4,K)-C(6,4,K)+RCSE+C(6,4,K))/C(1,4,K) С SALINITY INCLUDING DILUTION EFFECT С С C94=C(5,4,K)+C(6,4,K)+RCSE+C(6,4,K) С C CHARGED SURFACTANT С IF (C(1,4,K).LT.1.0E-10.0R.C94.LT.1.0E-10) GO TO 130 C91=C94/C(1+4+K) C69=C(6+4+K)/C94 GO TO 140 130 C91=0.0 C69=0.0 140 EXP3=EXP(BETA3+C(7,4,K)) CSE(K)=(C91+BETA1+C69+BETA2+C(3+4+K))+EXP3 C С C A3D=AD31+AD32+CSE(K) С IF (C(3+4+K)+LT+1+DE+6) GO TO 150 IF (A3D.LT.1.0E-8) GO TC 150 C3PH=AMAX1(C(3,1,K),C(3,2,K),C(3,3,K)) IF (NPHASE(K).EQ.1) C3PH=C(3,4,K) С CALL CHEMADN (C(3,4,K),C3ADSS(K),A3DS(K)) С CTOT=C(1,4,K)+C(2,4,K)+C(3,4,K)+C(7,4,K) 150 C(1,4,K)=C(1,4,K)/CTOT C(2,4,K)=C(2,4,K)/CTOT C(3,4,K)=C(3,4,K)/CTCT C(7,4,K)=C(7,4,K)/CTOT С С С IF (C(4,4,K).LT.1.0E-8) GO TO 170 IF (A40.LT.10E-R) GC TO 170 С C4PH=AMAX1(C(4,1,K),C(4,2,K),C(4,3,K)) IF (NPHASE(K).EQ.1) C4PH=C(4,4,K) С

```
CALL POLYADN (C(4,4,K),C4ADSS(K))
С
 170 CONTINUE
С
С
     С
     DO 180 I=1.3
 180 IF (C(I;4,K).LT.0.0) GC TO 190
    IF (C(7,4,K).LT.0.0) GO TO 190
     GO TO 200
 190 IERROR=1
    PRINT 290. K.VP
     RETURN
 200 CONTINUE
С
С
     С
    DO 210 I=1.NCOMP
       C(I,4,ICT+2)=0.0
     DO 210 J=1,3
       C(I,4,ICT+2)=C(I,4,ICT+2)+C(I,J,1)+FF(J,1)
 210 CONTINUE
С
    SALINITY IN PRODUCER
С
С
     IF (C(1,4,ICT2).LT.1.0E-10) GC TC 250
    CSA(ICT+2)=(C(5,4,ICT+2)+C(6,4,ICT+2)+RCSE+C(6,4,ICT+2))/C(1,4,ICT
    1+2)
    C94=C(5,4,ICT2)-C(6,4,ICT2)+RCSE+C(6,4,ICT2)
    IF (C(1.4,ICT2).LT.1.0E-10.0R.C94.LT.1.0E-10) GO TO 230
    C91=C94/C(1,4,ICT2)
    C69=C(6+4+ICT2)/C94
    GO TO 240
 230 C91=0.0
    C94=0.0
 240 EXP3=EXP(BETA3+C(7+4+ICT2))
    CSE(ICT2)=(C91+BETA1+C69+BETA2+C(3+4+ICT2))+EXP3
    GO TO 260
 250 CSA(ICT2)=CSA(1)
    CSE(ICT2)=CSE(1)
 260 CONTINUE
С
     С
C
    CALL PROPRTY
С
    С
С
    DO 270 K=1,ICT
       PRES(K)=PHTLU/PHT(K)
 270 CONTINUE
     PRESUM=0.0
     DO 280 K=ICTL+ICTU
       PRESUM=#RESUM+PRES(K)
 280 CONTINUE
     PRESUM=PRESUM/FLOAT(ICTU-ICTL+1)
С
     +++++ APPARENT VISCOSIYT AT 0.5 AND 1.0 PV +++++++++++++
С
C
    PHTH=(PHT(20)+PHT(21)+PHT(22))/3.0
     ABVISH=1.0/PHTH
    PHTF=(PHT(1)+PHT(2)+PHT(3))/3.0
```

```
ABVISE=1.0/PHTE
С
      RETURN
С
С
С
      C
 290 FORMAT (2X./.10X.29HNEGATIVE TOT. CONC. IN BLOCK: 14,5X,6HAT VP: F
     15.3./)
 300 FORMAT (/, 3X, 11HINJECTION :, 4X, 4HVPI=, F6.4, 4X, 4HC11=, F6.4, 4X, 4HC21
     1= +F6+4+4X+4HC31=+F6+4+4X+4HC41=+F6+4+4X+4HC51=+F6+4+4X+4HC61=+F6+4
     2,4X,4HC71=,F6.4)
С
     END
     SUBROUTINE SOLVE1
C----
                                         THIS SUBPROGRAM SOLVES CONTINUITY EQUATIONS.
С
  SEMI-DISCRETE METFOD WITH NUMERICAL 0.D.E. INTEGRATOR IS USED.
C
  0.D.E. INTEGRATOR IS SELECTED ACCORCING TO ISEM AS FOLLOWS:
C
С
       ISEM =1 : RK12
С
            =2 : RK1
С
            =3 : DGEAR
C--
C
     DIMENSION CC(280), IWK(280), WK(1), FFOLD(3), COLD(7,3)
C
     COMMON/GEAR/DUM(52), IDUM(38)
С
     COMMON/SEMID1/DTMAX, ERR, YBIAS, PCT, IPASS
     COMMON/SEMID2/IEVA, DTOLD, RTEMAX, NREJ, IADS
     COMMON/SEMID3/NEQ, ISEM, XEND, METH, MITER
     COMMON/NO/ICT.ICT1.ICT2.XICT.NCOMP.NF
     COMMON/SOL/C(7,4,42),S(3,42),FF(3,42),NPHASE(42),EPSME
     COMMON/INJECT/DVPP+DVP+VP+VT+VPI
     COMMON/IN/VIN(10).CIN(7.10)
     COMMON/PRODIN/ER, P(7), P8, ZI(7), ZE(7), S2
     COMMON /CSE/ CSE(42),CSA(42),CSEL,CSEU,RCSE,CSEOP,DCSE,CSELI,CSEUI
     COMMON /TRAP/ T11, T12, T21, T22, T31, T32, S1RH, S2RH, PHT(40), EPSMOB, ICO
     INT, IPMAX
     CONMON/PRESS/PHTLU, PRESUN, ICTL, ICTL, PRES(40)
     COMMON/REST/IERROR . IH. IK. II. VPP. KK. IFLAG. ISLUG
     COMMON/DIL/BETA1.BETA2.BETA3
     CONMON/ABVIS/IPRES, ABVISH, ABVISF, ABHAX, ABVMAX
     EXTERNAL DER.FCNJ
     DATA IPASSOL, IPASS, INDEX/0,0,1/
     DATA IPV/0/
С
C++++++ REARRANGE TOTAL CONCENTRATION ARRAY CNLY AT THE FIRST TIME +++
     IF(IPASSOL.NE.0)GO TO 10
     IPASSOL=1
     DO 20 K=1,ICT
     DO 20 I=1.NCOMF
     I1=(K-1)+NCOMP+I
  20 CC(I1)=C(I,4,K)
  10 CONTINUE
С
C******* COMPOSITION OF PRODUCTION *******
     D0 32 I=1,NCOMF
     C(I.4.ICT2)=0.0
     00 32 J=1,3
     C(I,4,ICT2)=C(I,4,ICT2)+C(I,J,1)+FF(J,1)
   32 CONTINUE
```

```
С
      SALINITY IN PRODUCER
C
      IF (C(1,4,ICT2).LT.1.0E-10) GC TC 250
      CSA(ICT2)=(C(5,4+ICT2)-C(6,4+ICT2)+RCSE+C(6,4+ICT2))/C(1,4+ICT2)
      C94=C(5,4,ICT2)-C(6,4,ICT2)+RCSE+C(6,4,ICT2)
      IF (C(1+4,ICT2).LT.1.0E-10.0R.C94.LT.1.0E-10) GO TO 230
      C91=C94/C(1,4,ICT2)
      C69=C(6,4,ICT2)/C94
      GO TO 248
  230 C91=0.0
      C94=0+0
  240 EXP3=EXP(BETA3+C(7,4,ICT2))
      CSE(ICT2)=(C91+BETA1+C69+BETA2+C(3+4+ICT2))+EXP3
      GO TO 260
  250 CSA(ICT2)=CSA(1)
      CSE(ICT2)=CSE(1)
  260 CONTINUE
С
C******* SAVE OLD VALUES FOR CALCULATION OF CUMULATIVE PRODUCTION *****
      DO 36 J=1,3
   36 FFOLD(J)=FF(J,1)
C
C+++++++ OBTAIN SOLUTION WITH SENI-DISCRETE METHOD +++++++
      IF(ISEM.NE.3)GC TO 60
С
    DGEAR USED TO BE HERE, BUT SHOULD NOLONGER BE USED.
С
    IF ONE DESIRES TO USE DEEAR, DIMENSION OF WK MUST BE CHANGED.
C
      PRINT 999
  999 FORMAT(//10X, * SET ISEM TO ANOTHER VALUE*/
     1
           +DGEAR(ISEM=3) SHCULD NOT BE LSED+)
      STOP
      IF(INDEX.EG.1) DVP=0.0001
      IF(DVP.GE.(VPI-VP))INDEX=2
      DUM(4) = DTMAX
      CALL DGEAR(NEQ, DER, FCNJ, VP, DVP, CC, XEND, ERR, NETH, MITER, INDEX,
                 IWK,WK,IER)
     1
      XEND=VPI
      INDEX=3
      IF((VPI-VP).GT.1.E-12)G0 TC 70
      INDEX=1
      XEND=XEND+0.0001
   70 CONTINUE
      PRINT 900, VP, DVP, DUM(8), IDUM(6), IE VA, IDUM(7), IDUM(9), INDEX
  900 FORMAT(8X,+VP, DVP, HUSED, ORDER, IE VA, NSTEP, NJE, INDEX+, 5X, 3G15.5, 5I6)
      GO TO 62
C
   RK12 OR RK1 IS USED
C
   60 CONTINUE
      IF(DVP.LT.1.0E-6)DVP=0.001
      IF (DVP.GT. (VPI-VP))DVP=VPI-VP
      IF(DVP.GT.(VT-VP))DVP=VT-VP
      IF(ISEM.EQ.1)CALL RK12(VP.CC.NEQ.DVP)
      IF(ISEM.EQ.2)CALL RK1(VP,CC,NEQ,CVF)
   62 CONTINUE
С
C****** CHANGE BOUDARY CONDITION AT INJECTOR IF NEEDED ******
      IF((VT-VP).LT.1.E-6)60 TO 80
      IF((VPI-VP).GT.1.E-6)GC TO 80
      ISLUG=ISLUG+1
      VPI=VIN(ISLUG)
      IPASS=0
      DO B2 I=1,NCOMP
```

```
82 C(I,1,ICT1)=CIN(I,ISLUG)
      PRINT 800+VPI+(C(I+1+ICT1)+I=1+NCOMP)
   80 CONTINUE
  800 FORMAT(/, 3X, 11 HINJECTION :, 4X, 4m WP I=, F6.4, 4X, 4HC11=, F6.4, 4X,
     1
           4HC21=+F6+4+4X+4HC31=+F6+4+4X+4HC41=+F6+4+4X+4HC51=+F6+4+
     1
           4X,4HC61=,F6.4,4X,4HC71=,F6.4)
С
C++++++ RELATIVE PRESSURE DROP AND TOTAL PRESSURE DROP +++++++
      PRESUM=0.0
      00 40 K=1,ICT
      PRES(K)=PHTLU/PHT(K)
   40 PRESUN=PRESUM+FRES(K)
      PRESUM=PRESUM/FLOAT(ICTU-ICTL+1)
С
C******* APPARENT VISCOSITY AT XD=0.5 AND 1.0 ********
      PHTH=(PHT(20)+PHT(21)+PHT(22))/3.0
      ABVISH=1.0/PHTH
      PHTF=(PHT(1)+PHT(2)+PHT(3))/3.0
      ABVISF=1.0/PHTF
C
C******* CUMULATIVE PRODUCTION *******
      IF (ISEN.EQ.3) DTOLD=DVP
      DO 50 I=1, NCOMP
   50 P(I)=P(I)+DTOLD+C(I+4+ICT2)
     ER=P(2)/S2
С
C******* STORE DTOLD FOR PLCT *******
      IPV=IPV+1
C
     XDT(IPV+1)=VP
С
      YDT(IPV,1)=CTOLD
С
      RETURN
     END
      SUBROUTINE FCNJ(N, X, Y, PD)
      RETURN
      END
     SUBROUTINE RK12(T, X, N', DT)
THIS IS AN O.D.E INTEGRATOR WITH STEP SIZE CONTROL.
С
  RUNGE-KUTTA-FEHLBERG ALGORITHM OF FIRST AND SECOND ORDER IS USED.
C
 COMPOSITION OF PRODUCTION IS CALCULATED IN THIS SUBPROGRAM.
C
C--
          ------
С
     COMMON/SEMID1/DTMAX, ERR, YBIAS, PCT, IPASS
      COMMON/SEMID2/IEVA,DTOLD,RTEMAX,NREJ,IADS
      COMMON/NO/ICT+ICT1+ICT2+XICT+NCOMP+NF
      COHMON/SOL/C(7,4,42),S(3,42),FF(3,42),NPHASE(42),EPSME
      REAL X(1), Y(280), F1(280), F2(280), F3(280)
      REAL PP1(7), PP2(7)
      DATA NREJ/0/
С
      IF (IPASS .NE. 0) GO TO 8
      IPASS = 1
      B21 = A2 = 1./2.
      C1 = 831 = 1./256.
      C2 = B32 = 255./256.
      D1 = CH1 = CH3 = 1./512.
      CH2 = 255./256.
      EBIAS = 1 \cdot E - 12
      CALL DER(N,T,X,F1)
    8 CONTINUE
      IADS=0
```

```
С
     DO 20 I=1.NCOMF
     PP1(I)=0.0
     D0 20 J=1.3
   20 PP1(I)=PP1(I)+FF(J,1)+C(I,J,1)
C
    9 CONTINUE
     TY = T + A2 + DT
     BB21 = B21 * DT
     D0 2 I = 1.N
    2 Y(I) = X(I)+BB21+F1(I)
     CALL DER(N,TY,Y,F2)
С
     DO 30 I=1+NCOMP
     PP2(I)=0.0
     00 32 J=1,3
  32 PP2(I)=PP2(I)+FF(J,1)+C(I,J,1)
   30 C(I+4+ICT2)=(PP1(I)+255++PP2(I))/256+
С
     TY = T+DT
     BB31 = B31+DT
     BB32 = B32 \pm DT
     D0 3 I = 1,N
    3 Y(I) = X(I) + BB 31 + F1(I) + BB 32 + F2(I)
     CALL DER(N+TY+Y+F3)
     DD1 = D1 + DT.
     RTEMAX = EBIAS
     DO 4 I = 1 + N
     ATE = ABS(F1(I)-F3(I))+DD1
     AY = ABS(Y(I))
     IF (AY .LT. YBIAS) AY = YBIAS
     RER = ATE/AY
     IF (RER .GT. RTEMAX) RTEMAX=RER
    4 CONTINUE
     DTOLD = DT
     DT=DTOLD+PCT+(ERR/RTEMAX)++.5
     DT = AMIN1 (DT,DTMAX)
     IF (RTEMAX .LE. ERR) GC TO 7
     DT = DT + .9
     NREJ=NREJ+1
     IADS=2
     60 TO 9
   7 T = T+DTOLD
     D0 15 I = 1,N
     F1(I) = F3(I)
  15 X(I) = Y(I)
     RETURN
     END
     SUBROUTINE RK1(T,X,N,DT)
С-
                                         С
 THIS IS AN O.D.E. INTEGRATOR WITH STEP SIZE CONTROL.
С
  RUNGE-KUTTA METHODS OF FIRST AND SECOND CREER ARE USED.
C--
       С
     CDMMON/SEMID1/DTMAX, ERR, YBIAS, PCT, IPASS
     COMMON/SEMID2/IEVA.DTOLD.RTEMAX.NREJ.IADS
     COMMON/NO/ICT, ICT1, ICT2, XICT, NCOMP, NF
     REAL X(1), Y(280), F1(280), F2(280), F3(280)
     DATA NREJ/0/
С
     IF (IPASS .NE. 0) GO TO 8
     IPASS = 1
```

```
821=A2=1.
      C1=1.
      CH1=CH2=1./2.
      D1=1./2.
      EBIAS = 1 \cdot E - 12
      CALL DER(N,T,X,F1)
    8 CONTINUE
      IADS=0
    9 CONTINUE
      TY = T + A2 + DT
      BB21 = B21 + DT
      DO 2 I = 1.N
    2 Y(I) = X(I) + BB21 + F1(I)
      CALL DER(N,TY,Y,F2)
      D01 = 01 + 0T
      RTEMAX = EBIAS
      DO 4 I = 1 \cdot N
      ATE = ABS(F1(I)-F2(I)) + DD1
      AY = ABS(Y(I))
      IF (AY .LT. YBIAS) AY = YBIAS
      RER = ATE/AY
      IF (RER.GT.RTEMAX)RTEMAX=RER
    4 CONTINUE
      DTOLO = DT
      DT=DTOLD+PCT+(ERP/RTEMAX)++.5
      DT = AMIN1 (DT.DTMAX)
      IF (RTEMAX .LE. ERR) GC TO 7
      DT = DT + .9
      NREJ=NREJ+1
      IADS=2
      GO TO 9
    7 T = T + DTOLD
      D0 15 I = 1 \cdot N
      F1(I) = F2(I)
   15 \times (I) = Y(I)
      RETURN
      END
      SUBROUTINE DER (N, T, Y, DY)
C----
С
  THIS SUBROUTINE CALCULATES CHANGE IN CONCENTRATION AS DERIVATIVE
  WIYH RESPECT TO TIME
C
--------------
      DIMENSION DY(280), Y(280), FFUN(7,40), GFUN(7,40)
      DIMENSION C3ADOLD(40), A3DOLD(40), C4ACOLD(40), C3PH0(40), C4PH0(40)
С
      COMMON/SEMID2/IEVA,DTCLD,RTEMAX, NREJ,IADS
      COMMON/NO/ICT, ICT1, ICT2, XICT, NCOMP, NF
      COMMON/SYSTEM/UT, ABPERM, PHI, EPHI3, EPHI4, CISPJ(4)
      COMMON/SOL/C(7,4,4),S(3,42),FF(3,42),NPHASE(42),EPSME
      COMMON /CSE/ CSE(42), CSA(42), CSEL, CSEU, RCSE, CSEOP, DCSE, CSELI, CSEUI
      COMMON/CHEMAD/C3PH, A3D, B3D, AD31, AD32, A3DS(40)
      COMMON/POLYAD/C4PH, A4D, B4D
      COMMON/HH8/XKC,XK96,XK86,XKHAT,QV
      COMMON/ADSCRP/C3ADSS(40),C4ADSS(40),C6ADSS(40),C6ADSS(40)
      COMMON /DIL/ BETA1, BETA2, BETA3
      DATA IEVA/0/
      DATA IPASDER, IADS/0,0/
С
       IEVA=IEVA+1
С
C****** SAVE VALUES WHICH SHOULD BE USED IN CASE OF REJECTION *******
      IF(IADS.NE.0)GO TO 50
```

```
DO 52 K=1.ICT
      C3AD0LD(K)=C3ADSS(K)
      A3DOLD(K) = A3DS(K)
      C4ADOLD(K)=C4ADSS(K)
   52 CONTINUE
   50 CONTINUE
      IF(IPASDER.FQ.0)G0 TO 30
С
C******* RESET VALUES IN CASE OF REJECTION ******
      IF(IADS.NE.2) GO TO 56
      DO 58 K=1.ICT
      C3ADSS(K)=C3ADCLD(K)
      A3DS(K)=A3DOLD(K)
   58 C4ADSS(K)=C4ADCLD(K)
   5E CONTINUE
C
C****** RESET TCTAL COMPOSITION FROM Y'S SENT FROM RK12 ********
      DO 20 K=1.ICT
      DO 10 I=1+NCOMP
      I1=(K-1)+NCOMP+I
      C(I,4,K)=Y(I1)
      IF(C(I+4+K)-GT--1-E-5)G0 TO 10
      PRINT 100, I, K, C(I, 4, K)
  100 FORMAT(//5X,+NEGATIVE CONCENTRATION OCCURED IN SUBPROGRAM DER+//
             8X,2HC(,11,3H,4,,12,3H) =,E15.7//)
     1
      CALL PREPRINT
      CALL PREPLOT
      STOP
10
      CONTINUE
С
C******* ION EXCHANGE ******
      IF(QV.GE.0.0001)CALL IONCNG
С
C******* SALINITY INCLUDING DILUTION EFFECT *******
         CSA(K) = (C(5+4+K) - C(6+4+K) + RCSE + C(6+4+K))/C(1+4+K)
С
      SALINITY INCLUCING DILUTION EFFECT
С
С
         C94=C(5,4,K)-C(6,4,K)+RCSE+C(6,4,K)
С
      CHARGED SURFACTANT
С
С
         IF (C(1,4,K).LT.1.0E-10.0R.C94.LT.1.0E-10) GO TO 130
         C91=C94/C(1+4+K)
         C69=C(6,4,K)/C94
         GO TO 140
  130
         C91=0.0
         C69=0.0
  140
         EXP3=EXP(BETA3+C(7,4,K))
         CSE(K)=(C91+BETA1*C69+BETA2*C(3+4+K))*EXP3
С
C******* CHEMICAL ADSORPTION *******
      A3D=AD31+AD32*CSE(K)
      IF(C(3,4,K).LT.1.0E-8)G0 TC 28
      IF(A3D .LT. 1.0E-8) GO TO 28
      C3PH=AMAX1(C(3+1+K)+C(3+2+K)+C(3+3+K))
      IF(NPHASE(K).EG.1)C3PH=C(3,4,K)
      IF(IADS.EQ.0)C3PH0(K)=C3PH
      IF (IADS.EQ.2)C 3PH=C3PHO(K)
      CALL CHEMADN(C(3,4,K),C3ADSS(K),A3ES(K))
С
C+++++++ CHANGE DEFINITION OF TOTAL COMFOSITION
```

```
EXCLUDING ADSORBED AMOUNT OF SURFACTANT *******
C
28
      CTOT=C(1,4,K)+C(2,4,K)+C(3,4,K)+C(7,4,K)
     C(1,4,K)=C(1,4,K)/CTCT
      C(2,4,K)=C(2,4,K)/CTOT
      C(3,4,K)=C(3,4,K)/CTOT
      C(7,4,K)=C(7,4,K)/CTOT
C
С
C****** POLYMER ADSORPTICN *******
     IF(C(4,4,K).LT.1.0E-8)G0 TC 20
     IF (A4D .LT. 10E-8) GO TO 20
     C(4,4,K)=C(4,4,K)-C4ADSS(K)
     C4PH=AMAX1 (C(4+1+K)+C(4+2+K)+C(4+3+K))
      IF(NPHASE(K).EG.1)C4PH=C(4,4,K)
      IF (IADS.EQ.0)C4PH0(K)=C4PH
     IF(IADS.EQ.2)C4PH=C4PHC(K)
     CALL POLYADN(C(4,4,K),C4ADSS(K))
20
     CONTINUE
r
C++++++ NEW PHASE COMPOSITIONS AND PROPERTIES ++++++++
     CALL PROPRTY
С
   30 CONTINUE
     IPASDER=1
C
C******* CALCULATE DERIVATIVES *******
     D0 29 IK=1,ICT
     K=ICT+1-IK
     DO 36 I=1,NCOMP
     FFUN(I,K)=GFUN(I,K)=0.0
     D0 25 J=1.3
     IF(K .EQ. 1) GC TO 80
С
     MATERIAL TRANSPORT BY DISPERSION
C
     FFUN(I,K)=FFUN(I,K)-DISPJ(J)+(FF(J,K+1)+(C(I,J,K+1)-C(I,J,K))-
     1FF(J,K)+(C(I,J,K)-C(I,J,K-1)))+FLOAT(ICT)++2
     GO TO 25
     FFUN(I,K) = FFUN(I,K) - DISPJ(J) * (FF(J,2) * (C(I,J,2) - C(I,J,1)) -
69
     1FF(J,1)*(C(I,J,1)-C(I,J,2)))*FLOAT(ICT)**2
С
     MATERIAL TRANSPORT BY CONVECTION
С
25
     GFUN(I,K)=GFUN(I,K)+(FF(J,K+1)+C(I,J,K+1)-FF(J,K)+C(I,J,K))
     1+FLOAT(ICT)
     EPHI1=1.0
С
     INACCESSIBLE PORE VOLUMES TO SURFACTANT AND/OR POLYMER
C
     IF(I .EQ. 3) EPHI1=EPHI3
     IF(T .EQ. 4) EPHI1=EPHI4
     I1=(K-1)+NCOMP+I
     DY(I1)=(GFUN(I,K)-FFUN(I,K))/EPHI1
 36
 29
     CONTINUE
     IADS=1
     RETURN
     END
     SUBROUTINE PROPRTY
С
С
         C
     MODIFIED ON MARCH 5 1981
С
     THIS SUBROUTINE CALCULATE NEW PHASE COMPOSITIONS (PHCOMP),
С
     VISCOSITIES, RESIDUAL SATURATION (RELPERM), RELATIVE
С
     PERMEABILITIES (RELPERH) RELATIVE FOBILITY RATICS AND
     FRACTIONAL FLOW
C
```

```
С
     MOST SURFACTANT RICH PHASE IS DEFINED AS PHASE 3 EVEN FOR TWO PHAS
С
     NEW VISCOSITY EQUATION IS IMPLEMENTED
С
С
     SHEAR EFFECT ON VISCOSITY USED IF ISHEAR=1
     SECANT METHOD IS USED TO CALCULATE FRACTIONAL FLOW ITERATIVELY
С
С
     NON-EXISTING VISCOSITY IS MADE TO BE ZERO
     THE EFFECT OF ALCHOL IS INCLUEED
С
     DILUTION EFFECT INCLUDED IN CSE - NCT USED FOR POLYPER VISCOSITY
C
     CALCULATIONS
C
     IF IPRNT IS SET TO BE CNE. NUMBER OF ITERATIONS AT EACH BLOCK AND
C
     CONVERGENCE AT 40TH BLOCK IS PRINTED
С
С
        _____
С
     DIMENSION ABPE(10), PHTOLD(10), F3(LD(10), IT(40)
С
     COMMON /NO/ ICT+ICT1+ICT2+XICT+NCOMP+NF
     COMMON /PRINT/ VPRINT, HINC, PIAC, IHFRAT, IHPLOT, IPPRAT, IPPLOT, IPRAT
