EFFECTS AND MECHANISMS 
IN 
CARBON DIOXIDE-FOAM FLOODING 
(A Micromodel Visualization Study)

A THESIS 
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL 
OF THE NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY

BY 
KARIM SALEHPOOR

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS 
FOR THE DEGREE OF 
MASTER OF SCIENCE 
IN PETROLEUM ENGINEERING

December 1993
Abstract

The result of a visualization study of CO₂-foam is presented. The main concern of this study has been finding out the conditions at which foam is best generated, most stable, and results in a uniform flow front, the latter being desired in enhanced oil recovery.

This work introduces a new tool, the Pressure Parameter ($P_p$), which is used to evaluate the results of micromodel visualization experiments at different conditions. A lower value for the Pressure Parameter is an indication of a more uniform flow front. Average pressure drop across the micromodel and the pressure parameter are used as two different evaluation tools.

The effects of surfactant concentration, flow rate, gas-liquid injection ratio, and in situ vs. external foam generation have been examined. Oil sweep efficiencies have been compared when brine, surfactant solution, pure CO₂, surfactant solution alternating with CO₂, brine alternating with CO₂, and a pregenerated CO₂-foam have been used as the displacing fluid.

The high viscosity of foam, the role of surfactant in foam stability, controlling the average bubble size, and the role of oil in foam destabilizing are explained.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Introduction and Literature Review</td>
<td></td>
</tr>
<tr>
<td>A.1</td>
<td>Introduction</td>
<td>2</td>
</tr>
<tr>
<td>A.2</td>
<td>Literature Review</td>
<td></td>
</tr>
<tr>
<td>A.2.1</td>
<td>General Aspects</td>
<td>4</td>
</tr>
<tr>
<td>A.2.2</td>
<td>Foam by Nature</td>
<td>7</td>
</tr>
<tr>
<td>A.2.3</td>
<td>Foam Generation, Propagation, and Destruction</td>
<td></td>
</tr>
<tr>
<td>A.2.3.1</td>
<td>Foam Generation Mechanisms</td>
<td>10</td>
</tr>
<tr>
<td>A.2.3.2</td>
<td>Foam Propagation Mechanisms</td>
<td>13</td>
</tr>
<tr>
<td>A.2.3.3</td>
<td>Foam Destruction Mechanisms</td>
<td>14</td>
</tr>
<tr>
<td>A.2.4</td>
<td>Foam Flow Through Porous Media</td>
<td>15</td>
</tr>
<tr>
<td>A.2.5</td>
<td>Modeling Foam Mobility in Porous Media</td>
<td>18</td>
</tr>
<tr>
<td>A.2.6</td>
<td>Simulation Work on Foam Rheology in Porous Media</td>
<td>19</td>
</tr>
<tr>
<td>A.2.7</td>
<td>The Use of Foam for Mobility Control</td>
<td>22</td>
</tr>
<tr>
<td>A.2.8</td>
<td>Flow Visualization</td>
<td>23</td>
</tr>
<tr>
<td>B</td>
<td>Introducing the New Evaluation Tool</td>
<td></td>
</tr>
<tr>
<td>B.1</td>
<td>Introduction</td>
<td>25</td>
</tr>
<tr>
<td>B.2</td>
<td>Uniform Flow Front</td>
<td>27</td>
</tr>
<tr>
<td>B.3</td>
<td>Bubble Analogy</td>
<td>29</td>
</tr>
<tr>
<td>B.4</td>
<td>Introducing the Tool</td>
<td>31</td>
</tr>
<tr>
<td>C</td>
<td>Experimental Apparatus and Procedure</td>
<td></td>
</tr>
<tr>
<td>C.1</td>
<td>Apparatus</td>
<td>35</td>
</tr>
<tr>
<td>C.2</td>
<td>Experimental Procedure</td>
<td>38</td>
</tr>
<tr>
<td>D</td>
<td>Results and Discussion</td>
<td></td>
</tr>
<tr>
<td>D.1</td>
<td>General reminders</td>
<td>43</td>
</tr>
<tr>
<td>D.2</td>
<td>Results in the absence of surfactant</td>
<td></td>
</tr>
<tr>
<td>D.2.1</td>
<td>Results with brine</td>
<td>45</td>
</tr>
<tr>
<td>D.2.2</td>
<td>Effect of salinity</td>
<td>72</td>
</tr>
<tr>
<td>D.3</td>
<td>Results in the presence of surfactant</td>
<td></td>
</tr>
<tr>
<td>D.3.1</td>
<td>Surfactant Molecular Structure</td>
<td>79</td>
</tr>
<tr>
<td>D.3.2</td>
<td>The Role of Surfactant in Foam Stability</td>
<td>80</td>
</tr>
<tr>
<td>D.3.3</td>
<td>Effect of Surfactant on the Average Bubble Size</td>
<td>81</td>
</tr>
<tr>
<td>D.3.4</td>
<td>Foam high apparent viscosity</td>
<td>82</td>
</tr>
<tr>
<td>D.3.5</td>
<td>Effect of Initial Saturation</td>
<td>83</td>
</tr>
<tr>
<td>D.3.6</td>
<td>Effect of gas-liquid ratio (In Situ Generation)</td>
<td>84</td>
</tr>
<tr>
<td>D.3.7</td>
<td>Effect of Gas-Liquid Ratio (Pregeneration)</td>
<td>85</td>
</tr>
<tr>
<td>D.3.8</td>
<td>Effect of surfactant concentration</td>
<td>86</td>
</tr>
<tr>
<td>D.3.9</td>
<td>Effect of Flow Rate (In Situ Generation)</td>
<td>87</td>
</tr>
<tr>
<td>D.3.10</td>
<td>Effect of Flow Rate (Pregeneration)</td>
<td>88</td>
</tr>
<tr>
<td>D.3.11</td>
<td>The Role of Oil in Foam Destabilizing</td>
<td>89</td>
</tr>
<tr>
<td>E</td>
<td>Miscellaneous Observations</td>
<td>157</td>
</tr>
<tr>
<td>F</td>
<td>Conclusions</td>
<td>161</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>164</td>
</tr>
<tr>
<td>Appendix A</td>
<td>Tables</td>
<td>173</td>
</tr>
<tr>
<td>Appendix B</td>
<td>Micromodel Fabricating Procedure</td>
<td>176</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENT

The author wishes to express his sincere appreciations to his advisor Dr. Reid Grigg for his scientific guidance, supervision, and support.

The author would like to thank his committee members, Dr. Robert Bretz, Dr. Randy Seright, and Dr. Shih-Hsien Chang for their advice and encouragement.

The author has learned from professors, staff, and graduate students, in PRRC and the petroleum engineering department by their discussions in classes and seminars. However direct advice from Dr. John P. Heller, Dr. J.J. Taber, and Dr. Jim Smith have been much helpful. Advice from Mary Graham, on making micromodel is appreciated.

The author wishes to thank Dave F. Martin, director of PRRC, for the financial support through research assistantship during the program.

Many thanks to my family especially my wife, Manijeh, for their support, patience, and encouragement.
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1</td>
<td>Micromodel Characteristics</td>
<td>173</td>
</tr>
<tr>
<td>Table 2</td>
<td>Brine Composition</td>
<td>173</td>
</tr>
<tr>
<td>Table 3</td>
<td>Composition of Maljamar Crude Oil</td>
<td>174</td>
</tr>
<tr>
<td>Table 4</td>
<td>Summary of Experiments</td>
<td>175</td>
</tr>
</tbody>
</table>
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Fig. B.1.1:</th>
<th>Different pressure drop variations with the same average value.</th>
<th>26</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. B.2.1:</td>
<td>Flow front in a porous media is uniform if the least possible amount of mass and at the shortest possible time interval flows through any point such as (A) before flow stops temporarily at that point and starts at a different point.</td>
<td>28</td>
</tr>
<tr>
<td>Fig. B.3.1:</td>
<td>Gas bubble does not have any restrictive effect on the pore throat.</td>
<td>30</td>
</tr>
<tr>
<td>Fig. B.3.2:</td>
<td>Gas bubble has plugged the pore throat.</td>
<td>30</td>
</tr>
<tr>
<td>Fig. B.4.1:</td>
<td>Piping system representing bubble effects in porous media.</td>
<td>34</td>
</tr>
<tr>
<td>Fig. B.4.2:</td>
<td>Pressure drop variation due to single valve operation.</td>
<td>34</td>
</tr>
<tr>
<td>Fig. B.4.3:</td>
<td>Pressure drop variation due to irregular multi-valve operation.</td>
<td>34</td>
</tr>
<tr>
<td>Fig. C.1.1:</td>
<td>Schematic of flow visualization apparatus (from Chang 1991).</td>
<td>37</td>
</tr>
<tr>
<td>Fig. C.2.1:</td>
<td>Flow diagram of flow visualization apparatus (from Chang 1991).</td>
<td>41</td>
</tr>
<tr>
<td>Fig. C.2.2:</td>
<td>Modified layered micromodel (MLAY) shown in actual size. Pore space is dark.</td>
<td>42</td>
</tr>
<tr>
<td>Fig. C.2.3:</td>
<td>Modified heterogeneous micromodel (MHET) shown in actual size. Pore space is dark.</td>
<td>42</td>
</tr>
<tr>
<td>Fig. D.2.1:</td>
<td>CO₂ avoided entering pores which were already occupied by trapped CO₂.</td>
<td>49</td>
</tr>
<tr>
<td>Fig. D.2.2a:</td>
<td>Pressure parameter is compared at different flow rates. The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected.</td>
<td>51</td>
</tr>
<tr>
<td>Fig. D.2.2b:</td>
<td>Pressure drop is compared at different flow rates. The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected.</td>
<td>52</td>
</tr>
<tr>
<td>Fig. D.2.2c:</td>
<td>Average pressure parameter is compared at different flow rates. The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected.</td>
<td>53</td>
</tr>
<tr>
<td>Fig. D.2.2d:</td>
<td>Average pressure drop is compared at different flow rates. The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected.</td>
<td>54</td>
</tr>
<tr>
<td>Fig. D.2.3a:</td>
<td>Pressure parameter is compared at different flow rates. The MLAY micromodel and foam generator were both</td>
<td></td>
</tr>
</tbody>
</table>
saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator. ..............................................................56

Fig. D.2.3b: Pressure drop is compared at different flow rates. The MLAY micromodel and foam generator were both saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator. ..............................................................57

Fig. D.2.3c: Average pressure parameter is compared at different flow rates. The MLAY micromodel and foam generator were both saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator. ..............................................................58

Fig. D.2.3d: Average pressure drop is compared at different flow rates. The MLAY micromodel and foam generator were both saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator. ..............................................................59

Fig. D.2.4a: Pressure parameter is compared at different gas-liquid ratios. The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. ..............................................................61

Fig. D.2.4b: Pressure drop is compared at different gas-liquid ratios. The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. The average pressure drop corresponding to injecting only brine (G/L=0.0) was about 0.0028 psi. ..............................................................62

Fig. D.2.4c: Average pressure parameter is compared at different gas-liquid ratios. The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. ..............................................................63

Fig. D.2.4d: Average pressure drop is compared at different gas-liquid ratios. The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. ..............................................................64

Fig. D.2.5a: Pressure parameter is compared at different gas-liquid ratios. The MLAY micromodel and foam generator were both saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator. ..............................................................66

Fig. D.2.5b: Pressure drop is compared at different gas-liquid ratios. The MLAY micromodel and foam generator were both saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator. ..............................................................67

Fig. D.2.5c: Average pressure parameter is compared at different gas-liquid ratios. The MLAY micromodel and foam generator were both saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator. ..............................................................68

Fig. D.2.5d: Average pressure drop is compared at different gas-
liquid ratios. The MLAY micromodel and foam generator were both saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator. .........................69

Fig. D.2.6a: Average pressure parameter is compared for foam generation by in situ and pregeneration. In Situ: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. Pregenerated: The MLAY micromodel and foam generator were saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator. .........................70

Fig. D.2.6b: Average pressure drop is compared for foam generation by in situ and pregeneration. In Situ: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. Pregenerated: The MLAY micromodel and foam generator were saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator. .........................71