     COMMON /SOL/ C(7,4,42),S(3,42),FF(3,42),NPHASE(42),EPSME
     COMMON /CSE/ CSE(42),CSA(42),CSEL,CSEU,RCSE,CSEOP,DCSE,CSELI,CSEUI
     COMMON /CSEVIS/ VIS1,VIS2, AP1, AP2, AP3, SSLOPE
     COMMON /SHEVIS/ ISHEAR, GAMHF, POWN, CSE1, RKMAX, BRK
     COMMON/SYSTEM/LT, ABPERM, PHI, EPHI3, EPHI4, CISPJ(4)
     COMMON /TRAP/ T11, T12, T21, T22, T31, T32, S1RW, S2RW, PHT(40), EPSMOB, ICO
    1NT, IPMAX
     COMMON /ALPHA/ ALPHA1, ALPHA2, ALPHA3, ALPHA4, ALPHA5, ALPHA6
     COMMON /PERMC/ PERM(3,40), SRED(3,40), SN(3,40), VIS(3,40), LPERM(40)
     COMMON /PERM/ IPERM, P1RW, P2RW, E1, E2, E3, P1RC, P2RC
     COHMON /INJECT/ DVPP, DVP, VP, VT, VPI
     COMMON /ION/ FFDVP+FFDV+DC3+K
     COMMON /REST/ IERROR, IH, IK, II, VPP, KK, IFLAG, ISLUG
C
С
     С
С
     CALL PHCOMP
С
     С
С
     DO 10 K=1,ICT
        IF (NPHASE(K).EQ.1) GO TO 20
     DO 10 N=1.3
        IF (S(N,K).GT.-0.001) GO TO 10
        PRINT 360. K.VP
        IERROR=1
        RETURN
  10 CONTINUE
С
     С
                              ******
С
C
  20 CONTINUE
     DO 270 K=1,ICT
C
     +++++++ DETERMINE FOR WHICH PHASE VISCOSITY IS CALCULATED ++
С
С
        N3=1
        N1=N3
        N2 = 3
        IF (NPHASE(K).EQ.3) GO TO 50
        IF (NPHASE(K).EQ.1) GO TO 40
        IF (C(3+4+K)+LT+EPSME) GO TO 30
        IF (CSE(K).GE.CSEU.OR.NPHASE(K).EG.4) N3=2
```

```
IF (CSE(K).LE.CSEL.OR.NPHASE(K).EQ.5) N1=2
         GO TO 50
   30
         N2=2
         GO TO 50
         IF (C(3.4.K).LT.EPSME) N2=1
IF (C(3.4.K).GE.EPSME) N1=3
   40
   50
         CONTINUE
С
С
      PHASE NUMBER WHERE POLYMER EXISTS
С
         JP=1
         IF (N1.NE.1) JP=3
C
      ++++++ POLYMER VISCOSITY EXCEPT SHEAR RATE EFFECT ++++++++
C
С
        VISPP=VIS1
         IF (C(4,4,K).LE.1.E-10) GO TO 60
C
C
      PERM REDUCTION FACTOR RK
С
         RK=1.0+(RKMAX-1.0)+BRK+C(4.JP.K)/(1.+BRK+C(4.JP.K))
С
Ċ
      SALINITY EFFECT
С
         CSEM=CSA(K)
         IF (CSA(K).LT.CSE1) CSEM=CSE1
         VISPP=VIS1+RK+(1.+(AP1+C(4.JP+K)+AP2+C(4.JP+K)++2+AP3+C(4.JP+K)
    1
         **3)*CSEM**SSLOPE)
  60
        CONTINUE
С
      C
С
        CSAOP=(CSELI+CSEUI)/2.0
         IF (CSA(K). ET.CSAOP) GO TO 70
         CSAV=CSA(K)+1.0
         GO TO 80
        CSAV=2.0+CSA0P-CSA(K)+1.0
   70
         ALPH6=ALPHA6+CSAV
   80
         IF (ALPH6.LT.1.0) ALPH6=1.0
С
         VIS(3,K)=1.0
         VIS(2+K)=VIS(3+K)
         VIS(1,K)=VIS(2,K)
         DO 90 N=N1, N2, N3
            VISP=VIS1
            IF (N.EQ.JP) VISP=VISPP
            C37=C(3+N+K)+C(7+N+K)
            VIS(N,K)=C(1,N,K)+VISP+EXP(ALP+A1+(C(2,N,K)+C37))+C(2,N,K)+V
            IS2+EXP(ALPHA2+(C(1+N+K)+C37))+C37+ALPHA3+ALPH6+EXF(ALPHA4+C
     1
            (1 + N + K) + ALPHA5 + C(2 + N + K))
    2
            IF (VIS(N,K).LT.VIS1) VIS(N.K)=VIS1
   90
         CONTINUE
         IF (NPHASE(K).EQ.1) GO TO 120
С
      ++++++++ PHASE TRAPPING AND RELATIVE PERMEABILITIES +++++++
С
С
         IPHT=0
  100
         CONTINUE
         IPHT=IPHT+1
         PHTOLD(IPHT)=PHT(K)
         F30LD(IPHT)=FF(3,K)
С
```

```
С
      TEST FOR THE TOTAL REL. MOBILITY RATIC
C
          IF (PHT(K).GT.0.0) GO TO 110
         PRINT 310, K, VP
         IERROR=1
         RETURN
         CONTINUE
  110
С
С
         CALL RELPERF(K)
         GO TO 160
С
Ċ
      SINGLE PHASE FLOW
С
  120
         CONTINUE
         SRED(3,K)=0.0
         SRED(2,K)=SRED(3,K)
         SRED(1,K)=SRED(2,K)
         PERM(3,K)=0.0
         PERM(2+K)=PERM(3+K)
         PERM(1.K)=PERM(2.K)
         IF (C(3+4+K).LT.EPSHE) GO TO 130
         LPERM(K)=1
         PERM(3,K)=P1RC
         60 TO 150
  130
         IF (LPERM(K).NE.1) GO TO 140
         PERM(1,K)=P1RC
         GO TO 150
  140
         PERN(1.K)=1.0
  150
         CONTINUE
С
С
      ++++++++ SHEAR RATE EFFECT ON POLYMER VISCOSITY +++++++++++
С
С
  160
         CONTINUE
         IVIS=0
С
      CHECK WHETHER SHEAR RATE EFFECT IS NEEDED
С
С
         IF (IVIS.LE.1.AND.NPHASE(K).NE.1) GO TO 180
         IF (ISHEAR.NE.1) GO TO 180
         IF (PERM(JP,K).LE.1.0E-8) 60 TO 180
         IF (S(JP.K).LE.1.0E-8) GO TO 180
С
      SHEAR RATE DEPENDENT VISCOSITY
С
С
  170
         CONTINUE
         IVIS=IVIS+1
         REQ=(7.89536E-8*ABPERM/PHI)**0.5
         GANHAC=4.0+UT/REG/PHI
         IF (NPHASE(K).NE.1) GAMMA=GAMMAC*(FF(JP,K)++2/PERM(JP,K)/S(JP,K
     1
         ))**0.5
         IF (NPHASE(K).EQ.1) GAMMA=GAMMAC
         VISP=VIS1+(VISPP-VIS1)/(1.0+(GAPHA/GAPHF)**(POWN-1.0))
C
         C37=C(3, JP, K)+C(7, JP, K)
         VIS(JP,K)=C(1,JP,K)+VISP+EXP(ALFHA1+(C(2,JP,K)+C37))+C(2,JP,K)+
         VIS2+EXP(ALPHA2+(C(1,JP,K)+C37))+C37+ALPHA3+ALPH6+EXP(ALPHA4+C(
     1
     2
         1, JP, K) + ALP + A5 + C(2, JP, K))
         IF (VIS(JP,K).LE.VIS1) VIS(JP,K)=VIS1
  180
         CONTINUE
С
```

```
+++++++ RELATIVE MOBILITY RATIO AND FRACTIONAL FLOW +++++++
С
C
         PH1=PERM(1,K)/VIS(1,K)
         PH2=PERM(2,K)/VIS(2,K)
         PH3=PERM(3,K)/VIS(3,K)
         PHT(K)=PF1+FH2+PH3
C
         FF(1,K)=P#1/PHT(K)
         FF(2,K)=PH2/PHT(K)
         FF(3,K)=1.0-FF(1,K)-FF(2,K)
C
С
      ++++++ RECALCULATE VISCOSITY WITH SHEAR RATE EFFECT +++++++
C
         IF (ISHEAR.NE.1) GO TO 190
         IF (C(4,4,K).LE.1.E-10) GO TO 150
           (PERM(JP,K).LE.1.E-8.UR.S(JP,K).LE.1.E-8) GO TO 190
         TF
         IF (IVIS.LE.1.AND.NPHASE(K).NE.1) GO TO 170
         CONTINUE
  190
C
      +++++++ UPDATE PHT(K) AND RECALCULATE TRAPPING FUNCTION +++++
С
С
         IF (NPHASE(K).EQ.1) GO TO 230
         ABPE(IPHT)=FHT(K)-PHTOLD(IPHT)
         RELPE=ABS(AEPE(IPHT)/PHTOLD(IPHT))
         IF (RELPE.LT.EPSMCB) GO T.C 230
         IF (IPHT.GE.IPMAX) GO TO 210
         IF (IPHT.GE.2) GO TO 200
         GO TO 100
         CONTINUE
  200
         PHT(K)=P+TOLD(IPHT)-ABPE(IPHT)+(PHTOLD(IPHT)-PHTOLD(IPHT-1))/(A
     1
         BPE(IPHT)-ABPE(IPHT-1))
         GO TO 100
C
C
     UNLESS CONVERGED, PRINT MESSAGE AND SHOW ITERATION
C
  210
         PRINT 330, IPHT,K,VP
         PRINT 340
         IPP=IPHT-1
         D0 220 IP=1.IPP
         PRINT 350, IP, PHTOLD(IP), F30LC(IP), ABPE(IP)
  220
         PRINT 350, IPHT, PHTOLD(IPHT), F3CLD(IPHT), ABPE(IPHT), RELPE
         IF (ICONT.EQ.0) STOP
         IPHT=0
  230
         CONTINUE
         IF (NPHASE(K).EQ.1) IPHT=1
         IT(K)=IPHT
         F30LD(IPHT+1)=FF(3+K)
С
      ++++++ MAKE ALL NON-EXSISTING VISCOSITIES EQUAL ZERO ++++++
C
C
         IF (NPHASE(K).EQ.3) GO TO 260
         IF (NPHASE(K).EG.1) GO TC 250
         IF (C(3,4,K).LT.EPSME) GO TO 240
         IF (CSE(K).GE.CSEU.GR.NPHASE(K).EQ.4) VIS(2+K)=0.0
         IF (CSE(K).LE.CSEL.OR.NPHASE(K).EQ.5) VIS(1.K)=0.0
         GO TO 260
  240
         VIS(3,K)=0.0
         GO TO 260
  250
         IF (C(3,4,K).LT.EPSME) VIS(2,K)=VIS(3,K)=0.0
         IF (C(3,4,K).GE.EPSME) VIS(1,K)=VIS(2,K)=0.0
         CONTINUE
  260
  270 CONTINUE
```
```
IF (IPRNT.NE.1) GO TO 300
С
     +++++++ PRINT NO. OF ITERATION AND CONVERGENCE AT 40TH BLOCK
C
С
     PRINT 320, VP+(K+K=1+ICT)
     PRINT 370, (IT(K),K=1,ICT)
     PRINT 380, NPHASE(40)
     IF (NPHASE(40).EQ.1) GC TO 290
     D0 280 IP=1, IPHT
  280 PRINT 390, IP, PHTOLD(IP), ABPE(IP), F30LD(IP+1)
  290 CONTINUE
  300 CONTINUE
     RETURN
C
      C
C
 310 FORMAT (//,35HTOT. REL. MOBILITY = 0.0 IN BLOCK :, I3,5X,9HAT P.V.
    1:,F9.4,1H1)
  320 FORMAT (//5X,4HVP =,F7.4//8X.7HBLOCK ,4013)
  330 FORMAT (//5X,39HTOT. REL. MOBILITY DID NCT CONVERGE ON ,13,2X,10HI
     ITERATIONS,/,5X,10HIN BLOCK :,13,3X,12HAT INJ. PV.:,F9.4,/,52(2H++)
    2)
  340 FORMAT (/8X,20HITERATION SEQUENCE :,T30,4HITER,T42,6HPHT0LD,T58,5H
    1F30LD, T74, 9HABS, ER ROR, T90, 9HREL, ER ROR, //)
  350 FORMAT (8X+T30+I3+T38+E12+6+T55+E12+6+T72+E12+6+T90+E12+6)
  360 FORMAT (//5X, 3DHNEGATIVE SATURATION IN BLOCK :, I3, 3X, 20HAT INJ. PO
    1REVOLUME :, F9.4,//)
  370 FORMAT (8X.7H IT
                         ,4013)
  380 FORMAT (/15X,24HAT 40 TH BLOCK (NPFASE =,I3,1H),/20X,2HIP,4X,3HPHT
    1+12X+4HABPE+11X+3HFF3)
 390 FORMAT (20X,12,3E15.7)
C
     END
     SUBROUTINE RELPERM(K)
C--
  THIS SUBPROGRAM GIVES RESIDUAL SATURATION AND RELATIVE PERMEABILITY.
C
  WHEN THREE PHASES APPEAR, A RELATIVE PERMEABILITY MODEL IS SELECTED
C
  ACCORDING TO IPERM.
С
      IPERN = 0 : PCPE'S MODEL
С
            = 1 : HIRASAKI'S NODEL
C
            = 2 : MODIFIED HIRASAKI'S MCDEL
С
С
            = 3 : LAKE'S MODEL
                       C-
С
     COMMON/SOL/C(7+4+42)+S(3+42)+FF(3+42)+NPHASE(42)+EPSME
     COMMON /CSE/ CSE(42),CSA(42),CSEL,CSEU,RCSE,CSEOP,DCSE,CSELI,CSEUI
     COMMON/PERM/IPERM+P1RW+P2RW+E1+E2+E3+P1RC+P2RC
     COMMON/TRAP/T11,T12,T21,T22,T31,T32,S1RW,S2RW,PHT(40),EPSMOB,
                 ICONT, IPMAX
    1
     CONMON/PERMC/PERM(3,40), SRED(3,40), SN(3,40), VIS(3,40), LPERM(40)
     COMMON/XIFT/XIFT1(42), XIFT2(42), XIFT3(42), XIFTW
     COMMON/RESID/S1R,S2R,S3R
С
  CALCULATE RESIDUAL SATURATIONS BASED IN CAPILLARY NUMBER
C
     S1R=S1RW+(1.0+T11+(ALOG10(PHT(K))+XIFT1(K)+T12))
     S2R=S2RW+(1.0+T21+(AL0G10(PHT(K))+XIFT2(K)+T22))
     IF(S1R.LE.0.0)S1R=0.0
     IF(S2R.LE.0.0)S2R=0.0
     IF(S1R.GT.S1RW)S1R=S1RW
      IF(S2R.GT.S2RW)S2R=S2RL
      IF (NPHASE(K).E0.3) G0 T0 10
С
```

```
C++++++ THO PHASE FLOW +++++++
C
   DEFINE WETTING PHASE AND NON-WETTING PHASE SATURATIONS
С
      SWET=S(1,K)
      SNON=S(2+K)
      IF (C(3,4,K).LT.EPSNE)G0 TO 201
      IF (CSE(K).GE.CSEU.OR.NPHASE(K).EG.4)SACN=S(3.K)
      IF(CSE(K).LE.CSEL.OR.NPHASE(K).EG.5)SHET=S(3,K)
  201 CONTINUE
С
   DETERMINE RESIDUAL SATURATION
С
      IF (SWET.LT.SIR)SIR=SWET
      IF(SNON.LT.S2R)S2R=SNON
      S3R=0.0
С
   NORMALIZED SATURATION
С
      SN(1,K)=(SWET-S1R)/(1.0-S1R-S2R)
      IF(SN(1,K).LT.0.0)SN(1,K)=0.0
      IF (SN(1,K).GT.1.0) SN(1,K)=1.0
      SN(2,K)=1.0-SN(1,K)
      SN(3,K)=0.0
C
   END POINT AND CURVATURE OF RELATIVE PERMEABILITY CURVE
С
      P1R=P1RW+(S2RW-S2R)+(P1RC-P1RW)/S2RW
      P2R=P2RW+(S1RW-S1R)+(P2RC=P2RW)/S1RW
      E1C=1.0+(E1-1.0)+S2R/S2RW
      E2C=1.0+(E2-1.0)+S1R/S1RW
С
   RELATIVE PERMEABILITY, RESIDUAL SATURATION, NORMALIZED SATURATION
C
      PERM(1+K)=P1R+ ABS(SN(1+K))++E1C
      PERM(2+K)=P2R+ABS(SN(2+K))++E2C
      PERM(3,K)=0.0
      IF(C(3+4+K)+LT+EPSHE)G0 T0 99
      IF(CSE(K).GE.CSEU.OR.NPHASE(K).E0.4)GO TO 20
      PERM(3,K)=PERM(1,K)
      PERM(1+K)=0+0
      S3R=S1R
      S1R=0.0
      SN(3,K)=SN(1,K)
      SN(1,K)=0.0
      GO TO 99
   20 CONTINUE
      PERM(3+K)=PERM(2+K)
      PERM(2+K)=0.0
      S3R=S2R
      S2R=0.0
      SN(3,K)=SN(2,K)
      SN(2+K)=0+0
      GO TO 99
r
C******* THREE PHASE FLOW *******
   10 CONTINUE
      IF(IPERM.EQ.0)CALL POPE(K)
      IF (IPERM.EQ.1) CALL HIRA(K)
      IF(IPERM.EQ.2)CALL OHNC(K)
      IF(IPERM.EQ.3)CALL LAKE(K)
С
   99 CONTINUE
С
   RENAME RESIDUAL SATURATIONS
С
      SRED(1,K)=S1R
      SRED(2,K)=S2R
```

```
SRED(3,K)=S3R
      RETURN
      END.
      SUBROUTINE POPE(K)
C-
                                   ------
   THIS IS A THREE PHASE RELATIVE PERMEABILITY MODEL.
С
C
   THIS MODEL WAS USED BY G.A. POPE IN HIS ORIGINAL SIMULATOR.
C-
      COHMON/SOL/C(7+4+42)+S(3+42)+FF(3+42)+NPHASE(42)+EPSHE
      COMMON/PERM/IPERM, P1RW, P2RW, E1, E2, E3, P1RC, P2RC
      COMMON/TRAP/T11,T12,T21,T22,T31,T32,S1RW,S2RW,PHT(40),EPSMOB,
                  ICONT, IPMAX
     1
      COMMON/PERMC/PERM(3,40),SRED(3,40),SN(3,40),VIS(3,40),LPERM(40)
      COMMON/XIFT/XIFT1(42), XIFT2(42), XIFT3(42), XIFTW
      COMMON/RESID/S1R,S2R,S3R
С
      P3R=1.0
      S3R=T31+T32+(AL0G10(PHT(K))+XIFT3(K))
      IF(S(1,K).LT.S1R)S1R=S(1,K)
      IF(S(2,K).LT.S2R)S2R=S(2,K)
      SM=1.0-(S1R+S2R+S3R)
      SN(1+K)=(S(1+K)-S1R)/SH
      SN(2+K)=(S(2+K)-S2R)/SM
      IF(SN(1,K).LT.0.0)SN(1,K)=0.0
      IF(SN(2,K).LT.0.0)SN(2,K)=0.0
      IF(SN(1,K).GT.1.0)SN(1,K)=1.0
      IF(SN(2,K).GT.1.0)SN(2,K)=1.0
      SN(3,K)=1.0-(SN(1,K)+SN(2,K))
      P1R=P1RW+(S2RW-S2R)+(P1RC-P1RW)/S2RW
      P2R=P2RH+(S1RH-S1R)+(P2RC-P2RH)/S1RH
С
      PERM(1,K)=P1R+SN(1,K)
      PERM(2+K)=P2R+SN(2+K)
      PERM(3+K)=P3R+SN(3+K)++E3
      RETURN
      END
      SUBROUTINE FIRA(K)
C-
С
 THIS IS A THREE PHASE RELATIVE PERMEABILITY MODEL.
 THIS MODEL WAS PRESENTED BY G. HIRASAKI.
С
C---
С
      COHMON/SOL/C(7,4,42),S(3,42),FF(3,42),NPHASE(42),EPSHE
      COMMON/PERM/IPERM, P1RW, P2RW, E1, E2, E3, P1RC, P2RC
      COMMON/TRAP/T11+T12+T21+T22+T31+T32+S1RW+S2RW+PHT(40)+EPSMOB+
                  ICONT, IPMAX
     1
      COMMON/PERMC/PERMC3,40),SRED(3,40),SN(3,40),VIS(3,40),LPERM(40)
      COMMON/XIFT/XIFT1(42),XIFT2(42),XIFT3(42),XIFTW
      COMMON/RESID/S1R+S2R+S3R
С
C
   RESIDUAL SATURATION
      S32R=S2RW*(1.+T21*(ALOG10(PHT(K))+)IFT1(K)+T22))
      S31R=S1RH+(1.+T11+(ALOG10(PHT(K))+XIFT2(K)+T12))
      IF(S32R.LT.0.0)S32R=0.0
      IF(S31R.LT.0.0)S31R=0.0
      IF (S32R.GT.S2RW) S32R=S2RW
      IF(S31R.GT.S1RW)S31R=S1RW
      S1RP=S31R-S(3+K)
      $2RP=$32R-$(3,K)
      S3R1=S32R-S(2+K)
      S3R2=S31R-S(1,K)
      S1R=AMAX1(S1R,S1RP)
```

```
S2R=AMAX1(S2R, S2RP)
             S3R=AMAX1(S3R1.0.0.S3R2)
C
      NORMALIZED SATURATION
C
             SN(1,K)=(S(1,K)-S1R)/(1.-(S32R+S1R))
             SN(2,K)=(S(2,K)-S2R)/(1.-(S31R+S2R))
             SN(3,K)=(S(3,K)-S3R)/(1.-(S1R+S2R+S3R))
             IF(SN(1+K)+LT+0+0)SN(1+K)=0+0
             IF(SN(2,K).LT.0.0) SN(2,K)=0.0
             IF(SN(3+K).LT.0.0)SN(3+K)=0.0
С
C
      END POINT AND CURVATURE OF RELATIVE PERMEABILITY CURVE
             S1T=AMIN1(S1R+S(1+K))
             S2T=AMIN1(S2R, S(2,K))
             WEI=S2T/(S1T+S2T)
             P1R=P1RC-(P1RC-P1RW) +S32R/S2RW
             P2R=P2RC-(P2RC-P2RW)+S31R/S1RW
             P3R=WEI*P1R+(1.-WEI)*P2R
             E1C=1.0+(E1-1.0)+S32R/S2RW
             E2C=1.0+(E2-1.0)+S31R/S1RW
             E3C=WEI*E1C+(1.-WEI)*E2C
С
      RELATIIVE PERMEABILITY
C
             PERM(1+K)=P1R*SN(1+K)**E1C
             PERM(2+K)=P2R+SN(2+K)++E2C
             PERM(3,K)=P3R+SN(3,K)++E3C
             RETURN
             END
             SUBROUTINE OHNC(K)
C-
      THIS IS A THREE PHASE RELATIVE PERMEABILITY MODEL.
С
      THIS IS A MODIFIED VERSION OF HIRASAKI'S MODEL.
С
     THIS SUBPROGRAM IS NOT COMPLETED YET (NEED HORE MCDIFICATION).
C
C----
                 - 2.5 ビジャネンシン・ 2.5 マンシン・ 2.5 マン・ 2.5 
С
             COMMON/SOL/C(7+4+42)+S(3+42)+FF(3+42)+NPHASE(42)+EPSHE
             COMMON/PERM/IPERM, P1RW, P2RW, E1, E2, E3, P1RC, P2RC
            COMMON/TRAP/T11, T12, T21, T22, T31, T32, S1RW, S2RW, PHT(40), EPSMOB,
                                       ICCNT, IPMAX
           1
             COMMON/PERMC/PERM(3,40),SRED(3,40),SN(3,40),VIS(3,40), LPERM(40)
             COMMON/XIFT/XIFT1(42), XIFT2(42), XIFT3(42), XIFTH
             COMMON/RESID/S1R+S2R+S3R
C
      RESIDUAL SATURATION
C
             $32R=$2RH+(1++T21+(ALOG10(PHT(K))+XIFT1(K)+T22))
             S31R=S1RW+(1.+T11+(ALOG10(PHT(K))+XIFT2(K)+T12))
             IF($32R.LT.0.0)$32R=0.0
             IF(S31R.LT.0.0)S31R=0.0
             IF (S32R.GT.S2RW) S32R=S2RW
             IF(S31R.GT.S1RW)S31R=S1RW
             S1R=AMIN1(S(1+K)+S1R)
             S2R=AMIN1(S(2,K),S2R)
             S3R1=S31R-S1R
             S3R2=S32R-S2R
             S3R=AMAX1(S3R1+0.0+S3R2)
             IF (S(3,K).LT.S3R)S3R=S(3,K)
С
C END POINT AND CURVATURE OF RELATIVE PERPEABILITY CURVE
            IF((S1R+S2R).LT.1.E-4) GO TO 10
             S32RC=AMIN1(S32R+(S3R+S2R))
             S31RC=AHIN1(S31R,(S3R+S1R))
             WEI=S2R/(S1R+S2R)
```