Fig. D.2.7a: Pressure parameter is compared for different initial saturation and injection fluid salinity. #1: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. #2: The MLAY micromodel was saturated with distilled water and then brine alternating with CO₂ was injected. #3: The MLAY micromodel was saturated with distilled water and then distilled water alternating with CO₂ was injected. 73

Fig. D.2.7b: Pressure drop is compared for different initial saturation and injection fluid salinity. #1: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. #2: The MLAY micromodel was saturated with distilled water and then brine alternating with CO₂ was injected. #3: The MLAY micromodel was saturated with distilled water and then distilled water alternating with CO₂ was injected. 74

Fig. D.2.8a: Pressure parameter is compared for different initial saturation and injection fluid salinity. #1: The MLAY micromodel was saturated with distilled water and then distilled water alternating with CO₂ was injected. #2: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. 75

Fig. D.2.8b: Pressure drop is compared for different initial saturation and injection fluid salinity. #1: The MLAY micromodel was saturated with distilled water and then distilled water alternating with CO₂ was injected. #2: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. 76

Fig. D.2.9a: Pressure parameter is compared for different initial saturation conditions. #1: The MLAY micromodel was saturated with distilled water and then brine alternating with CO₂ was injected. #2: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. 77
Fig. D.2.9b: Pressure drop is compared for different initial saturation conditions. #1: The MLAY micromodel was saturated with distilled water and then brine alternating with CO₂ was injected. #2: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. .................78

Fig. D.3.1: Surfactant molecules will locate at the interface in a two phase system. ..............................................83

Fig. D.3.2: Orientation of surfactant molecules with uncharged head groups at the interface. .................................83

Fig. D.3.3: Bubble division is accompanied with increase in total surface area. ..............................................91

Fig. D.3.4: Foam viscosity depends on the bubble size. Foam with smaller bubble size has higher viscosity. ...............95

Fig. D.3.5a: Pressure parameter is compared for different initial saturations. #1: The MLAY micromodel was saturated with surfactant solution and then brine alternating with CO₂ was injected. #2: The MLAY micromodel was saturated with brine and then surfactant solution alternating with CO₂ was injected. .........................103

Fig. D.3.5b: Pressure drop is compared for different initial saturations. #1: The MLAY micromodel was saturated with surfactant solution and then brine alternating with CO₂ was injected. #2: The MLAY micromodel was saturated with brine and then surfactant solution alternating with CO₂ was injected. .........................103

Fig. D.3.6a: Pressure parameter is compared for different initial saturations. #1: The MLAY micromodel was saturated with surfactant solution and then brine alternating with CO₂ was injected. #2: The MLAY micromodel was saturated with brine and then surfactant solution alternating with CO₂ was injected. .........................104

Fig. D.3.6b: Pressure drop is compared for different initial saturations. #1: The MLAY micromodel was saturated with surfactant solution and then brine alternating with CO₂ was injected. #2: The MLAY micromodel was saturated with brine and then surfactant solution alternating with CO₂ was injected. .........................105

Fig. D.3.7a: Pressure parameter is compared at different gas-liquid ratios. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected. .........................109

Fig. D.3.7b: Pressure drop is compared at different gas-liquid ratios. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected. When only surfactant solution was injected (G/L=0.0), the corresponding pressure drop was about 0.003 psi. .........................110

Fig. D.3.7c: Average pressure parameter is compared at different gas-liquid ratios. The MLAY micromodel was saturated with
surfactant solution and then surfactant solution alternating with CO₂ was injected. .................111

Fig. D.3.7d: Average pressure drop is compared at different gas-liquid ratios. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected. When only surfactant solution was injected (G/L=0.0), the corresponding pressure drop was about 0.003 psi. .................112

Fig. D.3.8a: Pressure parameter is compared at different gas-liquid ratios. The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator. .................116

Fig. D.3.8b: Pressure drop is compared at different gas-liquid ratios. The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator. .................117

Fig. D.3.8c: Average pressure parameter is compared at different gas-liquid ratios. The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator. .................118

Fig. D.3.8d: Average pressure drop is compared at different gas-liquid ratios. The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator. .................119

Fig. D.3.9a: Pressure parameter is compared at different surfactant concentrations. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected. .................122

Fig. D.3.9b: Pressure drop is compared at different surfactant concentrations. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected. .................122

Fig. D.3.9c: Average pressure parameter is compared at different surfactant concentrations. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected. .................123

Fig. D.3.9d: Average pressure drop is compared at different surfactant concentrations. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected. .................124

Fig. D.3.10a: Pressure parameter is compared at different surfactant concentrations. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected. .................125

Fig. D.3.10b: Pressure drop is compared at different surfactant concentrations. The MLAY micromodel was saturated with
surfactant solution and then surfactant solution alternating with CO₂ was injected.

Fig. D.3.10c: Average pressure parameter is compared at different surfactant concentrations. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.

Fig. D.3.10d: Average pressure drop is compared at different surfactant concentrations. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.

Fig. D.3.11: Two bubbles may come together at a point with opposite charge.

Fig. D.3.12a: Pressure parameter is compared at different flow rates. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.

Fig. D.3.12b: Pressure drop is compared at different flow rates. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.

Fig. D.3.12c: Average pressure parameter is compared at different flow rates. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.

Fig. D.3.12d: Average pressure drop is compared at different flow rates. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.

Fig. D.3.13: Foam flow through porous media. Pressure drop increases linearly with increase in flow rate if bubble size remains constant.

Fig. D.3.14: Comparing experimental and theoretical pressure drop versus flow rate.

Fig. D.3.15a: Average pressure parameter is compared for WAG and SAG. WAG: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. SAG: The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.

Fig. D.3.15b: Average pressure drop is compared for WAG and SAG. WAG: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. SAG: The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.

Fig. D.3.16a: Pressure parameter is compared at different flow rates. The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel.
Fig. D.3.16b: Pressure drop is compared at different flow rates. The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator. ..........................147

Fig. D.3.16c: Average pressure parameter is compared at different flow rates. The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator. .........................148

Fig. D.3.16d: Average pressure drop is compared at different flow rates. The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator. .........................149

Fig. D.3.17: Average pressure drop is compared for foam generation by in situ and pregeneration. In Situ: The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected. Pregenerated: The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator. ....150

Fig. D.3.18: Stability of the non-wetting phase depends on the orientation of surfactant molecules at the interface. ......................................................151

Fig. E.1: CO₂ slug and the small bubble propagate at different velocities. ......................................................156

Fig. E.2: The small bubble is stationary close to a propagating slug. ......................................................159

Fig. E.3: A propagating bubble is stuck at a point and is stretched. ......................................................160

Fig. E.4: Bubble is divided due to mass discontinuity at division point. ......................................................160
A: Introduction and Literature Review

A.1: Introduction

Foams are widely used in the oil industry for drilling, fracturing, acidizing, and gas flooding. All of these applications rely on reducing gas mobility in rock. In gas flooding processes, major problems occur as a result of the displacement fluid’s high mobility compared to that of reservoir fluids. This high mobility ratio can cause channelling, that results in early breakthrough, reduced sweep efficiency, and reduced oil recovery. The injection of gas along with surfactant solution can produce a foam that exhibits an apparent viscosity much higher than its constituent phases: liquid and gas. Because of its high apparent viscosity, foam has a mobility much lower than the mobility of gas alone and, therefore, provides an effective means of reducing mobility of the displacing fluid.

Foam performance is affected by several parameters. Foam stability is affected by surfactant type and surfactant concentration. Foam is destabilized by oil and the destabilization mechanism is still under investigation. Different researchers have attempted to determine the conditions that improve the efficiency of a foam flooding; however, the results have not indicated a unique trend.

Although numerous laboratory studies have been undertaken to understand the behavior of foams in porous media, the application of foam in the field is still in its developmental stages, and continues to need adequate models or scaling rules to describe
the behavior of foam. This work examines a number of parameters and attempts to quantify their effects on foam performance.
A.2: Literature Review

A.2.1: General aspects

Foam was first proposed as an EOR agent by Bond and Holbrook (1958). The usefulness of this method was first studied by Fried (1961) who reported an increase in gas breakthrough time. Bernard (1963) conducted experiments and observed an improvement in the gas drive efficiency in the presence of foam. Bernard et al. (1965) demonstrated an improvement in oil recovery over a conventional waterflood using foam. A successful field application of foam was reported by Holm (1970) in selectively plugging a high permeability channel.