P1R=P1RC-(F1RC-P1RW)+S32RC/S2RW P2R=P2RC-(P2RC-P2RW)+S31RC/S1RW P3R=WEI*P1R+(1.+WEI)*P2R E1C=1.0+(E1-1.0)+S32RC/S2RH E2C=1.0+(E2-1.C)+S31RC/S1RW E3C=WEI+E1C+(1.-WEI)+E2C C NCRMALIZED SATURATION С SMOB=1.-(S1R+S2R+S3R) SN(1,K)=(S(1,K)-S1R)/SMOB SN(2,K)=(S(2,K)-S2R)/SMOB SN(3+K)=(S(3+K)-S3R)/SMOB IF (SN(1,K).LT.0.0) SN(1,K)=0.0 IF(SN(2,K).LT.0.0) SN(2,K)=0.0 IF(SN(3,K).LT.0.0)SN(3,K)=0.0 С RELATIIVE PERMEABILITY C PERM(1+K)=P1R+SN(1+K)++E1C PERM(2,K)=P2R+SN(2,K)++E2C PERM(3+K)=P3R+SN(3+K)++E3C RETURN 10 D0 20 J=1.3 20 PERM($J_{*}K$)=S($J_{*}K$) RETURN END SUBROUTINE LAKE(K) C---------THIS IS A THREE PHASE RELATIVE PERMEABILITY MODEL. C THIS MODEL WAS DEVELOPPED BY L. LAKE. C C----COMMON/SOL/C(7,4,42),S(3,42),FF(3,42),NPHASE(42),EPSME COMMON/PERM/IPERM, P1RW, P2RW, E1, E2, E3, P1RC, P2RC COMMON/TRAP/T11,T12,T21,T22,T31,T32,S1RW,S2RW,PHT(40),EPSMOB, ICONT, IPMAX 1 COMMON/PERMC/PERM(3,40),SRED(3,40),SN(3,40),VIS(3,40),LPERM(40) COMMON/XIFT/XIFT1(42),XIFT2(42),XIFT3(42),XIFTW COMMON/RESID/S1R .S2R .S3R С GLAKE=S(2,K)+(1,-S(1,K))/(S(1,K)+S(2,K)) S3R=S2R+GLAKE*(S1R-S2R) С ACTUAL RESIDUAL SATURATION С S1R=AMIN1(S1R,S(1,K)) S2R=AMIN1(S2R,S(2,K)) S3R=AMIN1(S3R,S(3,K)) C INTERPOLATION FACTORS С S1IP=(S2RW-S2R)/S2RW S2IP=(S1RW-S1R)/S1RW С END POINT OF RELATIVE PERMEABILITIES C P1R=P1RW+S1IP*(P1RC=P1RW) P2R=P2RW+S2IP+(P2RC-P2RW) P3R=P2R+GLAKE+ (P1R-P2R) C CURVATURE OF RELATIVE PERMEABILITY CURVES С E1C=E1+S1IP+(1.-E1) E2C=E2+S2IP+(1.-E2) E3C=E2C+GLAKE+(E1C-E2C) С С NCRMALIZED SATURATION SMOB=1.-(S1R+S2R+S3R)

```
SN(1,K)=(S(1,K)-S1R)/SFOB
     SN(2,K)=(S(2,K)-S2R)/SMOB
     SN(3,K)=(S(3,K)-S3R)/SMOB
С
  RELATIVE PERMEABILITIES
С
     PERM(1+K)=P1R+SN(1+K)++E1C
     PERM(2+K)=P2R+SN(2+K)++E2C
     PERM(3,K)=P3R+SN(3,K)++E3C
С
     RETURN
     END
     SUBROUTINE PHCOMP
C
C
С
     SUBROUTINE PHC5 - UPDATED 03/05/81
     DILUTION EFFECT INCLUDED IN SALINITY (CSE)
C
     THIS SUBROUTINE IS USED TO FIND THE PHASE ENVIRONMENT AND TO
С
     CALCULATE THE PHASE COMPOSITIONS AND SATURATIONS
C
     MOST SURFACTANT RICH PHASE IS DEFINED AS PHASE 3
C
     COMPARED WITH FHASE 3, WETTING PHASE IS PHASE 1, NON WETTING PHASE
С
     IS PHASE 2
C
С
     SINGLE PHASE WITH SOME SURFACTANT IS PHASE 3, REGARDLESS OF
     PHASE BEHAVIOR
С
С
                   С
     COMMON /NO/ ICT+ICT1+ICT2+XICT+NCOMP+NF
     COMMON /SOL/ C(7,4,42),S(3,42),FF(3,42),NPHASE(42),EPSME
     COMMON /CSE/ CSE(42)+CSA(42)+CSEL+CSEU+RCSE+CSEOP+DCSE+CSELI+CSEUI
     COMMON /PHASE/ F1+F2+F3+B1+B2+B3+C2PLC+C2PRC
     COMMON /A/ A11,A12,A21,A22
     COMMON /IFT/ G11+G12+G13+G21+G22+G23
     COMMON /XIFT/ XIFT1(42)+XIFT2(42)+XIFT3(42)+XIFTW
     COMMON /TRY/ A, B, G, F, IFX, ALPHA, BETA, XR, XL, EPSTIE
     COMMON /REST/ IERROR, IH, IK, II, VPF, KK, IFLAG, ISLUG
     COMMON /INJECT/ DVPP, DVP, VP, VT, VPI
     COMMON /ALC/ AA, BB, CC
С
     KK=0
С
     D0 440 K=1,ICT2
        KK=KK+1
        ICT1=ICT+1
        IF (K.EQ.ICT1) GO TO 440
С
     TEST FOR CHEMICAL
С
С
        IF (C(3,4,K).LT.EPSME) GO TO 290
С
     SET UP CURRENT SURFACTANT TO ALCOHOL RATIO RSA
С
С
        RSA=1.0/1.0E-8
        IF (C(7,4,K).GE.1.0E-8) RSA=C(3,4,K)/C(7,4,K)
С
     COMBINE SURFACTANT AND ALCOHOL TOGETHER AS COMPONENT THREE
C
C
        C(3,4,K)=C(3,4,K)+C(7,4,K)
С
     TEST FOR PHASE BEHAVIOR
С
C
        IF (CSE(K).LT.CSEU) GO TO 60
С
      С
```