The history of foam in porous media was prepared in a literature survey by Marsden (1985). According to him, work on foam was started by Fried in late 1956, but his original report had an unusually long gestation time in the review process and was not actually published until 1961 in a greatly abbreviated form. The first publication suggesting foam generation in an oil reservoir belongs to Bond and Holbrook (1958). An extensive laboratory study has been done by Bernard and Holm (1964) on the effect of foam on permeability of porous media to gas. The use of externally generated aqueous foam to displace oil from unconsolidated and consolidated sands was suggested by Craig and Lummus (1965). They claimed that more oil was recovered by externally generated foam than from that generated within the core. Sharma (1965) observed oil displacement by foam in a thin, packed bead cell at low rates in a piston-like manner, but at higher rates there was significant fingering, and at still higher rates foam bubbles
became dispersed in the oil itself. Bond and Bernard (1966) presented results on the
effect of sand wettability on foam flow, although their data was difficult to interpret.
Marsden and Khan (1966) found the apparent viscosity of foam varied from 30 to 100
cp and that it increased with increasing surfactant concentration.

Considering the methods of foam generation (pregeneration or in situ generation),
Hardy and Mc Arthur (1966) suggested a method of producing foam in the reservoir
away from the injection wells. To accomplish this, an aqueous solution of both the
foaming agent and a soluble gas were to be injected into the formation at a pressure
above the bubble point. When the gas came out of solution at lower pressures out in the
reservoir, foam was generated. Bernard and Holm (1967) first suggested the use of foam
in CO₂ injection. The physical properties of foam and their applications in petroleum
operations were reviewed by Marsden et al. (1967). Bernard (1967) recommended the
use of brine instead of fresh water in preparing the surfactant solution to prevent
blockage from clay swelling. Needham (1968) suggested that foam made with steam as
the gaseous phase be injected into a reservoir to get a better injection profile than with
steam alone. Holm (1970) described the use of foam in injection tests in the Siggins
field, a small shallow field in Illinois. Surfactant solutions and compressed air were
injected either simultaneously or alternately in one well and production observed in five
offset production wells. The foam reduced the mobility of both water and gas to less
than 50% of their original values. A more uniform injection profile was observed and
severe channeling to one production well was stopped.

The flow of foam through etched-glass micromodels saturated with detergent
solutions was described first by Mast (1972). Wang (1984) reported that CO2 foam stability increased with increasing pressure and decreased with increasing temperature. Foams deteriorated rapidly when they came in contact with Sacroc and Rock Creek crude oils. The effect of temperature on various foam properties was described by Sharma et al. (1985). Average bubble size decreased with increasing temperatures, but increased with elapsed time, and while the ability of their surfactant to generate foam increased with temperature, the foam stability decreased.

A survey of foam rheology literature was also prepared by Heller and Kuntamukkula (1987). They discuss foam rheology both in tubes and in porous media. Geometry dependence of apparent viscosity of foam or foam rheology in tubes was explained. From a thermodynamic viewpoint, according to Heller and Kuntamukkula (1987), foams are unstable and should eventually break into individual component phases in the direction of decreasing total surface free energy. Drainage of the continuous liquid and mass transfer across the foam lamellae are the mechanisms which contribute to foam decay. Heller and Kuntamukkula (1987) also explain that gravitational drainage of liquid through the lamellae that surround the foam cells leads to gradual thinning and finally to rupture of foam bubbles. According to them, for any foam to be reasonably long lasting, the continuous phase must carry in solution one or more surfactants as foaming agents. According to Heller and Kuntamukkula (1987), the following factors have been mentioned to have influence on the flow behavior of foams:

a. the ratio (mean bubble size/flow channel size),

b. size distribution of bubbles,
c. flow-induced anisotropy of bubble distribution,
d. foamant-channel wall interactions such as slip and adsorption,
e. characteristics of flow geometry and flow rate,
f. quality of foam,
g. properties of the two fluid phases,
h. absolute pressure,
i. physicochemical nature and concentration of foamant, and
j. interfacial rheological properties of foam lamellae and their variation with time

Liquid drainage from the interfacial films and coalescence and rupture of bubbles have been mentioned as factors that can alter the size distribution of bubbles and, thus, the rheology of foam. The concept of apparent viscosity as a measure of the resistance to the flow of foam in either pipes, capillary tubes, or porous media has been mentioned to be only qualitatively useful.