C

A1=A11+A12+CSE(K) IF (C(2,4,K).LT.0.0010) GG TO 270 R32=C(3,4,K)/C(2,4,K) R31=(R32/A1)**(1.0/P1) 'C(1,3,K)=R32/(R32+R32+R31+R31) C(2,3,K)=1.0-(R31+1.0)+C(1,3,K)C(3,3,K)=1.0-C(1,3,K)-C(2,3,K)IF (C(3+3+K)+LT+C(3+4+K)) GC 10 270 NPHASE(K)=2 C2PL=C2FLC IF (ABS(CSE(K)-CSEU).LT.DCSE) C2PLC=0.0 IF (ABS(C2PLC).GT.1.0E-5.AND.ABS(F1).GT.1.0E-5) GO TO 10 C(1,1,K)=1.0 C(2,1,K)=0.0 C(3,1,K)=0.0 C2PLC=C2PL GO TO 30 10 A=A1 8=81 F=F1 C3PLC=.5+(-A+C2PLC+((A+C2PLC)++2+4.+A+C2PLC+(1.-C2PLC))++.5) G=(1.-C3PLC-C2PLC)/C2PLC С C CALCULATE R31 ,R32 AT FLAIT POINT С XR=C3PLC/C2FLC-1.0E-20 XL=1.0E-18 С С CALCULATE THE CONCENTRATIONS OF COPPONENTS OF TWO PHASES С CALL TIELINE IF (IERROR.EG.1) RETURN DO 20 I=1+6 20 C(I,3,K)=C(I,2,K) 30 DO 40 I=1.6 40 C(I+2+K)=0.0 DO 50 J=1.3.2 C(5+J+K)=C(5+4+K)+C(1+J+K)/C(1+4+K) 50 S(1,K)=(C(1,4,K)-C(1,3,K))/(C(1,1,K)-C(1,3,K))S(3,K)=1.0-S(1,K) S(2,K)=0.0 C(4,1,K)=C(4,4,K)/S(1,K) C(4,3,K)=0.0 С С CALCULATE INTERFACIAL TENSION BETWEEN MICROEMULSION AND WATER С C3=C(3,3,K)*RSA/(1.0+RSA) IF (RSA.GT.1.0E7) C3=C(3,3,K) XIFT1(K)=G12+G11/(G13+C(1,3,K)/C3+1.C) XIFT2(K)=XIFT1(K) GO TO 400 60 IF (CSE(K).GT.CSEL) GO TO 120 C С С A2=A21+A22*CSE(K) R31=C(3,4,K)/C(1,4,K) R32=A2*R31**B2 C(1+3+K)=R32/(R32+R32+R31+R31) C(2,3,K)=1.0-(R31+1.0)+C(1,3,K)C(3,3,K)=1.0-C(1,3,K)-C(2,3,K)

```
IF (C(3,3,K).LT.C(3,4,K)) GC 10 270
         NPHASE(K)=2
         C2PR=C2PPC
         IF (ABS(CSE(K)-CSEL).LT.DCSE) C2PRC=1.0
         IF (ABS(C2PRC).LT.1.0. AND. ABS(F2).GT.1.0E-5) GO TO 70
         C(1+2+K)=0.0
         C(2,2,K)=1.0
         C(3,2,K)=0.0
         C2PRC=C2PR
         GO TO 90
  70
         A=A21+A22+CSE(K)
         8=82
         F=F2
         C3PRC=.5*(-A+C2PRC+((A+C2PRC)*+2+4.*A+C2PRC*(1.-C2PRC))*+.5)
         G=(1.-C3PRC-C2PRC)/C2PRC
C
С
      CALCULATE R321,R311 AT PLAIT POINT
С
         XR=G*R31**F
         XL=1.0E-20
С
      CALCULATE THE CONCENTRATIONS OF COPPONENTS OF THO PHASES
С
C
         CALL TIELINE
         IF (IERROR.EQ.1) RETURN -
         DO 80 I=1.6
   80
         C(I,3,K)=C(I,1,K)
   91
         DO 100 I=1+6
  100
         C(I,1,K)=0.0
         DO 110 J=2,3
  110
         C(5+J+K)=C(5+4+K)+C(1+J+K)/C(1+4+K)
         S(3,K)=(C(1,4,K)-C(1,2,K))/(C(1,3,K)-C(1,2,K))
         S(2,K)=1.0-S(3,K)
         S(1,K)=0.0
         C(4,3,K)=C(4,4,K)/S(3,K)
         C(4,2,K)=0.0
С
      CALCULATE INTERFACIAL TENSION BETWEEN MICRCEMULSION AND OIL
С
C
         C3=C(3+3+K)+RSA/(1+0+RSA)
         IF (RSA.GT.1.0E7) C3=C(3.3.K)
         XIFT2(K)=G22+G21/(G23+C(2+3+K)/C3+1.0)
         XIFT1(K)=XIFT2(K)
         GO TO 400
С
      ++++++ TYPE III BEHAVIOR : INTERMEDIATE SALINITY ++++++++
С
С
         C2M=(CSE(K)-CSEL)/(CSEU-CSEL)
  120
         IF (CSE(K)+.5+(CSEU+CSEL)) 13C+130+140
         A3=A21+A22+CSE(K)
  130
         GO TO 150
  140
         A3=A11+A12+CSE(K)
         A=A3
  150
         B=83
         F=F3
         C3M=+5+(-A+C2H+((A+C2H)++2+4++A+C2H+(1++C2H))+++5)
         C1M=1.-C2H-C3M
         IF (C2M.LT.1.0E-10) C2M=1.0E-10
         IF (C1M.LT.1.0E-10) C1M=1.0E-10
         IF (C(2+4+K)+GT+C2H) GO TO 200
C
      TEST FOR THREE PHASES
С
```

```
С
         IF (C(3+4+K)+LT+C3H+C(2+4+K)/C2P) G0 T0 250
C
С
      TYPE II(+) LOBE
С
         IF (C(2,4,K).LE.0.001) GC TC 270
         NPHASE(K)=4
         R32=C(3,4,K)/C(2,4,K)
         R31=(R32/A3)**(1.0/83)
         C(1,3,K)=R32/(R32+R32+R31+R31)
         C(2,3,K)=1.0-(R31+1.0)+C(1,3,K)
         C(3_{3},K)=1_{0}-C(1_{3},K)-C(2_{3},K)
         IF (C(3+3+K)+LT+C(3+4+K)) GO TO 270
         C2PL=C2PLC
         IF (ABS(CSE(K)+CSEU).LT.DCSE) C2PLC=0.0
         IF (ABS(C2PLC).GT.1.9E-5) GO TO 160
         C(1,1,K)=1.0
         C(2,1,K)=0.0
         C(3,1,K)=0.0
         C2PLC=C2PL
         GO TO 170
  160
         C2PL=C2PLC+ (CSE(K)-CSEU)+C2PLC/(CSEU-CSEL)
         C3PL=.5+(-A+C2PL+((A+C2PL)++2+4.+A+C2PL+(1.-C2PL))++.5)
         C1PL=1.-C2PL-C3PL
         ALPHA=C3M/C2M
         BETA=SQRT (C2M++2+C3M++2)/C2M
         G=(1.+(ALPHA-BETA)+C2PL-C3PL)/(BETA+C2PL)
         XR=C3PL/C1PL-1.0E-20
         XL=1.0E-20
         CALL TIELINE
         IF (IERROR.EQ.1) RETURN
  170
         CONTINUE
         DO 180 I=1.6
  180
         C(I+2+K)=0.0
         IF (C(3+4+K)+GT+C(3+3+K)) GO TO 270
         DO 190 J=1.3.2
         C(5_{9}J_{9}K)=C(5_{9}4_{9}K)+C(1_{9}J_{9}K)/C(1_{9}4_{9}K)
  190
         S(1,K) = (C(1,4,K) - C(1,3,K)) / (C(1,1,K) - C(1,3,K))
         S(3,K)=1.0-S(1,K)
         S(2,K)=0.0
         C(4,1,K)=C(4,4,K)/S(1,K)
         C(4,3,K)=0.0
         C3=C(3,3+K)+RSA/(1.0+RSA)
         IF (RSA.GT.1.DE7) C3=C(3.3.K)
         XIFT1(K)=G12+G11/(G13+C(1+3+K)/C3+1+0)
         XIFT2(K)=XIFT1(K)
         GO TO 400
  200
         IF (C(3+4+K)+LT+C3H+C(1+4+K)/C1F) G0 T0 250
С
      TYPE II(-) LOBE
С
C
         NPHASE(K)=5
         R31=C(3,4,K)/C(1,4,K)
         R32=A3*R31**B3
         C(1+3+K)=R32/(R32+R32+R31+R31)
         C(2,3,K)=1.0-(R31+1.0)+C(1,3,K)
         C(3,3,K)=1.0-C(1,3,K)-C(2,3,K)
         IF (C(3,4,K).GT.C(3,3,K)) GC TO 270
         C2PR=C2PPC
         IF (ABS(CSE(K)-CSEL).LT.DCSE) C2PRC=1.0
         IF (ABS(C2PRC).LT.1.) GC TC 210
         C(1,2,K)=0.0
```

```
C(2+2+K)=1.0
         C(3.2.K)=0.0
         C2PRC=C2PR
         GO TO 220
  210
         C2PR=C2PRC+(1.-C2PRC)+(CSE(K)-CSEL)/(CSEU-CSEL)
         C3PR=.5+(-A+C2PR+((A+C2PR)++2+4.+A+C2PR+(1.-C2PR))++.5)
         C1PR=1.-C2PR-C3PR
         ALPHA=C3H/C1M
         BETA=SQRT(C3M++2+C1M++2)/C1M
         G=BETA+C1PR/(1.+(ALPHA-BETA)+C1FR-C3PR)
         XR=G+R31++F-1.0E-20
         XL=1.0E-20
         CALL TIELINE
         IF (IERROR.EQ.1) RETURN
  220
         00 230 I=1.6
         C(I,1,K)=0.0
  230
         DC 240 J=2,3
  240
         C(5+J_{9}K)=C(5+J_{9}K)+C(1+J_{9}K)/C(1+J_{9}K)
         S(2+K)=(C(2+4+K)-C(2+3+K))/(C(2+2+K)-C(2+3+K))
         S(3,K)=1.-S(2,K)
         S(1,K)=0.0
         C(4,3,K)=C(4,4,K)/S(3,K)
         C(4,2,K)=0.0
         C3=C(3+3+K)+RSA/(1+0+RSA)
         IF (RSA.GT.1.0E7) C3=C(3.3.K)
         XIFT2(K)=G22+G21/(G23+C(2+3+K)/C3+1+C)
         XIFT1(K)=XIFT2(K)
         GO TO 400
С
С
     THREE PHASES
C
 250
         NPHASE(K)=3
         C(1+1+K)=1.0
         C(2,1,K)=0.0
         C(3+1+K)=0+0
         C(1,2,K)=0.0
         C(2,2,K)=1.0
         C(3,2,K)=0.0
         C(1+3+K)=C1M
         C(2,3,K)=C2M
         C(3,3,K)=C3P
         DO 260 J=1,3
         C(5+J+K)=C(5+4+K)+C(1+J+K)/C(1+4+K)
  260
         S(2,K)=((C(1,4,K)-C(1,3,K))+C(2,3,K)+(1.0-C(1,3,K))+(C(2,4,K)-C
         (2,3,K)))/(1.0-C(1,3,K)-C(2,3,K))
     1
         S(1,K)=((C(1,4,K)-C(1,3,K))+(1,0-C(2,3,K))+(C(2,4,K)-C(2,3,K))+
         C(1+3+K))/(1.0-C(1+3+K)-C(2+3+K))
     1
         S(3,K)=1.0-S(1,K)-S(2,K)
         C(4+1+K)=C(4+4+K)/S(1+K)
         C(4,2,K)=0.0
         C(4,3,K)=0.0
С
      CALCULATE TWO INTERFACIAL TENSIONS
С
С
         C3=C(3,3,K)*RSA/(1.0+RSA)
         IF (RSA.GT.1.0E7) C3=C(3,3,K)
         XIFT1(K)=G12+G11/(G13+C(1+3+K)/C3+1+0)
         KIFT2(K)=G22+G21/(G23+C(2,3,K)/C3+1.C)
         XIFT3(K)=AMIN1(XIFT1(K)+XIFT2(K))
         GO TO 400
С
С
      +++++++++ SINGLE PHASE REGION : TYPE II(+), III, (-) ++++++++
```

```
С
  270
        NPHASE(K)=1
        DC 230 I=1.6
            C(I+2+K)=0.0
           C(I_{1},K) = C(I_{2},K)
           C(I_{3},K)=C(I_{4},K)
  280
        CONTINUE
        FF(1,K)=0.0
        FF(2.K)=0.0
        FF(3,K)=1.0
         S(1,K)=0.0
        S(2,K)=0.0
        S(3+K)=1+0
       _ GO TO 400
C
C
     C
C
     CALCULATING SATURATIONS
С
 290
        S(2,K)=C(2,4,K)
        S(1,K)=1.-S(2,K)
        S(3.K)=0.0
        C(2,2,K)=0.0
        C72=0.0
        C71=C(7,4,K)
С
С
     -WITH ALCOHOL
С
        IF (C(7,4,K).LT.1.0E-6) GO TO 300
        A0=AA+BB+CSA(K)+CC+CSA(K)++2
        IF (A0.GT.1.0) A0=1.0
        IF (A0.LT.0.0) A0=0.0
        C72=C(7+4+K)+A0
        C71=C(7.4.K)-C72
 300
        CONTINUE
С
С
     CONCENTRATION AND SATURATION IN CLEIC PHASE
Ċ
        IF (S(2+K).LT.1.0E-E) GC TO 330
        IF (S(1,K).GT.1.0E-6) GO TO 310
        C72=C(7+4+K)
        C71=0.0
        S(1,K)=0.0
        S(2,K)=C(2,4,K)+C72
 310
        DO 320 I=1,7
 320
        C(I,2,K)=0.0
        C(2,2,K)=C(2,4,K)/S(2,K)
        C(7,2,K)=C72/S(2,K)
        GO TO 340
 330
        S(2+K)=0+0
        C(2+2+K)=0.0
        C(7+2+K)=0.0
        C71=C(7,4,K)
С
С
     CONCENTRATIONS AND SATURATION IN AQUEOUS PHASE
С
 340
        IF (S(1+K).LT.1.0E-6) GO TC 350
        S(1+K)=1.0-S(2+K)
        C(3+1+K)=C(3+4+K)/S(1+K)
        C(7,1,K)=C71/S(1,K)
        .C(1+1+K)=1+0+C(3+1+K)+C(7+1+K)
        C(2,1,K)=0.0
```

```
C(4,1,K)=C(4,4,K)/S(1,K)
         C(5+1+K)=C(5+4+K)/S(1+K)
C
         C(6,1,K)=C(6,4,K)/S(1,K)
         GO TO 370
  350
         D0 360 I=1.7
  360
         C(I+1+K)=0.C
         CONTINUE
  37 C
С
     CONCENTRATIONS IN MICROEMULSION FHASE
С
С
         00 380 I=1,7
  380
        C(I.3,K)=0.0
C
         IF (S(1+K).LE.0.99999) GO TO 390
        NPHASE(K)=1
        FF(1,K)=1.0
        FF(2+K)=0+0
        FF(3,K)=0.0
         GC TO 440
         NPHASE(K)=2
  390
         XIFT1(K)=XIFTW
         XIFT2(K)=XIFTW
         GO TO 440
С
С
      ++++++ SEPARATE SURFACTANT AND ALCCHOL FRCM COMPONENT THREE
С
 400
         IF (C(7,4,K).GE.1.0E-8) GO TO 420
        DO 410 J=1.4
  410
        C(7,J,K)=0.0
        60 TO 440
  420
         DO 430 J=1+4
           C(7, J,K)=C(3, J,K)/(1.+RSA)
  430
        C(3+J+K)=C(7+J+K)+RSA
  440 CONTINUE
     RETURN
С
     END
     SUBROUTINE TIELINE
С
C
                        _____
                                               -------
     SUBROUTINE TIE2 - MODIFIED 03/05/81
C
С
     USING HALF INTERVAL METHOD TO FIND THE CORRECT ANSWER
     OF C31/C21
С
     TEST FOR CONVERGENCE : WHEN FX <= EPSTIE
С
С
     С
     COMMON /REST/ IERROR, IH, IK, II, VPP, KK, IFLAG, ISLUG
     COMMON /TRY/ A,B,G,F,IFX,ALPHA,BETA,XR,XL,EPSTIE
     COMMON /INJECT/ DVPP, DVP, VP, VT, VFI
     IFX=0
С
     ++++++ FIRST TWO INITIAL GUESSES ON C31/C21 (R32) ++++++++
С
C
     CALL TRY (XR+FXR)
     IF (IERROR.EQ.1) RETURN
     CALL TRY (XL.FXL)
      IF (IERROR.EQ.1) RETURN
С
С
     +++++++++ FURTHER ITERATION ON FX BY BISECTION METHOD ++++++
С
   10 APP=(XL+XR)/2.
     CALL TRY (APP, FXAPP)
```

```
IF (IERROR.EQ.1) RETURN
     IF (FXAPP+FXL) 20,40,30
  20 KR=APP
     FXR=FXAPP
     IF (ABS(FXAPP).LE.EPSTIE) GC TC 40
     GO TO 10
  30 XL=APP
     FXL=FXAPP
     IF (ABS(FXAPP).LE.EPSTIE) GO TO 40
     GO TO 10
  40 CONTINUE
     RETURN
С
     END
     SUBRCUTINE TRY (X.FX)
С
C
     SUBROUTINE TRY2 - UPDATED 08/20/80
С
     USING EQUATION OF DISTRIBUTION CURVE AND EQUATION OF BINCDAL
C
     CURVE TO CALCULATE PHASE COMPOSITIONS
C
С
     *******
С
     COMMON /SOL/ C(7+4+42)+S(3+42)+FF(3+42)+NPHASE(42)+EPSHE
     COMMON /TRY/ A+B+G+F+IFX+ALPHA+BETA+XR+XL+EPSTIE
     COMMON /REST/ IERROR, IH, IK, II, VPP, KK, IFLAG, ISLUG
     COMMON /INJECT/ DVPP, DVP, VP, VT, VFI
     Z=0.0
     K=KK
     IFX=IFX+1
С
     С
C
     IF (IFX.LE.20) GO TO 20
  10 IERROR=1
     PRINT 60. KK, VP, X. IFX. FX.Z
     RETURN
С
  20 IF (NPHASE(K)-4) 30,40,50
С
     +++++++++ CALCULATE TIELINES FOR TYPE II(-) AND TYPE II(+) +++
С
С
  30 Y = (X/A) * * (1./B)
     Z=G++(-1+F)+X++(1+F)
     IF (Z.LT.1.0E-30) GO TO 10
     ¥=A+Z++B
     C(1+2+K)=X/(X+X+Y+Y)
     C(2,2,K)=1.-(1.+Y)+C(1,2,K)
     C(3,2,K)=1-C(1,2,K)-C(2,2,K)
     C(1+1+K)=W/(Z+Z+W+W)
     C(2+1+K)=1-(1+Z)+C(1+1+K)
     C(3+1+K)=1.0-C(1+1+K)-C(2+1+K)
     FX={C(3+2+K)-C(3+4+K))+{C(2+1+K)-C(2+4+K)}-{C(3+1+K)-C(3+4+K)}+{C(
    12,2,K)-C(2,4,K))
     RETURN
С
     С
С
С
     LEFT NODE -TYPE II(+) BEHAVIOR
С
С
         Y=R32(1) X=R31(1) W=R32(3) Z=R31(3)
     Ĉ
C
  40 Y=A+X++B
```

```
C(2+1,K)=X/(X+X+Y+Y)
     C(3,1,K)=C(2,1,K)*Y
     C(1+1+K)=1-C(2+1+K)-C(3+1+K)
     P=G+((C(3,1,K)+C(2,1,K)+ALPHA)/(1++C(3,1,K)+C(2,1,K)+(ALPHA-BCTA))
    1) * * F
     W=BETA+(P+ALPHA/BETA)
     Z=(W/A)++(1./B)
     C(2+3+K)=Z/(Z+Z+W+W)
     C(3+3+K)=C(2+3+K)+W
     C(1,3,K)=1,-C(2,3,K)-C(3,3,K)
     FX=(C(3,3,K)-C(3,4,K))+(C(2,3,K)-C(2,1,K))-(C(3,3,K)-C(3,1,K))+(C(
    12,3,K)-C(2,4,K))
     RETURN
С
С
     RIGHT NODE - TYPE II(-) BEHAVIOR
C
C
     X=R32(2) Y=R31(2) W=R32(3) Z=R31(3)
C
  50 Y=(X/A)++(1./8)
     C(2,2,K)=Y/(X+Y+X+Y)
     C(3+2+K)=C(2+2+K)+X
     C(1+2+K)=1+-C(2+2+K)-C(3+2+K)
     P=((C(3,2,K)-ALPHA+C(1,2,K))/G/(1.+C(1,2,K)+(ALPHA-BETA)-C(3,2,K))
    1) * * (1 \cdot /F)
     Z=BETA+(P+ALPHA/BETA)
     W=A+Z++B
     C(2,3,K)=Z/(Z+Z+H+W)
     C(3,3+K)=C(2,3+K)+W
     C(1,3,K)=1.-C(2,3,K)-C(3,3,K)
     FX={C(3+2+K)-C(3+4+K))+{C(2+3+K)-C(2+2+K)}-{C(3+3+K)-C(3+2+K)}+{C(
    12+2+K)-C(2+4+K))
     RETURN
С
С
     С
  60 FORMAT (/,5X,8HIERROR=1,/,5X,7HBLOCK :,13,T30,5HVP :,F6.4,/,5X,8H
           :+E10.3+T30+12HITERATIONS :+I3+T5C+5HFX :+E10.3+T70+9HZ-VA
    1R32
    2LUE :, E10.3,/)
С
     END
     SUBROUTINE IONCNG
С
С
     *************************
     SUBROUTINE ION2 - UPDATED 05/12/81
С
С
     С
     COMMON /SOL/ C(7,4,42),S(3,42),FF(3,42),NPHASE(42),EPSME
    COMMON /ADSCRP/ C3 ADSS(40),C4 ADSS(40),C6 ADSS(40),C6 HATS(40)
     COMMON /CALC/ C6J0(40)
     COMMON /COMPLX/ XKC:XKS:QV
     COMMON /ION/ FFDVP+FFDV+DC3+K
С
С
        ------
C
     ALL CONCENTRATIONS MUST BE IN UNITS OF MEG/ML
     С
C
     CHE0=2.326
     EPS=1.0E-13
     ITER=0
     IF(C(3,3,K).LE.1.0E-4) GOTO 10
     C630=C6J0(K)
     C3H=C3ADSS(K)+CMEQ
```

	C33K=C(3,3,K)+CMEQ
	C53=C(5,4,K)+C(1,3,K)/C(1,4,K)
	B6=C(6,4,K)+C6ADSS(K)+C6HATS(K)
50	C6=C630
60	NF=1 C9=C53_C4
00	R96C=XKC+QV+C9++2/C6
	C68=0.5*(2.0*QV+R96C=SQRT(4.0*QV+R96C+R96C+*2))
	R96S=XKS+C33K+C9++2/C6
	C63S=0.5*(2.0+C33K+R96S-SQRT(4.0+C33K+R96S+R96S++2))
	C610=C630*C(1,1,K)/C(1+3+K)
	C620=C630+C(1+2+K)/C(1+3+K)
	C61S=C63S+C(3,1,K)/C(3,3,K)
	C62S=C63S+C(3+2+K)/C(3+3+K)
	C6H=C63S+C3H/C33K
	C60=C610+S(1+K)+C620+S(2+K)+C6+S(3+K)
	C6S=C61S+S(1+K)+C62S+S(2+K)+C63S+S(3+K)
	F6=C60+C6S+C6H+C6H-B6
	$\frac{1}{1} \left(\frac{1}{1} + 1$
	LD=LD*(1+U+ULJ) EC=E2
	NF=2
	60T0 60
70	FP=(F6-FS)/(C6+DC3)
	C630=C6-F6/FP
	ITER=ITER+1.
	IF(ITER.GT.40) GOTO 100
	IF(C630.LT.0.0) C630=C6/2.0
С	IF(ABS((C630-C6)/C6).GT.0.0001) G0T0 50
	IF(ABS(FS)+L1+LFS) 0010 120 COTO 50
120	C(6+4+K)=B6-C6B-C6H
	CGADSS(K)=CEB
	C6HATS (K)=C6H
	C6J0(K)=C630
	C(6+1+K)=C610+C61S
	C(6+2+K)=C620+C62S
-	$C(6_{4}3_{9}K)=C630+C63S$
Ç	F65(K)=(650/((650+(635)
10	C610=C6JD(K)
c	IF(K_EQ.40) PRINT 1000+K+C(6+4+K)+C6AESS(K)
1000	FORMAT(1X, T5, 2HK=, I4, T25, 4HC64=, F9.7, T45, 5HC6AD=, F9.7)
	C3H=C3ADSS(K) + CHEQ
	C51=C(5,4,K)+C(1,1,K)/C(1,4,K)
	B6=C(6,4,K)+C6ADSS(K)
90	C6=C610
	NF=1
30	U7=U51=U6 PR/C=V/C+0V+CP++2/CF
	C68=0.5+(2.0+0V+896C+S08T(4.0+0V+896C+896C++2))
	E6=C6+S(1+K)+C6B-B6
	IF(NF = EQ = 2) GOTO 20
	C6S=C6
	C6=C6+(1.0+DC3)
	FS=F6
	C688=C68
	NF=2
	GOTO 30 FR-154 FR1404-0671
20	rr=irb=r3)/((b=U(3)) r210-r2_52/50
	LDIV-LD-FD/FF ITFR=ITFRA1

.

```
IF(K.EQ.40) PRINT 2000, ITER, C610, C6, F6, FS, C6B, B6
C
2000 FORMATC1X, T5, 3HIT=, 13, T15, 5HC61C=, F9.7, T35, 3HC6=, F9.7,
           T55, 3HF6=, E9. 3, T75, 3HFS=, E9. 3, T95, 4HC6B=, F9. 7, T115, 3HB6=,
    1
           F9.7)
    2
     IF(ITER.GT.40) GOTO 100
     IF(C610.LT.0.0) C610=C6/2.0
     IF (ABS(FS).LT.EPS) GOTO 110
     GOTO 90
С
     IF(ABS((C610-C6)/C6).GT.0.0001) COTO 90
110
     C(6+4+K)=86-C68B
     C6ADSS(K)=C6BB
     C6J0(K)=C6S
     C(6.1.K)=C6S
     C(6,2,K)=0.0
     C(6,3,K)=0.0
     RETURN
100 PRINT 5000+ITER+K
     IERROR=1
     RETURN
5000 FORMAT(1X,18H DID NOT CONVERGE , 15,15)
     END
     SUBROUTINE POLYADN (X4, ADX4)
C
     C
     SUBROUTINE POL1 - ORIGINAL POLYMER ADSORPTICN ROUTINE
C
     IRREVERSIBLE LANGHUIR-TYPE ADSORTION
С
С
     ******************
C
     COMMON /POLYAD/ C4PH, A4D, B4D
     C4ADS=A4D+C4PH/(1.+B4D+C4PH)
     DC4ADS=C4ADS-ACX4
     IF (DC4ADS.LE..00001) RETURN
     IF (DC4ADS.GE.X4) GO TC 10
     X4=K4-DC4ADS
     ADX4=C4ADS
     RETURN
  10 ADX4=X4+ADX4
     X4=0.0
     RETURN
С
     END
     SUBROUTINE CHEMADN (X3, ADX3, OLDA3D)
С
С
     SUBROUTINE CHE1 - ORIGINAL CHEMICAL ADSCRPTICN ROUTINE
С
     PARTIALLY REVERSIBLE LANGMUIR-TYPE ADSORTION
C
     THE ASORPTION IS REVERSIBLE WITH SALINITY, BUT NOT WITH
С
С
     SURFACTANT CONCENTRATION
     С
С
     COMMON /CHEMAD/ C3PH, A3D, B3D, AC31, AC32, A3DS(40)
     C3ADS=A3D+C3PH/(1.+B3D+C3PH)
     C3ADSI=A3D + ADX3/OLDA3D
     IF (C3ADSI.GE.ADX3) C3ADSI=ADX3
     DC3ADS=C3ADS-C3ADSI
     IF (DC3ADS.LE..00001) GD TO 20
     IF (C3ADS.GE.X3) GO TO 10
     X3=X3-C3ADS
     ADX3=C3ADS
     GO TO 30
  10 ADX3=X3
     X3=0.0
```

```
GO TO 30
  20 X3=X3-C3ADSI
     ADX3=C3ADSI
  30 OLDA3D=A3D
     RETURN
С
     FND
     SUBROUTINE MATBAL
С
С
         _____
С
     SUBROUTINE MAT1 - UPDATED 08/20/80
С
     THIS SUBROUTINE CALCULATE OVERALL PATERIAL BALANCE AND
     RELATIVE -, ABSCLUTE MATERIAL BALANCE ERRCR
С
     *****
C
С
     COMMON /NO/ ICT.ICT1.ICT2.XICT.NCOPP.NF
     COMMON/SYSTEM/UT, ABPERN, PHI, EPHI3, EPHI4, DISPJ(4)
     COMMON /SOL/ C(7,4,42),S(3,42),FF(3,42),NPHASE(42),EPSME
     COMMON / PPODIN/ ER.P(7),P8,ZI(7),ZE(7),S2
     COMMON /ADSORP/ CJADSS(40),C4ADSS(40),C6ADSS(40),C6HATS(40)
     COMMON /CALC/ C6J0(40)
     COMMON /REST/ IERROR, IH, IK, II, VPF, KK, IFLAG, ISLUG
     COMMON / MAT/ E(7), RE(7), PR(7), ADS(7), CHOB(7)
С
     DO 10 N=1+NCOMP
       ADS(N)=0.0
  10 CMOB(N)=0.0
     C6HAT=0.0
С
     С
C
     D0 20 K=1,ICT
       ADS(3)=ADS(3)+C3ADSS(K)+XICT
       ADS(4)=ADS(4)+C4ADSS(K)+XICT
       ADS(6)=ADS(E)+C6ADSS(K)+XICT+C6HATS(K)+XICT
  20 CGHAT=CGHAT+CGHATS(K)+XICT
     ADS(3) = ADS(3) + EPHI3
     ADS(4) = ADS(4) + EPHI4
С
     Ċ
С
     DO 30 K=1, ICT
       X=1.0-C3ADSS(K)
       C MOB(1) = C MOB(1) + C (1 + 4 + K) + X I CT + X
       CM0B(2)=CM0B(2)+C(2+++K)+XICT+X
       CHOB(5)=CHOB(5)+C(5+4+K)+XICT
       CHOB(6)=CHOB(6)+C(6:4+K)+XICT
       CHOB(7)=CHOB(7)+C(7+4+K)+XICT+X
       CMOB(3)=CHOB(3)+C(3+4+K)+XICT+X
  30 CHOB(4)=CHOB(4)+C(4,4,K)+XICT
     CMOB(3)=EPHI3+CMOB(3)
     CNOB(4)=CMOB(4)+EPHI4
C
     С
С
     DO 40 I=1,NCOMP
  40 PR(I)=P(I)
     PR(3) = PR(3) + P8
С
С
     PR(6)=PR(6)+P8+2.
     DO 60 I=1,NCOMP
        IF ((ZI(I)+ZE(I)).LE.1.0E-5) 60 TO 50
        E(I)=PR(I)+ADS(I)+CHOB(I)-ZI(I)-ZE(I)
```

RE(I)=E(I)/(ZI(I)+ZE(I)) GO TO 60 50 E(I)=0.0 60 CONTINUE RETURN C END

.

.

APPENDIX C

TABULATED RESULTS OF OIL RECOVERY EXPERIMENTS

TABLE C.1

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-01

Sample No.	Sample Volume (ml)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	01eic Cut	Total 011 Cut	Fractional Oil Recovery
	. ,		• •		. ,			Ū
SE_1	5.0	0 011	5.0	1 0		0.00		
2	5.0	0.022	5.0	1.0		0.00		
3	5.0	0.033	5.0	1.0		0.00		
ů,	5.0	0.044	5.0	1.0		0.00		
5	5.0	0.055	5.0	1.0		0.00		
Cumulative	25.0	• .	25.0		0.0			0.000
SF-6	4.9	0.066	4.7	0.96	0.2	0.04	0.04	
7	5.0	0.077	4.0	0.80	1.0	0.20	0.20	
8	5.1	0.089	3.6	0.70	1.5	0.30	0.29	
9	5.0	0.100	3.2	0.64	1.8	0.36	0.36	
10	2.6	0.105	1.6	0.62	1.0	0.38	0.38	
Cumulative	47.6		42.1		5.5	•		0.038
PF1-1	6.3	0.120	3.1	0.49	3.2	0.51	0.51	
2	5.1	0.130	3.2	0.63	1.9	0.37	0.37	
3	5.1	0.142	3.0	0.59	2.1	0.41	0.41	
4	5.1	0.153	3.1	0.61	2.0	0,39	0.39	
5	5.0		3.0	0.60	2.0	0.40	0.40	
Çumulative	74.2	· · .	57.5		16.7			0.114

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-01

Sample No.	Sample Volume (ml)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	0]eic Cut	Total Oil Cut	Fractional Oil Recovery
PF1-6	5.5 5.1	0.176	3.3 3.0	0.60	2.2	0.40 0.41	0.40 0.41	
8 9	5.0 5.1	0.199 0.210	2.9 3.0	0.57	2.1 2.1	0.43 0.41	0.42 0.41	
10	5.0	0.220	2.9	0.58	2.1	0.42	0.42	
Cumulative	99.9		72.6	•	27.3			0.186
PF1-11 12 13 14 15	5.1 5.0 5.1 5.2 5.0	0.232 0.243 0.254 0.266 0.277	2.7 2.7 2.9 2.9 2.8	0.53 0.54 0.57 0.56 0.56	2.4 2.3 2.2 2.3 2.2	0.47 0.46 0.43 0.44 0.44	0.47 0.46 0.43 0.44 0.44	
Cumulative	125.3		86.6		38.7			0.264
PF1-16 17 18	5.0 5.2 5.0	0.288 0.299 0.311	3.0 2.9 2.9	0.60 0.56 0.58	2.0 2.3 2.1	0.40 0.44 0.42	0.40 0.44 0.42	
Cumulative	140.5		95.4		45.1	•		0.307
PF2-1 2 3 4 5	6.0 5.0 5.0 5.0 5.0	0.324 0.335 0.346 0.357 0.368	3.0 3.1 2.9 2.8 2.8	0.50 0.62 0.58 0.56 0.56	3.0 1.9 2.1 2.2 2.2	0.50 0.38 0.42 0.44 0.44	0.50 0.38 0.42 0.44 0.44	
Cumulative	165.5		110.0		56.5			0.385

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-01

Sample No.	Sample Volume (ml)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	Oleic Cut	Total Oil Cut	Fractional Oil Recovery
PF2-6	5.0	0.379	2.8	0.56	2,2	0.44	0.44	
7	5.0	0.390	2.7	0.54	2.3	0.46	0.46	
8	4.9	0.401	2.8	0.5/	2.1	0.43	0.43	
9 10	5.0	0.412	2.8	0.56	2.2	0.44	0.44	
Cumulative	191.4		123.8		67.6			0.461
PF2-11	4.9	0.434	2.7	0.55	2.2	0.45	0.45	
12	4.9	0.445	2.8	0.57	2.1	0.43	0.43	
13	5.0	0.456	2.9	0.58	2.1	0.42	0.42	
14	5.0	0.467	2.9	0.58	2.1	0.42	0.42	
15	5.0	0.4/8	3.0	0.60	2.0	0.40	0.40	
Cumulative	216.2		138.1		78.1			0.533
PF2-16	4.9	0.489	2.9	0.59	2.0	0.41	0.41	
17	4.9	0.500	2.9	0.59	2.0	0.41	0.41	
18	5.0	0.511	2.9	0.58	2.1	0.42	0.42	
Cumulative	231.0		146.8		84.2			0.574
	2 5	0 510	0.0	0.57	1 5	0.42	0.42	
PF3-1	3.5	0.519	2.0	0.57	1.5	0.43	0.43	
2	4.2	0.520	3.C 2.6	0.70	1.0	0.24	0.24	
3	4.3	0.556	2.0	0.00	1.7	0.40	0.40	
4 5	4.1	0.556	2.4	0.59	1.7	0.41	0.42	
Cumulative	251.3		159.4		91.9			0.627

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-01

Sample No.	Sample Volume (ml)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	Oleic Cut	Total Oil Cut	Fractional Oil Recovery
PF3-6	4.2	0.566	2.5	0.60	1.7	0.40	0.40	
7	4.5	U.575	2.7	0.60	1.8	0.40	0.40	
8	4.5	0.585	2.8	0.62	1.7	0.38	0.38	
9	4.4	0.595	2.9	0.66	1.5	0.34	0.34	
10	4.4	0.605	3.0	0.08	1.4	0.32	0.32	
Cumulative	273.3		173.3		100.0			0.682
PF3-11	4.4	0.615	3.1	0.70	1.3	0.30	0.30	
12	4.6	0.625	3.2	0.70	1.4	0.30	0,30	
13	4.6	0.635	3.3	0.72	1.3	0.28	0.30	
14	4.5	0.645	3.2	0.71	1.3	0.29	0.29	
15	5.0	0.656	3.3	0.66	1.7	0.34	0.34	
Cumulative	296.4		189.4		107.0			0.729
PF3-16	5.4	0.668	3.7	0.69	1.7	0.31	0.31	
17	5.0	0.679	2.4	0.48	2.6	0.52	0.52	
18	4.9	0.690	2.3	0.47	2.6	0.53	0.53	
19	5.0	0.701	3.1	0.62	1.9	0.38	0.38	
20	5.0	0.712	3.1	0.62	1.9	0.38	0.38	
Cumulative	321.7		204.0		117.7			0.808
PF3-21	5.0	0.723	3.4	0.68	1.6	0.32	0.32	
22	4.6	0.733	3.7	0.80	0.9	0.20	0.20	
23	5.0	0.744	3.8	0.76	1.2	0.24	0.24	
Cumulativ-	226.2		214 0		1 21 A			0.828
cullurative	330.3		L14.3		164.4			0.010

.

TABLE C.2

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-02

Sample	Sample Volume	Cumulative Pore	Aqueous	Aqueous	Oleic Volume	Oleic	Total	Fractional	Aqueous Polymer	Pressi ^{∆P} 1	Ire Drop ^{ΔP} 2
No.	(m1)	Volume	(m1)	Cut	(m1)	Cut	Cut	Recovery	(ppm)	(psi)	(psi)
1	1.4		1.4	1.00							
2	6.9	0.018	6.9	1.00						22.1	7.50
3	8.3	0.035	8.3	1.00						21.2	5.97
4	8.0	0.054	8.6	1.00						19.8	6.50
5	8.0	0.0/2	8.3	0.97	0.3	0.03	0.04			16.9	5.50
Cumulative	33.8		33.5		0.3			0.0018			
6	4.8	0.083	3.7	0.77	1.1	0.23	0.23			15.7	5.00
7	4.3	0.092	2.7	0.63	1.6	0.37	0.37			10.7	0.00
8	7.7	0.108	4.9	0.64	2.8	0.36	0.36			15.2	3.65
9	8.1	0.126	4.3	0.53	3.8	0.47	0.47			16.0	3.50
10	8.1	0.143	3.9	0.48	4.2	0.52	0.52			16.5	3.46
Cumulative	66.8		53.0		13.9			0.082			
11	8.2	0 160	37	0 45	4 5	0 55	0 55				
12	8.3	0.178	3.5	0.43	4.8	0.55	0.55				
13	8.2	0.195	3.3	0.40	4.9	0.60	0.50				
14	8.3	0.213	3.3	0.40	5.0	0.60	0.60				3 12
15	8.1	0.230	3.1	0.38	5.0	0.62	0.62			19.4	3.50
Cumulative	107.9		69.9		38.0			0.226			
16	8.2	0.248	3.3	0.40	4.9	0.60	0.60				
17	8.1	0.265	3.0	0.37	5.1	0.63	0.63				3 53
18	8.3	0.283	4.0	0.48	4.3	0.52	0.52				0.00
19	8.2	0.300	3.8	0.46	4.4	0.54	0.54				
20	8.2	0.318	3.9	0.48	4.3	0.52	0.52			21.2	5.10
Cumulative	148.9		87.9		61.0			0.362			

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-02

Sample No.	Sample Volume (ml)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	Oleic Cut	Total Oil Cut	Fractional Oil Recovery	Aqueous Polymer Conc. (ppm)	Pressure ^{AP} 1 (psi)	Drop ^{∆P} 2 (psi)
21	8.3	0.335	4.2	0.51	4.1	0.49	0.49				
22	8.2	0.353	4.4	0.54	3.8	0.46	0.46				5.60
23	8.2	0.370	4.7	0.57	3.5	0.43	0.43				
24	8.2	0.388	4.8	0.59	3.4	0.41	0.42				
25	8.2	0.405	4.8	0.59	3.4	0.41	0.42			23.1	5.82
Cumulative	190.0		110.8		79.2			0.470			
26	8.2	0.423	4.9	0.60	3.3	0.40	0.40		7		
27	8.2	0.440	4.9	0.60	3.3	0.40	0.40		•		
28	8.3	0.458	5.0	0.60	3.3	0.40	0.40				
29	8.2	0.475	5.0	0.61	3.2	0.39	0.39				
30	8.1	0.493	4.9	0.60	3.2	0.40	0.40			24.6	6.20
Cumulative	231.0		135.5		95.5			0.568			
31	8.2	0.510	5.0	0.61	3.2	0.39	0.38				
32	8.2	0.525	5.0	0.61	3.2	0.39	0.39				
33	8.3	0.546	5.2	0.63	3.1	0.37	0.37				
34	8.1	0.563	5.2	0.64	2.9	0.36	0.36				
35	8.2	0.580	5.4	0.62	2.8	0.38	0.34			25.8	6.68
Cumulative	272.0		161.3		110.7			0.658			
36*	8.2	0.598	5.6	0.68	2.6	0.32	0.32				
37	8.2	0.615	5.7	0.70	2.5	0.30	0.31		16		
38	8.2	0.633	5.6	0.68	2.6	0.32	0.32		*0		
39	8.3	0.650	5.7	0.69	2.6	0.31	0.31				
40	8.2	0.668	5.6	0.68	2.6	0.32	0.32			27.0	6.88
Cumulative	313.1		189.5		123.6			0.735			

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-02

Sample	Sample Volume	Cumulative Pore	Aqueous Volume	Aqueous	0leic Volume	Oleic	Total 011	Fractional 0il	Aqueous Polymer Conc	Pressure 1	Drop ^{DP} 2
No.	(m1)	Volume	(m1)	Cut	(m1)	Cut	Cut	Recovery	(ppm)	(psi)	(psi)
41	8.2	0.686	5.8	0.71	2.4	0.29	0.29		17		
42	8.2	0.703	5.9	0.72	2.3	0.28	0.28				
43	8.2	0.720	5.8	0.71	2.4	0.29	0.29		40		
44	8.2 9.1	0.738	0.U 5 0	0.73	2.2	0.27	0.27		42	20.10	7 10
40	0.1	0.755	5.9	0.73	2.2	0.27	0.27			28.0	1.10
Cumulative	354.0		218.9		135.1			0.803			
46	8.2	0.773	6.0	0.73	2.2	0.27	0.27				
47	8.2	0.790	6.0	0.73	2.2	0.27	0.27		240		
48	8.2	0.807	6.2	0.76	2.0	0.24	0.24				
49	8.2	0.825	6.2	0.76	2.0	0.24	0.24				
50	8.3	0.843	6.5	0.78	1.8	0.22	0.28			29.1	7.45
Cumulative	395.1		249.8		145.3			0.864			
51	8.3	0.861	6.8	0.82	1.5	0.18	0.18		225		
52	8.3	0.878	6.9	0.83	1.4	0.17	0.17		LLU		
53	8.2	0.896	7.0	0.85	1.2	0.15	0.15				
54	8.3	0.914	7.2	0.87	1.1	0.13	0.13				
55	8.3	0.931	7.2	0.87	1.1	0.13	0.13			30.2	7.69
Cumulative	436.5		284.9	·	151.6			0.901			
56	8.2	0,949	7.4	0.90	0.8	0.10	0.10		420		
57	8.2	0.966	7.0	0.85	1.2	0.15	0.15		120		
58	8.2	0.984	7.6	0.93	0.6	0.07	0.07				
59	8.2	1.002	7.7	0.94	0.5	0.06	0.06				
60	8.4	1.019	7.9	0.94	0.5	0.06	0.06			31.5	7.82
Cumulative	477.7		322.5		155.2			0.921			

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-02

	Comple	Sample	Cumulative	Aqueous	A	01eic	01ete	Total	Fractional	Aqueous Polymer	Pressure ^{AP} 1	e Drop ∆P ₂
	No.	(ml)	Volume	(m1)	Cut	(ml)	Cut	Cut	Recovery	(ppm)	(psi)	(psi)
	61 62 63 64	8.2 8.3 8.3 8.3	1.037 1.054 1.072 1.090	8.1 8.1 8.2 8.3	0.99 0.98 0.99 1.00	0.1 0.2 0.1	0.01 0.02 0.01	0.01 0.02 0.01		740		
Cumulat	65 ive	8.3 519 1	1.108	8.3	1.00	155 6			0.025		32.0	7.82
	66 67 68 69 70	8.3 8.3 8.4 8.3 8.2	1.126 1.143 1.161 1.179	8.3 8.3 8.4 8.3	$1.00 \\ $	155.0			0.929	815	22.6	7 02
Cumulat	ive	560.6	1.150	405.0	1.00	155.6			0.925		52.0	7.05
	71 72 73 74 75	8.1 8.4 8.3 8.4 8.3	1.214 1.232 1.249 1.267 1.285	8.1 8.4 8.3 8.4 8.3	1.00 1.00 1.00 1.00 1.00					910	33.0	7.82
Cumulat	ive	602.1		446.5		155.6			0.925			
	76 77 78 79 80	8.3 8.3 8.3 8.3 8.2	1.302 1.320 1.338 1.356 1.373	8.3 8.3 8.3 8.3 8.2	1.00 1.00 1.00 1.00 1.00					840	33.5	8.28
Cumulat	ive	643.5		487.9		155.6			0.925			

(to be continued)

1. A. M.

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-02

	Sample No.	Sample Volume (ml)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	01eic Cut	Total Oil Cut	Fractional Oil Recovery	Aqueous Polymer Conc. (ppm)	Pressure ^{ΔP} 1 (psi)	^{ΔP} 2 (psi)	
	81 82 83	8.2 8.3 8.3	1.391 1.408 1.426	8.2 8.3 8.3	$1.00 \\ 1.00 \\ 1.00$					910			
	84 85	8.3 8.3	1.444 1.461	8.3 8.3	1.00 1.00						34.0	7.83	
Cumulat	ive	684.9		529.3		155.6			0.925				
	86 87 88	8.2 8.3 8.3	1.479 1.497 1.515	8.2 8.3 8.3	$1.00 \\ 1.00 \\ 1.00$					875			
	89 90	8.3 8.2	1.532 1.549	8.3 8.2	$1.00 \\ 1.00$						34.0	7.83	
Cumulat	ive	726.2		570.6		155.6			0.925				
	91 92 93 94 95	8.2 8.2 8.1 8.3 8.2	1.567 1.585 1.602 1.620 1.637	8.2 8.2 8.1 8.3 8.2	$1.00 \\ 1.00 \\ 1.00 \\ 1.00 \\ 1.00 \\ 1.00 $					955	34.6	7.90	
Cumulat	ive	767.2		611.6		155.6			0.925		0110	,	
	96 97	8.2 8.2	1.655 1.672	8.2 8.2	1.00 1.00					945			
Cumulat	ive	783.6		628.0		155.6			0.925				

* Trace Amount of Middle Phase Was Observed for Samples 36 Through 57.

TABLE C.3a

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-05 Produced Sample Volumes and Cuts

Sample No.	Sample Volume (ml)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	Oleic Cut
1 2	8.4 8.4	0.018	8.4 8.4	1.00		
3 4 5	8.4 8.3 7.4	0.054 0.069 0.088	8.4 7.2 5.2	1.00 0.87 0.70	1.1 2.2	0.13 0.30
Cumulative	40.9		37.6		3.3	
6 7 8 9 10	4.7 6.9 7.1 7.1 7.1	0.098 0.112 0.128 0.143 0.158	3.1 4.5 4.9 4.7 4.6	0.66 0.65 0.69 0.66 0.65	1.6 2.4 2.2 2.4 2.5	0.34 0.35 0.31 0.34 0.35
Cumulative	73.8		59.4		14.4	
11 12 13 14 15	7.0 6.8 6.8 6.7 6.4	0.173 0.188 0.202 0.216 0.230	4.2 4.0 4.0 3.8 3.7	0.60 0.59 0.59 0.57 0.58	2.8 2.8 2.9 2.7	0.40 0.41 0.41 0.43 0.42
Cumulative	107.5		79.1		28.4	
16 17 18 19 20	6.8 6.8 6.3 2.2 8.3	0.245 0.260 0.279 0.284 0.302	2.8 2.8 3.8 0.8 3.5	0.41 0.41 0.60 0.36 0.42	4.0 4.0 2.5 1.4 4.8	0.59 0.59 0.40 0.64 0.58
Cumulative	137.9		92.8		45.1	

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-05 Produced Sample Volumes and Cuts

	Sample No.	Sample Volume (ml)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	Oleic Cut
	21	8.0	0.311	4.8	0.60	3.2	0.40
	22	7.9	0.328	4.6	0.58	3.3	0.42
	23	7.8	0.345	4.5	0.58	3.3	0.42
	24	7.9	0.361	4.6	0.58	3.3	0.42
	25	8.0	0.379	4.6	0.58	3.4	0.42
Cumulat	ive	177.5		115.9		61.6	
	26	7.7	0.395	4.2	0.55	3.5	0.45
	27	7.9	0.412	4.4	0.56	3.5	0.44
	28	7.9	0.429	4.5	0.57	3.4	0.43
	29	7.7	0.445	4.4	0.57	3.3	0.43
	30	7.9	0.462	4.5	0.57	3.4	0.43
Cumulat	ive	216.6		137.9		78.7	
	31	6.9	0.477	3.9	0.57	3.0	0.43
	32	8.0	0.494	4.9	0.61	3.1	0.39
	33	7.6	0.510	4.3	0.57	3.3	0.43
	34	7.6	0.526	4.2	0.55	3.4	0.45
	35	7.4	0.542	4.1	0.55	3.3	0.45
Cumulat	ive	254.1		159.3		94.8	
	36	7.3	0.558	4.1	0.56	3.2	0.44
	37	7.5	0.574	4.3	0.57	3.2	0.43
	38	7.3	0.589	4.1	0.56	3.2	0.44
	39	6.8	0.604	3.8	0.56	3.0	0.44
	40	6.0	0.617	2.9	0.48	3.1	0.52
Cumu1at	ive	289.0		178.5		110.5	

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-05 Produced Sample Volume and Cuts

Sample No.	Sample Volume (ml)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	Oleic Cut
41	4.7	0.629	1.8	0.32	3.9	0.68
43	4.8	0.650	3.1	0.55	1 7	0.47
44	4.6	0.660	3.1	0.67	1.5	0.33
45	4.5	0,669	3.2	0.71	1.1	0.25
Cumulative	313.7		192.7		120.8	
46	4.6	0.679	3.3	0.72	1.0	0.22
47	4.6	0,689	3.3	0.72	1.0	0.22
48	1.4	0.692	1.0	0.71	0.4	0.29
49	6.2	0.705	4.3	0.69	1.4	0.23
50	6.2	0,719	4.4	0.71	1.3	0.21
Cumulative	336.7		209.0		125.9	
51	6.2	0,732	4.4	0.71	1.2	0.19
52	5.9	0.744	4.3	0.73	1.0	0.17
53	8.8	0,763	6.3	0.72	1.7	0.19
54	8.7	0,782	6.3	0.72	1.6	0.18
55	8.8	0.800	6.5	0.74	1.5	0.17
Cumulative	375.1		236.8		132.9	
56	8.9	0,819	6.8	0.76	1.4	0.15
57	8.9	0,838	7.1	0.80	1.2	0.13
58	8.8	0.857	7.8	0.89	1.0	0.11
59	8.7	0,876	8.0	0.92	0.7	0.08
60	8.9	0,895	8.4	0.94	0.5	0.06
Cumulative	419.3		274.9		137.7	

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-05 Produced Sample Volumes and Cuts

	Sample	Cumulative	Aqueous		01eic	
Sample	Volume	Pore	Volume	Aqueous	Volume	01eic
No.	(m1)	Volume	(m1)	Cut	(m1)	Cut
61	8.9	0.914	8.7	0.98	0.2	0.02
62	9.0	0.933	8.8	0.98	0.2	0.02
63	9.3	0.953	9.2	0.99	0.1	0 01
64	9.5	0.973	9.4	0 99	0 1	0 01
65	9.8	0.994	9.8	0.55	0.1	0.01
Cumulative	465.8		320.8		138.3	
66	9.7	1.015	9.7			
67	10.1	1.036	10.1			
68	10.2	1.058	10.2			
69	8.7	1.077	8.7			
70	8.6	1.095	8.6			
Cumulative	513.1		368.1		138.3	
71	9.8	1.116	9.8			
72	10.5	1.138	10.5			
73	10.4	1.160	10.4			
74	8.8	1.179	8.8			
75	9.0	1.198	9.0			
Cumulative	561.6		416.6		138.3	
76	9.0	1.218	9.0			
77	9.0	1.237	9.0			
78	9.0	1.256	9.0			
79	9.1	1.275	9.1			
80	9.0	1.295	9.0			
Cumulative	606.7		461.7		138.3	

440

(to be continued)

.....

. . . . **.** .

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-05 Produced Sample Volumes and Cuts

Samp No	Sample le Volume . (ml)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	Oleic Cut
81	9.3	1.315	9.3			
82	9.4	1.335	9.4		•	
83	9.3	1.354	9.3			
84	9.1	1.374	9.1			
85	9.4	1.394	9.4			
Cumulative	653.2		508.2		138.3	
86	9.4	1,414	9.4			
87	9.6	1.434	9.6			
88	9.7	1.455	9.7			
89	10.0	1.477	10.0			
90	10.0	1,498	10.0			
Cumulative	701.9		556.9		138.3	

TABLE C.3 b

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-05

Sample No.	Microemulsion Volume (ml)	Microemulsion Cut	Total 011 Cut	Fractional Oil Recovery	Aqueous Polymer Conc. (ppm)	Pressur ^{∆P} 1(ps	re Drop ^{AP} 2 si)
1 2 3 4 5			0.13 0.30	• •		4.40 4.00 3.80 3.60 3.40	1.10 1.06 1.04 1.94 0.88
6 7 8 9 10			0.34 0.35 0.31 0.34 0.35	0.09		3.40 3.80	0.88 0.90 0.90 0.88 0.84
11 12 13 14 15			0.40 0.41 0.41 0.43 0.42	0.77		3.81 3.82 4.10 4.20 4.40	0.80 0.74 0.68 0.66 0.64
16 17 18 19 20			0.59 0.59 0.40 0.64 0.58	0.28		4.40 4.40 4.41 4.60 4.40	0.62 0.52 0.48 0.46 0.46

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-05

Sample No.	Microemulsion Volume (ml)	Microemulsion Cut	Total Oil Cut	Fractional 011 Recovery	Aqueous Polymer Conc. (ppm)	$\frac{\Delta P}{1} 1 $
21 22 23 24 25			0.40 0.42 0.42 0.42 0.42	0.38	0	4.40 0.44 4.40 0.40 4.39 0.40 4.38 0.44 4.35 0.44
26 27 28 29 30			0.45 0.44 0.43 0.43 0.43	0.49 ·		4.35 0.48 4.40 0.54 4.41 0.60 4.50 0.70 4.60 0.78
31 32 33 34 35			0.43 0.39 0.43 0.45 0.45	0.59	0	4.71 4.55 4.56 4.45 1.00
36 37 38 39 40			0.44 0.43 0.44 0.44 0.52	0.69		4.00 4.40 4.40 4.30 4.10 1.12

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-05

Sample No.	Microemulsion Volume (ml)	Microemulsion Cut	Total Oil Cut	Fractional Oil Recovery	Aqueous Polymer Conc. (ppm)	Pressure Drop ^{AP} 1(psi) ^{AP} 2
41 42 43 44 45	0.2	0.04	0.68 0.47 0.35 0.33 0.25	0.75	180	3.95 3.80 1.14 3.60 1.08 3.60 1.04 3.60 1.00
Cumulative	0.2					
46 47 48 49	0.3 0.3 Trace 0.5	0.06 0.06 0.08	0.22 0.22 0.29 0.23	0.70	•••	
50 Cumulativo	0.5	0.08	0.21	0.78	200	3.60 0.90
51 52 53 54 55 Cumulative	0.6 0.6 0.8 0.8 0.8 0.8 5.4	0.10 0.10 0.09 0.10 0.09	0.19 0.17 0.19 0.18 0.17	0.83	250	3.61 0.78
56 57 58 59 60 Cumulative	0.7 0.6 Trace Trace Trace 6.7	0.09 0.07	0.15 0.13 0.11 0.08 0.06	0.86	760 1080	3.61 0.70 3.20 0.68

(to be continued)
TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-05

Sample No.	Microemulsion Volume (ml)	Microemulsion Cut	Total Oil Cut	Fractional 011 Recovery	Aqueous Polymer Conc. (ppm)	Pressur ^{ΔP} 1(ps	re Drop ^{AP} 2 si)	
61 62 63 64 65	Trace		0.02 0.02 0.01 0.01	0.86	1370	2.70	0.61	
Cumulative	6.7							
66 67 68 69					980			
70				0.86		2.40	0.50	
Cumulative	6.7							
71 72 73 74	· ·				970	2 10	0.00	
75 Cumulative	6.7			0.86	920	.2.10	0.36	
76 77 78 79					925			
80				0.86	880	1.70	0.30	
Cumulative	6.7			•				

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-05

.

-

Sample No.	Microemulsion Volume (ml)	Microemulsion Cut	Total Oil Cut	Fractional Oil Recovery	Aqueous Polymer Conc. (ppm)	Pressur ^{∆P} 1(ps	e Drop ∆ ^P 2 si)	
81 82								
83								
84				0.00	570	1 50	0.00	
85				0.80	570	1.50	0.20	
Cumulative	6.7							
86								
87					550			
88								
89								
90				0.86		1.30	0.24	
Cumulative	6.7							

TABLE C.4a

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-06 Produced Sample Volumes and Cuts

Samı Ne	ple o.	Sample Volume (ml)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	Oleic Cut	Microemulsion Volume (ml)	Microemulsion Cut
1	1	6.5	0.013	6.5	1.00				
2	2	8.4	0.030	8.4	1.00				
3	3	8.4	0.046	8.4	1.00				
L.	4	8.1	0.062	8.1	1.00				
į	5	7.9	0.078	7.9	1.00				
Cumulative		39.3		39.3		0.0			
e	6	8.0	0.094	8.0	1.00				
-	7	8.1	0.110	8.1	1.00				
8	8	8.1	0.126	8.1	1.00				
Q	9	8.1	0.142	8.1	1.00				
10	D	7.8	0.157	7.8	1.00				
Cumulative		79.4		79.4		0.0			
11	1	7.6	0.172	7.6	1.00				
1:	2	7.9	0.188	7.9	1.00				
13	3	8.0	0.203	8.0	1.00				
14	4	7.9	0.219	7.9	1.00				
1	5	8.0	0.235	7.4	0.93	0.6	0.07		
Cumulative		118.8		118.2		0.6			
16	6	8.1	0.251	2.9	0.36	5.2	0.64		
1	7	8.2	0.267	2.9	0.35	5.3	0.65		
18	8	8.2	0.283	2.9	0.35	5.3	0.65		
19	9	8.2	0.299	3.1	0.38	5.1	0.62		
20	Ó	8.2	0.316	3.2	0.39	5.0	0.61		
Cumulative		159.71		133.2		26.5			

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-06 Produced Sample Volumes and Cuts

Samp No	Sample le Volume . (m1)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	Oleic Cut	Microemulsion Volume (ml)	Microemulsion Cut
21	8.2	0.332	3.3	0.40	4.9	0.60		
22	8.2	0.348	3.3	0.40	4.9	0.60		
23	8.2	0.364	3.5	0.43	4.7	0.57		
24	8.1	0.380	3.6	0.44	4.5	0.56		
25	8.2	0.396	3.7	0.45	4.5	0.55		
Cumulative	200.6		150.6		50.0			
26	8.1	0.412	3.9	0.48	4.2	0.52		
27	8.2	0.429	4.0	0.48	4.2	0.52		
28	8.1	0.445	4.0	0.49	4.1	0.51		•
29	8.3	0.461	4.3	0.52	4.0	0.48		
30	8.1	0.477	4.2	0.52	3.9	0.48		
Cumulative	241.4		171.0		70.4			
31	8.1	0.493	4.4	0.54	3.7	0.46		
32	8.1	0.509	4.4	0.54	3.7	0.46		
33	8.2	0.525	4.6	0.56	3.6	0.44		
34	8.1	0.541	4.7	0.58	3.4	0.42		
35	8.1	0.557	4.6	0.57	3.5	0.43		
Cumulative	282.0		193.7		88,3			
36	8.1	0.573	4.7	0.58	3.4	0.42		
37	7.7	0.588	4.6	0.59	3.1	0.41		
38	8.0	0.604	4.7	0.59	3.3	0.41		
39	8.2	0.620	4.9	0.60	3.3	0.40		
40	8.1	0.637	4.7	0.58	3.4	0.42		
Cumulative	322.1		217.3		104.8			

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-06 Produced Sample Volumes and Cuts

Sa	mple No.	Sample Volume (ml)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	Oleic Cut	Microemulsion Volume (ml)	Microemulsion Cut
	41	8.2	0.653	4.7	0.57	3.5	0.43		
	42	8.2	0.669	4.6	0.56	3.6	0.44		
	43	8.4	0.686	4.5	0.54	3.9	0.46		
	44	8.3	0.702	5.1	0.61	3.2	0.39		
	45	8.4	01701	5.2	0.62	3.2	0.38		
Cumulativ	е	363.6	0.719	241.4		120.1			
	46	8.3	0.735	6.2	0.75	0.2	0.02	1.9	0.23
	47	8.2	0.751	6.3	0.77	0.2	0.01	1.7	0.22
	48	8.2	0.767	6.3	0.77	0.2	0.01	1.7	0.22
	49	8.2	0.784	6.4		0.3		1.5	
:	50	8.3	0.800	6.3	0.78	1.2	0.14	0.8	0.08
Cumulativ	е	404.8		272.9		124.3		7.6	
	51	8.1	0,816	6.2	0.77	1.1	0.14	0.8	0.09
	52	8.1	0.832	6.1	0.75	1.2	0.15	0.8	0.10
	53	8.1	0.848	5.9	0.73	1.2	0.15	1.0	0.12
	54	8.1	0.864	6.1	0.75	1.1	0.14	0.9	0.11
	55	8.1	0.880	6.0	0.74	1.0	0.12	1.1	0.14
Cumulativ	е	445.3		303.2		129.9		12.2	
	56	8.0	0.896	6.0	0.74	1.0	0.13	1.0	0.13
	57	8.1	0.912	6.2	0.77	1.0	0.12	0.9	0.11
	58	8.1	0.928	5.8	0.72	0.7	0.08	1.6	0.20
	59	8.1	0.944	5.8	0.72	0.5	0.06	1.8	0.22
	60	8.2	0.960	7,8	0,95	0.4	0.05	Trace	
Cumulativ	'e	485.8		334.8		133.5		17.5	

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-06 Produced Sample Volumes and Cuts

S	ample No.	Sample Volume (ml)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	Oleic Cut	Microemulsion Volume (ml)	Microemulsion Cut
	61	8.3	0.976	8.1	0.98	0.2	0.02	Trace	
	62	8.4	0.993	8.3	0.99	0.1	0.01	Trace	
	63	8.5	1.010	8.4	0.99	0.1	0.01	Trace	
	64	8.3	1.026	8.2	0.99	0.1	0.01	Trace	
	65	8.1	1.042	8.0	0.99	0.1	0.01	Trace	
Cumulat	ive	527.4		375.8		134.1	•	17.5	
	66	8.3	1.058	8.3	1.0	Trace	0.0		
	67	6.9	1.072	6.9	1.0	Trace	0.0		
	68	7.4	1.087	7.4	1.0	Trace	0.0		
	69	8.5	1.104	8.5	1.0	Trace	0.0		
	70	8.5	1.120	8.5	1.0	Trace	0.0		
Cumulat	ive	567.0		415.4		134.1		17.5	
	71	8.3	1,137	8.3	1.0		0.0		
	72	8.2	1,153	8.2	1.0		0.0		
	73	8.2	1.169	8.2	1.0		0.0		
	74	8.3	1,186	8.3	1.0		0.0		
	75	8.2	1.202	8,2	1.0		0.0		
Cumulat	ive	608.2		456.6		134,1		17.5	
•	76	8.2	1.218	8.2	1.0		0.0		
	77	8.1	1,234	8.1	1.0		0.0		
	78	8.1	1.250	8.1	1.0		0.0		
	79	8.2	1,266	8,2	1.0		0.0		
	80	8.1	1.282	8.1	1.0		0.0		
Cumulat	ive	648.9		497.3		134.1		17.5	

(to be continued)

.

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-06 Produced Sample Volumes and Cuts

	Sample No.	Sample Volume (ml)	Cumulative Pore Volume	Aqueous Volume (ml)	Aqueous Cut	Oleic Volume (ml)	Oleic Cut	Microemulsion Volume (ml)	Microemulsion Cut
	81	8.1	1.298	8.1	1.0		0.0		
	82	.8.2	1.314	8.2	1.0		0.0		
	83	8.2	1.331	8.2	1.0		0.0		
	84	/.9	1.346	7.9	1.0		0.0		
	85	8.3	1.363	8.3	1.0		0.0		
Cumulat	ive	689.6		538.0		134.1		17.5	
	86	8.4	1.379	8.4	1.0		กัก		
	87	8.7	1.396	8.7	1.0	•	0.0		
	88	8.5	1.413	8.5	1.0		0.0	•	
	89	8.2	1.429	8.2	1.0		0.0		
	90	8.1	1.446	8.1	1.0		0.0		
Cumulat	tive	731.5		579.9		134.1		17.5	
	91	8.0	1.461	8.0	1.0		0.0		
	92	8.5	1.478	8.5	1.0		0,0		
	93	8.4	1.495	8.4	1.0		0.0		
	94	2.7	1,500	2.7	1.0		0.0		
Cumulat	tive	759.1		607.5		134.1		17.5	

TABLE C.4b

.

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-06 Sample Composition and Pressure Drop

			Aqueous		Pressure Drop		
Sample No.	ample Oil No. Cut	tal Fractional Polymer il Oil Conc. ut Recovery (ppm)	Sodium Conc. (ppm)	Calcium Conc. (ppm)	Magnesium Conc. (ppm)	∆P <mark>1</mark> (psi)	
1 2 3 4 5							3.2 3.8 4.4 5.0 5.6
6 7 8 9 10				7818	24	· 5	6.2 6.6 7.0 7.5 7.9
11 12 13 14 15	0.08						8.2 8.4 8.7 9.1 9.1
16 17 18 19 20	0.64 0.65 0.65 0.62 0.61	0.136					9.1 9.0 9.0 8.9 8.8

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-06 Sample Composition and Pressure Drop

			Aqueous	Pressure Drop			
Sample No.	Total 0il Cut	Fractional Oil Recovery	Polymer Conc. (ppm)	Sodium Conc. (ppm)	Calcium Conc. (ppm)	Magnesium Conc. (ppm)	^{ΔP} 1 (psi)
	0 60		•				
21	0.00						0.0
23	0.57						87
24	0.55						87
25	0.55	0.256					8.7
	0.50						
26	0.52						8.7
27	0.51						8./
20	0.50						8./
29	0.40	0.360		4048	1.8	à	8.8
30	0.40	0.000		1010	14	Ζ	0.0
31	0.46						
32	0.46						
33	0.44						
34	0.42	0 450		4707			
35	0.43	0.452		4/3/	15	2	9.5
36	0.42						
37	0.40						
38	0.41						
39	0.40						
40	0 42	0.536		3482	11	1	10.6

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-06 Sample Composition and Pressure Drop

			Aqueous		Pressure Drop		
Samp1e	Total 0il	Fractional Oil	Polymer Conc.	Sodium Conc.	Calcium Conc.	Magnesium Conc.	ΔΡ1
No.	Cut	Recovery	(ppm)	(ppm)	(ppm)	(ppm)	(psi)
41	0.43		34				
42	0.44						
43	0.46		205				
44 45	0.39	0.625	200				11.0
	0.00			7750			
40 117	0.23		655	, 7758	34	3	
48	0.18		000	5834	26	9	
49	0.17		775	5556	30	5	
50	0.17	0.664		4840	23	6	11.2
51	0.17		830				
52	0.19						
53	0.17		840	4100	00	•	
54 55	0.17	0.709		4188	26	3	11.7
56 57	0.16 0.15		1050	2649	32	6	
58 50	0.11			2617	26	6	
60	0.06	0.727		3882	25	4	12.2

(to be continued)

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-06 Sample Composition and Pressure Drop

			Aqueous Total				Pressure Drop		
Sample No.	Total Oil Cut	Fractional Oil Recovery	Polymer Conc. (ppm)	Sodium Conc. (ppm)	Calcium Conc. (ppm)	Magnesium Conc. (ppm)	ΔP ₁ (psi)		
61 62 63 64 65	0.015 0.012 0.012 0.012 0.012 0.013	0.730	1300	2785	7	4	12.8		
66 67 68 69 70		0.730		2018	5	0.8	13.2		
71 72 73 74 75		0.730	1400	2519	4	2	13.4		
76 77 78 79 80		0.730		2338	3	1	13.7		

(to be continued)

455

ž

- - - -

TABULATED RESULTS OF OIL RECOVERY EXPERIMENT MPF-06 Sample Composition and Pressure Drop

			Aqueous		Total		Pressure Drop
Sample No.	Total Oil Cut	Fractional Oil Recovery	Polymer Conc. (ppm)	Sodium Conc. (ppm)	Calcium Conc. (ppm)	Magnesium Conc. (ppm)	ΔP ₁ (psi)
81 82 83			1460				
84 85		0.730					14.0
86 87 88							
89 90		0.730		2134	6	2	14.0
91 92			1480				
93 94		0.730					14.2

APPENDIX D

CALCULATION OF THE CONTINUOUSLY GRADED DRIVE USED BY HEDGES AND GLINSMANN

Hedges and Glinsmann used a continuously graded drive for their oil recovery experiment no. 24212-1142. In order to simulate this graded drive, the change of polymer concentration over time must be known. As mentioned in the experimental work section, this graded drive was achieved by continuous dilution of a 0.5 P.V., 2250 ppm polymer solution in a well-mixed container. By material balance over a small time change and assuming density equals one,

$$(qC_{in} - qC_{out}) dt = V dC$$
 (D-1)

where, $q = volumetric flow rate, cm^3/sec$ $V = volume of container, cm^3$ C = polymer concentration in container, ppm C_{in} = injected polymer concentration, ppm C_{out} = produced polymer concentration, ppm.

Knowing that,

$$C_{in} = 0$$

 $C_{out} = C$

Eq, (D-1) becomes,

$$-qC dt = V dC$$

or
$$\frac{-q}{V} dt = \frac{dC}{C}$$
 (D-2)

By integration from time zero to time t,

$$-\int_{0}^{t} \frac{q}{V} dt = \int_{C_{0}}^{C} \frac{dC}{C}$$

or
$$-\int_{0}^{t} \frac{q}{V} dt = \ln \frac{C}{C_{0}}$$
 (D-3)

Define a dimensionless time t_D ,

$$t_{\rm D} = \int_0^t \frac{q}{AL\phi} dt \qquad (D-4)$$

where, t_D = dimensionless time, P.V. $AL\phi$ = total pure volume, cm³

Since, V = 0.5 P.V., therefore eq. (D-4) becomes,

$$2t_{\rm D} = \int_0^t \frac{q}{V} dt \qquad (D-5)$$

Substituting eq. (D-5) in eq. (D-3)

$$-2t_{D} = \ln \frac{C}{C_{0}}$$

or $C = C_{0}e^{-2t_{D}}$ (D-6)

At $t_D = 0$, C = 2250 ppm, therefore, $C_0 = 2250$ ppm, eq. (D-6) becomes,

$$C = 2250 e^{-2t}D$$
 (D-7)

The polymer concentration was plotted against dimensionless time in Figure 4.1 using eq. (D-7). The calculated values are listed below:

t _D (P.V.)	C(ppm)
0.0	2250
0.1	1842
0.2	1508
0.3	1235
0.4	1010
0.5	828
0.75	502
1.0	304
1.25	185
1.5	112
2.0	41
2.5	15
3.0	6

REFERENCE

REFERENCE

- 1. Aziz, Khalid and Settari, Antonin; <u>Petroleum Reservoir Simula-</u> tion, Applied Science Publishers Ltd., 1979.
- Brashear, J.P. and Kuushraa, V.A.; "The Potential and Economics of Enhanced Oil Recovery," <u>J. Pet. Tech.</u>, Sept. 1978, pp. 1231– 1239.
- 3. Coats, K.H.; "Use and Misuse of Reservoir Simulation Models," SPE Reprint Series No. 11, Numerical Simulation, pp. 183-190.
- 4. Crichlow, Henry B.; Modern Reservoir Engineering A Simulation Approach, Prentice-Hall, Inc., 1977.
- 5. <u>Enhanced Oil Recovery</u>, prepared by National Petroleum Council, Dec. 1976.
- 6. Enhanced Oil Recovery Potential in the United States, Office of Technology Assessment, Congress of the United States, 1978.
- 7. <u>Fundamentals of Enhanced Oil Recovery</u>, H.K. van Poollen and Associates, Inc., PennWell Books, 1980.
- 8. Geffen, T.M.; "Improved Oil Recovery Could Help Ease Energy Shortage," World Oil 177, No. 5, 1973, p. 84.
- 9. Gogarty, W.B.; "Oil Recovery with Surfactants: History and a Current Appraisal," <u>Improved Oil Recovery by Surfactant and Polymer Flooding</u>, edited by Shah, D.O. and Schechter, R.S., Academic Press, 1976, pp. 27-54.
- Gogarty, W.B.; "Micellar/Polymer Flooding An Overview," J. Pet. Tech., Aug. 1978, pp. 1089-1101.
- 11. Herbeck, E.F.; Heintz, R.C. and Hastings, J.R.; <u>Fundamentals</u> of <u>Tertiary Oil Recovery</u>, Energy Communications, a division of HBJ, 1977.
- 12. Mathney, S.L. Jr.; "EOR Methods Help Ultimate Recovery," Oil & Gas J., March 31, 1980, pp. 79-124.
- 13. Odeh, A.S.; "Reservoir Simulation What Is It?" J. Pet. Tech., Nov. 1969, pp. 1383-1388.

- 14. Peaceman, Donald W.; Fundamentals of Numerical Reservoir Simulation, Elsevier Scientific Publishing Company, 1977.
- 15. Poettman, F.H. and Hanse, W.R.; "Micellar-Polymer Screening Criteria and Design," SPE 7068, presented at the 5th Symposium on Improved Oil Recovery, Tulsa, Oklahoma, April 16-19, 1978.
- 16. Salager, J.L.; Morgan, J.C.; Schechter, R.S.; Wade, W.H. and Vasquez E.; "Optimum Formulation of Surfactant/Water/Oil Systems for Minimum Interfacial Tension or Phase Behavior," Soc. Pet. Eng. J., April 1979, pp. 107-115.
- 17. Sharp, J.M.; "The Potential of Enhanced Oil Recovery Processes," SPE 5557, presented at the 50th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Dallas, Texas, Sept. 28-Oct. 1, 1975.
- 18. Thomas, G.W.; <u>Principles of Hydrocarbon Reservoir Simulation</u>, TAPIR, University of Trondheim, Norway, 1977.
- 19. Wilson, L.A. Jr.; "Physico-Chemical Environment of Petroleum Reservoirs in Relation to Oil Recovery Systems," <u>Improved Oil</u> <u>Recovery by Surfactant and Polymer Flooding</u>, edited by Shah, D.O. and Schechter, R.S., Academic Press, 1976, pp. 1-26.
- 20. Ayers, R.C. Jr.; "Two-Bank Miscible Tertiary Oil Recovery Process," SPE 3801, prepared for the SPE-AIME Improved Oil Recovery Symposium, Tulsa, Oklahoma, April 1972.
- Bourrel, M.; Salager, J.L.; Schechter, R.S. and Wade, W.H.;
 "A Correlation for Phase Behavior of Nonionic Surfactants,"
 J. Colloid and Interface Science, June 1980, p. 451.
- 22. Cayias, J.L.; Schechter, R.S. and Wade, W.H.; "The Measurement of Low Interfacial Tension via the Spinning Drop Technique," <u>Adsorption at Interfaces</u>, ACS Symposium Series, No. 8, 1975, pp. 234-248.
- Cayias, J.L.; Hayes, M.E.; Schechter, R.S. and Wade, W.H.; "Surfactant Aging: A Possible Detriment to Tertiary Oil Recovery," J. Pet. Tech., Sept. 1976, p. 985.
- 24. Cayias, J.L.; Schechter, R.S. and Wade, W.H.; "Modeling Crude Oils for Low Interfacial Tension," <u>Soc. Pet. Eng. J.</u>, Dec. 1976, pp. 351-357.

- 25. Davis, J.A. Jr.; Gogarty, W.B.; Jones, S.C. and Tosch, W.C.; "Oil Recovery Using Micellar Solutions," API Drilling and Production Practices, 1968, pp. 261-272.
- 26. Davis, J.A. Jr.; "Maraflood Process A New Oil Recovery Method," <u>Producers Monthly</u>, Feb. 1968.
- Davis, J.A. Jr. and Jones, S.C.; "Displacement Mechanisms of Micellar Solutions," <u>J. Pet. Tech.</u>, Dec. 1968, pp. 1415-1428.
- 28. Doe, P.H.; El-Emary, M.M.; Wade, W.H. and Schechter, R.S.; "The Influence of Surfactant Structure on Low Interfacial Tensions," <u>Chemistry of Oil Recovery</u>, edited by Robert T. Johansen and Robert L. Berg, ACS Symposium Series 91, 1979, pp. 17-34.
- 29. Gale, W.W. and Sandvik, E.I.; "Tertiary Surfactant Flooding: Petroleum Sulfonate Composition - Efficiency Studies," Soc. Pet. Eng. J. 13, No. 4, 1973, pp. 191-199.
- 30. Glinsmann, Gilbert R.; "Surfactantflooding with Microemulsions Formed In-Situ - Effect of Oil Characteristic," SPE 8326, presented at the 54th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Las Vegas, Nevada, Sept. 23-26, 1979.
- 31. Gogarty, W.B.; Meabon, H.P. and Milton, H.W.; "Mobility Control Design for Miscible Type Waterfloods Using Micellar Solutions," J. Pet. Tech., Feb. 1970, pp. 141-147.
- 32. Gogarty, W.B. and Surkalo, H.; "A Field Test of Micellar Solution Flooding," J. Pet. Tech., Sept. 1972, pp. 1161-1169.
- 33. Gogarty, W.B. and Tosch, W.C.; "Miscible-Type Waterflooding: Oil Recovery with Micellar Solutions," J. Pet. Tech., Dec. 1968, pp. 1407-1414.
- 34. Graciaa, A.; Fortney, L.N.; Schechter, R.S. Wade, W.H. and Yiv, S.; "Criteria for Structuring Surfactants to Maximize Solubilization of Oil and Water I: Commercial Non-Ionics," SPE 9815, presented at the Second Joint SPE/DOE Symposium on Enhanced Oil Recovery, Tulsa, Oklahoma, April 5-8, 1981.
- 35. Gupta, S.P. and Trushenski, S.P.; "Micellar Flooding The Propagation of the Polymer Mobility Buffer Bank," <u>Soc. Pet.</u> <u>Eng. J.</u>, Feb. 1978, pp. 5-12.

- 36. Gupta, Surendra P. and Trunshenski, Scott P.; "Micellar Flooding - Compositional Effects on Oil Displacement," <u>Soc. Pet. Eng. J.</u>, April 1979, pp. 116-128.
- 37. Gupta, Surendra, P.; "Compositional Effects on Displacement Mechanisms of the Micellar Fluid Injected in the Sloss Field Test," SPE 8827, presented at the First Joint SPE/DOE Symposium on Enhanced Oil Recovery, Tulsa, Oklahoma, April 20-23, 1980.
- 38. Gupta, S.P.; "Dispersive Mixing Effects on the Sloss Field Micellar System," SPE 9782, presented at the Second Joint SPE/DOE Symposium on Enhanced Oil Recovery, Tulsa, Oklahoma, April 5-8, 1981.
- Healy, R.N.; Reed, R.L. and Carpenter, C.W.; "A Laboratory Study of Microemulsion Flooding," <u>Soc. Pet. Eng. J.</u>, Feb. 1975, pp. 87-100.
- 40. Healy, R.N.; Reed, R.L. and Stenmark, D.G.; "Multiphase Microemulsion Systems," <u>Soc. Pet. Eng. J.</u>, June 1976, pp. 147-160.
- 41. Healy, R.N. and Reed, R.L.; "Immiscible Microemulsion Flooding," Soc. Pet. Eng. J., April 1977, pp. 129-139.
- 42. Hedges, James H. and Glinsmann, Gilbert R.; "Compositional Effects on Surfactantflood Optimization," SPE 8324, presented at the 54th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Las Vegas, Nevada, Sept. 23-26, 1979.
- 43. Hirasaki, George J.; van Domselaar, Hans R. and Nelson, Richard C; "Evaluation of the Salinity Gradient Concept in Surfactant Flooding," SPE 8825, presented at the First Joint SPE/DOE Symposium on Enhanced Oil Recovery, Tulsa, Oklahoma, April 20-23, 1980.
- 44. Holm, L.W. and Robertson, S.D.; "Improved Micellar-Polymer Flooding with High pH Chemical," SPE 7583, presented at the 53rd Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Houston, Texas, Oct. 1-3, 1978.
- 45. Holm, L.W.; "Soluble Oils for Improved Oil Recovery," <u>Improved</u> <u>Oil Recovery by Surfactant and Polymer Flooding</u>, edited by Shah, D.O. and Schechter, R.S., Academic Press, 1977, pp. 453-485.

- 46. Holm, L.W.; "Correlation of Oleic and Aqueous Micellar Process for Tertiary Oil Recovery," SPE 7066, presented at the 5th Symposium on Improved Oil Recovery, Tulsa, Oklahoma, April 16-19, 1978.
- 47. Jones, S.C. and Dreher, K.D.; "Cosurfactants in Micellar Systems Used for Tertiary Oil Recovery," <u>Soc. Pet. Eng. J.</u>, June 1976, pp. 161-167.
- 48. Morgan, J.C.; Schechter, R.S. and Wade, W.H.; "Recent Advances in the Study of Low Interfacial Tensions," <u>Improved Oil</u> <u>Recovery by Surfactant and Polymer Flooding</u>, edited by Shah, <u>D.O. and Schechter</u>, R.S.; Academic Press, 1977, pp. 101-118.
- 49. Nelson, R.C. and Pope, G.A.; "Phase Relationships in Chemical Flooding," <u>Soc. Pet. Eng. J.</u>, October, 1978, pp. 325-338.
- 50. Pope, G.A.; Tsaur, Kerming; Schechter, R.S. and Wang, Ben; "The Effect of Several Polymers on the Phase Behavior of Micellar Fluids," SPE 8826, presented at the First Joint SPE/DOE Symposium on Enhanced Oil Recovery, Tulsa, Oklahoma, April 20-23, 1980.
- 51. Pope, G.A.; "Mobility Control and Scaleup for Chemical Flooding," First Annual Report prepared for DOE under contract DE-AC19-79BC10095, Oct. 1, 1979-Sept. 30, 1980.
- 52. Rathmell, J.J.; Smith, F.W.; Salter, S.J. and Fink, T.R.; "Evaluation of the Optimal Salinity Concept for Design of a High Water Content Micellar Fluid," SPE 7067, presented at the 5th Symposium on Improved Oil Recovery, Tulsa, Oklahoma, April 16-19, 1978.
- 53. Reed, R.L. and Healy, R.N.; "Some Physico-Chemical Aspects of Microemulsion Flooding: A Review," <u>Improved Oil Recovery</u> <u>by Surfactant and Polymer Flooding</u>, edited by Shah, D.O. and Schechter, R.S., Academic Press, 1977, pp. 383-437.
- 54. Salager, J.L.; Bourrel, M.; Schechter, R.S. and Wade, W.H.; "Mixing Rules for Optimum Phase Behavior Formulations of Surfactant/Oil/Water Systems," <u>Soc. Pet. Eng. J.</u>, Oct. 1979, pp. 271-278.
- 55. Trushenski, S.P.; Dauben, D.L. and Parrish, D.R.; "Micellar Flooding - Fluid Propagation, Interaction, and Mobility," <u>Soc. Pet. Eng. J.</u>, Dec. 1974, pp. 633-645.

- 56. Trushenski, S.P.; "Micellar Flooding: Sulfonate-Polymer Interaction," <u>Improved Oil Recovery by Surfactant and Polymer</u> Flooding, edited by Shah, D.O. and Schechter, R.S., Academic Press, 1977, pp. 555-575.
- 57. Wade, W.H.; Morgan, J.C.; Schechter, R.S.; Jacobson, J.K. and Salager, J.L.; "Interfacial Tension and Phase Behavior of Surfactant Systems," Soc. Pet. Eng. J., Aug. 1978, pp. 242-252.
- 58. Wade, W.H.; Salager, J.L.; Vasquez, E.; El-Emary, M.; Koukownis, C. and Schechter, R.S.; "Interfacial Tension and Phase Behavior of Pure Surfactant Systems," <u>Solution Chemistry</u> of <u>Surfactants</u>, edited by L.K. Mittal, Vol. 2, 1979, p. 801.
- 59. Willhite, G.P.; Green, D.W.; Okoye, D.W. and Looney, M.D.; "A Study of Oil Displacement by Microemulsion Systems -Mechanisms and Phase Behavior," <u>Soc. Pet. Eng. J.</u>, Dec. 1980, pp. 459-472.
- 60. Pope, G.A. and Nelson, R.C.; "A Chemical Flooding Compositional Simulator," <u>Soc. Pet. Eng. J.</u>, Oct. 1978, pp. 339-354.
- 61. Wang, Ben; "A Sensitivity Study of Micellar/Polymer Flooding," M.S. Thesis, The University of Texas at Austin, Dec. 1978.
- 62. Pope, G.A.; Wang, Ben and Tsaur, Kerming; "A Sensitivity Study of Micellar/Polymer Flooding," <u>Soc. Pet. Eng. J.</u>, Dec. 1979, pp. 357-368.
- 63. Bondor, P.L.; Hirasaki, G.J. and Tham, M.J.; "Mathematical Simulation of Polymer Flooding in Complex Reservoirs," Soc. Pet. Eng. J., Oct. 1972, pp. 369-382.
- 64. Ben-Omran, A.M. and Green, D.W.; "A Two-dimensional, Two-Phase Compositional Model Which Uses a Moving Point Method," SPE 7415, presented at the 53rd Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Houston, Texas, Oct. 1978.
- 65. Coats, K.H.; "A Highly Implicit Steamflood Model," <u>Soc. Pet.</u> Eng. J., Oct. 1978, pp. 369-383.
- 66. Coats, K.H.; "An Equation of State Compositional Model," Soc. Pet. Eng. J., Oct. 1980, pp. 363-376.

- 67. Corteville, J.; Van Quy, N. and Simandoux, P.; "A Numerical and Experimental Study of Miscible or Immiscible Fluid Flow in Porous Media with Interphase Mass Transfer," SPE 3481, presented at the 46th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, New Orleans, Louisiana, Oct. 3-6, 1971.
- 68. Fleming, P.D. III; Thomas, C.P. and Winter, W.K.; "Formulation of a General Multiphase, Multicomponent Chemical Flood Model," Soc. Pet. Eng. J., Feb. 1981, pp. 63-67.
- 69. Grabowski, J.W.; Vinsome, P.K.; Lin, R.C.; Behie, A. and Rubin, B.; "A Fully Implicit General Purpose Finite Difference Thermal Model for In Situ Combustion and Steam," SPE 8396, presented at the 54th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Las Vegas, Nevada, Sept. 23-26, 1979.
- 70. Hong, C.H.; "Development of a 2-D Micellar/Polymer Simulator," Ph.D. dissertation, The University of Texas at Austin, 1981.
- 71. Huang, Edward T.S.; "A Sensitivity Study of Reservoir Performance Using a Compositional Reservoir Simulator," <u>Soc. Pet.</u> Eng. J., Feb. 1972, pp. 3-12.
- 72. Kazemi, H. and MacMillan, D.J.; "A Numerical Simulation Comparison of Five Spot vs. Line Drive in Micellar-Polymer Flooding," SPE 9427, presented at the 55th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Dallas, Texas, Sept. 1980.
- 73. Kossack, C.A. and Bilhartz, H.L.Jr.; "The Sensitivity of Micellar Flooding to Reservoir Heterogeneities," SPE 5808, presented at the Improved Oil Recovery Symposium of the Society of Petroleum Engineers of AIME, Tulsa, Oklahoma, March 22-24, 1976,
- 74. Larson, R.G.; "The Influence of Phase Behavior on Surfactant Flooding," Soc. Pet. Eng. J., Dec. 1979, pp. 411-422.
- 75. MacDonald, R.C.; "Reservoir Simulation with Interphase Mass Transfer," Ph.D. dissertation, The University of Texas at Austin, 1971.
- 76. Myhill, Norton N.; "A Check on Numerical Thermal Simulation," SPE 8822, presented at the First Joint SPE/DOE Symposium on Enhanced Oil Recovery, Tulsa, Oklahoma, April 20-23, 1980.

- 77. Nolen, J.S.; "Numerical Simulation of Compositional Phenomena in Petroleum Reservoirs," SPE 4274, presented at the 3rd Symposium on Numerical Simulation of Reservoir Performance of the Society of Petorleum Engineers of AIME, Houston, Texas, Jan. 11-12, 1973.
- 78. Pang, H.W. and Caudle, B.H.; "Modeling of a Micellar-Polymer Process," SPE 9009, presented at the 5th International Symposium on Oilfield and Geothermal Chemistry of the Society of Petroleum Engineers of AIME, Stanford, California, May 1980.
- 79. Pope, G.A.; Hong, C.H. and Sepehrnoori, K.; "Two-Dimensional Numerical Simulation of Chemical Flooding," SPE 9939, presented at the 51st Annual SPE California Regional Meeting, March 25-27, 1981.
- 80. Thomas, C.P.; Winter, W.K. and Fleming, P.D. III; "Application of a General Multiphase, Multicomponent Chemical Flood Model to Ternary, Two-Phase Surfactant Systems," SPE 6727, presented at the 52nd Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Denver, Colorado, Oct. 9-12, 1977.
- 81. Todd, M.R.; Dietrich, J.K.; Goldburg, A. and Larson, R.G.; "Numerical Simulation of Competing Chemical Flood Designs," SPE 7077, presented at the 5th Symposium on Improved Methods for Oil Recovery of the Society of Petroleum Engineers of AIME, Tulsa, Oklahoma, April 16-19, 1978.
- 82. Todd, Michael R. and Chase, Curtis A.; "A Numerical Simulator for Predicting Chemical Flood Performance," SPE 7689, presented at the 5th Symposium on Reservoir Simulation of the Society of Petroleum Engineers of AIME, Denver, Colorado, Feb. 1-2, 1979.
- 83. Vela, Saul; Peaceman, D.W. and Sandvik, E.I.; "Evaluation of Polymer Flooding in Layered Reservoir with Crossflow, Retention, and Degradation," <u>Soc. Pet. Eng. J.</u>, April 1976, pp. 82-96.
- 84. Wang, Ben; "Development of a 2-D Large-scale Micellar/Polymer Simulator," Ph.D. dissertation, The University of Texas at Austin, 1981.
- 85. Wang, Ben; Lake, L.W. and Pope, G.A.; "Development and Application of a Streamline Micellar/Polymer Simulator," SPE 10290, presented at the 56th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, San Antonio, Texas, Oct. 1981.

- 86. Chase, Curtis A.; "Variational Simulation with Numerical Decoupling and Local Mesh Refinement," SPE 7680, presented at the 5th Symposium on Reservoir Simulation of the Society of Petroleum Engineers of AIME, Denver, Colorado, Feb. 1-2, 1979.
- 87. Chaudhari, N.K.; "An Improved Numerical Technique for Solving Multidimensional Miscible Displacement Equations," <u>Trans. AIME</u> Vol. 251, 1971, pp. 277-284.
- 88. Garder, A.O. Jr.; Peaceman, D.W. and Pozzi, A.L. Jr.; "Numerical Calculation of Multidimensional Miscible Displacement by the Method of Characteristics," <u>Soc. Pet. Eng. J.</u>, March 1964, pp. 26-36.
- 89. Hales, H.B. and Odeh, A.S.; "An Improved Method for Simulating Ideal Low-Tension Flooding Process," <u>Soc. Pet. Eng. J.</u>, April 1976, pp. 53-56.
- 90. Kim, J.S.; "The Application of High Order Finite Difference Methods to the Diffusion-Convection Equation," M.S. thesis, The University of Texas at Austin, Aug. 1977.
- 91. Lantz, R.B.; "Quantitative Evaluation of Numerical Diffusion (Truncation Error)," Trans. AIME, Vol. 251, 1971, pp. 315-320.
- 92. Larson, Ronald G.; "A Novel Method for Controlling Numerical Dispersion in Finite Difference Simulation of Flow in Porous Media," SPE 8027, presented at the 54th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Las Vegas, Nevada, Sept. 23-26, 1979.
- 93. Laumbach, D.D.; "A High-Accuracy Finite-Difference Technique for Treating the Convection-Diffusion Equation," <u>Soc. Pet.</u> Eng. J., Dec. 1975, pp. 517-531.
- 94. Naiki, Motoyoshi; "Numerical Simulation of Polymer Flooding Including the Effects of Salinity," Ph.D. dissertation, The University of Texas at Austin, Aug. 1979.
- 95. Peaceman, D.W. and Rachford, H.H. Jr.; "The Numerical Solution of Parabolic and Elliptic Differential Equations," <u>J. Soc. Ind.</u> Appl. Math., Vol. 3, No. 1, March 1955, pp. 28-41.
- 96. Price, H.S.; Cavendish, J.C. and Varga, R.S.; "Numerical Methods of Higher-Order Accuracy for Diffusion-Convection Equations," Trans. AIME, Vol. 243, 1968, pp. 293-303.

- 97. Sepehrnoori, K.; Carey, G.F. and Knapp, R.; "Convection-Diffusion Computations," Proceedings of the Third International Conference in Australia on Finite Element Methods, July 1979, The University of New Wales.
- 98. Sepehrnoori, K. and Carey, G.F.; "Numerical Integration of Semidiscrete Evolution Systems," to appear in <u>The Journal of</u> Computer Methods in Applied Mechanics and Engineering, 1981.
- 99. Settari, A.; Price, H.S. and Dupont, T.; "Development and Application of Variational Methods for Simulation of Miscible Displacement in Porous Media," <u>Soc. Pet. Eng. J.</u>, June 1977, pp. 228-246.
- 100. Stone, H.L. and Brian, P.L.T.; "Numerical Solution of Convective Transport Problems," <u>AIChE Journal</u>, Vol. 9, No. 5, Sept. 1963, pp. 681-688.
- 101. Coats, K.H. and Smith, B.D.; "Dead-End Pore Volume and Dispersion in Porous Media," <u>Soc. Pet. Eng. J.</u>, March 1964, pp. 73-84.
- 102. Dawson, R. and Lantz, R.B.; "inaccessible Pore Volume in Polymer Flooding," Soc. Pet. Eng. J., Oct. 1972, pp. 448-452.
- 103. Liauh, W.C.; Duda, J.L. and Klaus, E.E.; "An Investigation of the Inaccessible Pore Volume Phenomena," SPE 8751, presented at the 84th National AIChE Meeting, Feb. 1978.
- 104. Shah, Bhupendra N.; Willhite, G. Paul and Green, Don W.; "The Effect of Inaccessible Pore Volume on the Flow of Polymer and Solvent Through Porous Media," SPE 7586, presented at the 53rd Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Houston, Texas, Oct. 1978.
- 105. Christopher, R.H. and Middleman, S.; "Power-Law Flow Through A Packed Tube," <u>I&EC Fund.</u>, Vol. 4, 1965, p. 442.
- 106. Dauben, D.L. and Menzie, D.E.; "Flow of Polymer Solutions Through Porous Media," J. Pet. Tech., Aug. 1967, pp. 1065-1073.
- 107. Dominguez, J.G. and Whillhite, G.P.; "Retention and Flow Characteristics of Polymer Solutions in Porous Media," Soc. Pet. Eng. J., April 1977, pp. 111-121.

- 108. Gogarty, W.B.; "Mobility Control with Polymer Solutions," Soc. Pet. Eng. J., June 1967, pp. 161-170.
- 109. Hill, H.J.; Brew, J.R.; Claridge, E.L.; Hite, J.R. and Pope, G.A.; "The Behavior of Polymers in Porous Media," SPE 4748, presented at the Symposium on the Improved Oil Recovery of the Society of Petroleum Engineers of AIME, Tulsa, Oklahoma, April 22-24, 1974.
- 110. Hirasaki, G.J. and Pope, G.A.; "Analysis of Factors Influencing Mobility and Adsorption in the Flow of Polymer Solution Through Porous Media," <u>Soc. Pet. Eng. J.</u>, Aug. 1974, pp. 337-346.
- 111. Jennings, R.R.; Rogers, J.H. and West, T.J.; "Factors Influencing Mobility Control by Polymer Solutions," <u>J. Pet.</u> Tech., March 1971, pp. 391-401.
- 112. Jones, W.M. and Maddock, J.L.; "Flow of Viscoelastic Liquids: Comparison of Departures from Laminar Flow in Porous Beds and in Tubes," SPE 1686, presented at the Symposium on Mechanics of Rheologically Complex Fluids of the Society of Petroleum Engineers of AIME, Houston, Texas, Dec. 15-16, 1966.
- 113. Marshall, R.J. and Metzner, A.B.; "Flow of Viscoelastic Fluids Through Porous Media," <u>I&EC Fund.</u>, Vol. 6, No. 3, Aug. 1967, pp. 393-400.
- 114. Mckinley, R.M.; Jahns, H.O. and Harris, W.; "Non-Newtonian Flow in Porous Media," <u>AIChE Journal</u>, Vol. 12, No. 1, Jan. 1966, pp. 17-20.
- 115. Meter, D.M. and Bird, R.B.; "Tube Flow of Non-Newtonian Polymer Solutions; Part I. Laminar Flow and Rheological Models," AIChE Journal, Vol. 10, No. 6, Nov. 1964, pp. 878-881.
- 116. Mungan, N.; Smith, F.W. and Thompson, J.L.; "Some Aspects of Polymer Floods," J. Pet. Tech., Sept. 1966, pp. 1143-1150.
- 117. Mungan, N.; "Rheology and Adsorption of Aqueous Polymer Solutions," J. Can. Pet. Tech., April-June 1969, pp. 45-50.
- 118. Mungan, N.; "Shear Viscosities of Ionic Polyacrylamide Solutions," Soc. Pet. Eng. J., Dec. 1972, pp. 469-473.

- 119. Pye, David J.; "Improved Secondary Recovery by Control of Water Mobility," J. Pet. Tech., Aug. 1964, pp. 911-916.
- 120. Savins, J.G.; "Non-Newtonian Flow Through Porous Media," I&EC Fund, Vol. 61, No. 10, Oct. 1969, pp. 18-47.
- 121. Smith, Frank W.; "The Behavior of Partially Hydrolyzed Polyacrylamide Solutions in Porous Media," <u>J. Pet. Tech.</u>, Feb. 1970, pp. 148-156.
- 122. Thakur, Ganesh C.; "Prediction of Resistance Effect in Porous Media," SPE 4956, presented at Permian Basin Oil Recovery Conference of the Society of Petroleum Engineers of AIME, Midland, Texas, March 1974.
- 123. Thomas, C.P.; "The Mechanism of Reduction of Water Mobility by Polymer in Glass Capillary Arrays," <u>Soc. Pet. Eng. J.</u>, June 1976, pp. 130-136.
- 124. Jones, K.; "Rheology of Viscoelastic Fluids for Oil Recovery," M.S. thesis, The University of Texas at Austin, 1981.
- 125. Wissler, E.H.; "Viscoelastic Effects in the Flow of Non-Newtonian Fluids Through A Porous Medium," <u>I&EC Fund.</u>, Vol. 10, No. 3, 1971, pp. 411-417.
- 126. Yuan, Mei-Kou; "A Rheological Study of Polymer and Microemulsion in Porous Media," M.S. thesis, The University of Texas at Austin, May 1981.
- 127. Flory, P.J.; <u>Principles of Polymer Chemistry</u>, Cornell University Press, 1953.
- 128. Tsaur, Kerming, "A Study of Polymer/Surfactant Interactions for Micellar/Polymer Flooding Applications," M.S. thesis, The University of Texas at Austin, Dec. 1978.
- 129. Szabo, Miklos T.; "A Comparative Evaluation of Polymers for Oil Recovery - Rheological Properties," J. Pet. Tech., May 1979, pp. 553-560.
- 130. Jeanes, A.; Pittsley, J.E. and Senti, F.R.; "Polysaccharide B-1459: A New Hydrocolloid Polyelectrolyte Produced From Glucose by Bacterial Fermentation," <u>J. Appl. Poly. Sci.</u>, Vol. V, No. 17, 1961, pp. 519-526.

- 131. Bourrel, M.; Lipow, A.M.; Wade, W.H.; Schechter, R.S. and Salager, J.L.; "Properties of Amphiphile/Oil/Water Systems at an Optimum Formulation for Phase Behavior," SPE 7450, presented at the 53rd Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Houston, Texas, Oct. 1-3, 1978.
- 132. Puerto, M.C. and Gale, W.M.; "Estimation of Optimal Salinity and Solubilization Parameters for Alkylorthoxylene Sulfonate Mixtures," Soc. Pet. Eng. J., June 1977, pp. 193-200.
- 133. Salter, S.J.; "The Influence of Type and Amount of Alcohol on Surfactant-Oil-Brine Phase Behavior and Properties," SPE 6843, presented at the 52nd Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Denver, Colorado, Oct. 9-12, 1977.
- 134. Dominguez, J.G.; Willhite, G.P. and Green, D.W.: "Phase Behavior of Microemulsion Systems with Emphasis on Effects of Paraffinic Hydrocarbons and Alcohols," <u>Solution Chemistry</u> of Surfactants, edited by Mittal, K.L., Plenum Press, 1979, pp. 673-697.
- 135. Salter, S.J.; "Selection of Pseudo-Components in Surfactant-Oil-Brine-Alcohol Systems," SPE 7056, presented at the 5th Symposium on Improved Methods of Oil Recovery, Tulsa, Oklahoma, April 16-19, 1978.
- 136. Wickert, B.L.; Willhite, G.P., Green, D.W. and Black, S.L.; "Interfacial and Phase Behavior of Microemulsion Systems Using a Quatenary Diagram," SPE 8037, presented at 85th National AIChE Meeting, Philadelphia, June 1978.
- 137. Vinatieri, J.E. and Fleming, P.D.III; "The Use of Pseudo-Components in the Representation of Phase Behavior of Surfactant Systems," Soc. Pet. Eng. J., Oct. 1980, pp. 289-300.
- 138. Perkins, T.K. and Johnston, O.C.; "A Review of Diffusion and Dispersion in Porous Media," <u>Soc. Pet. Eng. J.</u>, March 1963, pp. 70-84.
- 139. Mac Allister, D.; "Measurement of Relative Permeability and Dispersion for Micellar/Polymer Fluids in Sandpacks," M.S. thesis, The University of Texas at Austin, 1981.

- 140. Delshad, M.; "Measurement of Relative Permeability and Dispersion for Micellar Fluids in Berea Rock," M.S. thesis, The University of Texas at Austin, 1981.
- 141. Dubois, M.; Gilles, K.A.; Hamilton, J.K.; Rebers, P.A. and Smith, F.; "Colorimetric Method for Determination of Sugars and Related Substances," <u>Analytical Chemistry</u>, Vol. 28, No. 3, March 1956, pp. 350-356.
- 142. Lorenz, P.B.; Tham, M.K. and Bayazeed, A.F.; "A Laboratory Study of Surfactant Flooding in the Delaware-Childers Field," Enhanced Oil Recovery - Chemical Flooding, Vol. 2, annual report DOE/BETC/IC-80/3, U.S. Department of Energy, Oct. 1, 1979-Sept. 30, 1980.
- 143. "Bell Creek Field Micellar-Polymer Pilot Demonstration First Annual Report," prepared by Gary Energy Corporation for the Department of Energy under contract DE-AC03-78SF01802, July 1976-Sept, 1977.
- 144. Hirasaki, G.J.; "Ion Exchange with Clays in the Presence of Surfactant," SPE 9279, presented at the 55th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, Dallas, Texas, Sept. 21-24, 1980.
- 145. Claridge, E.I.; "A Method of Design of Graded Viscosity Banks," Soc. Pet. Eng. J., Oct. 1978, pp. 315-324.
- 146. Craig, Forrest F. III; "Enhanced Oil Recovery by Improved Waterflooding in the Storms Pool Field, Illinois," prepared by Energy Resources Co. Inc. for the Department of Energy under contract DE-AC01-78ET12065, 1980.
- 147. Mungan, N.; "Improved Waterflooding Through Mobility Control," Can. J. Chem. Eng., Vol. 49, No. 1, Feb. 1971, pp. 32-37.
- 148. Lake, Larry W.; Pope, Gary A.; Carey, Graham F. and Sepehrnoori, Kamy; "Isothermal, Multiphase, Multicomponent Fluid-Flow in Permeable Media, Part I: Description and Mathematical Formulation," Center for Enhanced Oil and Gas Recovery Research, The University of Texas at Austin.

- 149. Engelsen, S.; "Micellar/Polymer Flooding Simulation-Improvements in Modelling and Matching of Core Floods," M.S. thesis, The University of Texas at Austin, 1981.
- 150. Ohno, T.; "The Application of Improved Numerical Techniques to 1-D Micellar/Polymer Flooding Simulation," M.S. thesis, The University of Texas at Austin, 1981.

Eugene Ching-Tsao Lin was born in Taipei, Taiwan, on June 23, 1950, the first son of Mr. and Mrs. Sameul Lin. After receiving his Bachelor of Engineering degree at Chung-Yuan Christian University, Chung-Li, Taiwan, in 1972, he served as a second lieutenant in Chinese Army for two years. He came to the United States to pursue his graduate study in 1975. He received a degree of Master of Science in chemical engineering in August 1976 from The University of Mississippi. After one year of study in the Department of Chemical Engineering at the University of Cincinnati, he entered the Department of Petroleum Engineering at The University of Texas at Austin for his Ph.D. study. He married Ruth in August 1977 and has a daughter, Gloria.

Permanent Address:

4-1, Lane 24 Shao-Shin South Street Taipei, Taiwan Republic of China