A.2.2: Foam by Nature

Foam is a quantity of gas covered with a liquid film (lamellae). According to Falls (1988), foam in porous media can be defined as a dispersion of gas in a liquid, such that the liquid phase is continuous and at least some part of the gas is made discontinuous by thin liquid films called lamellae.

According to Armitage and Dawe (1989), foam in a porous medium on the macroscopic scale is defined as a gas-liquid system with the gas as a discontinuous phase
dispersed in a liquid, that contains a foaming agent (surfactant solution). Falls et al. (1988) determined two classes of foams. The first is a continuous-gas foam in which at least one gas channel is not interrupted by lamellae; thus, gas can flow through the pore network without having to displace lamellae. The second would be a discontinuous-gas foam in which there are no gas channels uninterrupted by lamellae; thus, lamellae must be transported through the pore system so that gas can flow.

Edwards and Wasan (1990) defined foam as a non-Newtonian material that can undergo shear and deformation. Plotting shear stress versus shear rate for the foam, Marsden and Khan (1966) understood that foam can be considered as a pseudoplastic substance. In addition, they observed that the apparent viscosity of foam also decreased with increasing shear rate and increased with increasing quality, which is defined as the ratio of gas volume to the total foam volume. Fried (1961) conducted experiments, and for the first time, proved the considerable difference between the viscosity of foam and its constituent phases of gas and liquid. According to Manlowe and Radke (1988), foam can be considered neither a true liquid nor a true gas, and it exhibits an apparent viscosity of up to 1000 times greater than its constituent phases, liquid and gas. Kasraie and Farouq Ali (1989) conducted experiments and understood that the apparent viscosity of foam depended on a number of factors, including flow velocity, pressure, and temperature.

Grove et al. (1951) expressed the apparent viscosity of foam as a function of foam mass density, which increased up to a maximum as the foam mass density increased. Foam mass density was increased by increasing pressure. Raza and Marsden (1967)
conducted experiments in capillary tubes and determined that foam viscosity was independent of quality, in contrast with the result obtained by Marsden and Khan (1966). According to Raza and Marsden the apparent viscosity of foam was found to decrease with an increase in temperature. Raza and Marsden (1967) and Raza (1970) also showed that anionic foaming agents produced low quality, stable foams, while nonionic agents yielded high quality, stable foams. Minssieux (1974) found that the liquid drainage was responsible for foam stability. According to the results obtained by Wang (1984) and Maini and Ma (1984), foam stability increases with increasing pressure, and decreases with increasing temperature. Foam quality decreases with an increase in pressure and decrease in temperature for a given surfactant condition. Persoff et al. (1984) found at a steady state, foam was shear thinning with respect to increasing gas flow but Newtonian with respect to increasing liquid flow. According to Hansen (1988), foams are not thermodynamically stable and decay into the gas and liquid phases, but foam can be mechanically stable.

Considering the triple factors of the liquid slugs, resistance to deformation of the interface of a bubble passing through a capillary, and surface tension gradient, a mathematical equation for the viscosity of foam was proposed by Hirasaki and Lawson (1985). Two useful properties of foam have been mentioned by David and Marsden (1969) and Wellington and Vinegar (1987). According to David and Marsden (1969), foam is a non-Newtonian fluid whose flow resistance decreases with increased velocity. According to Wellington and Vinegar (1987), foam can reduce the gas mobility even at a surfactant concentration less than 1000 ppm.
A.2.3: Foam Generation, Propagation, and Destruction

Regarding the mechanisms for foam generation and propagation, studies may be divided in two groups.

The first group of studies were conducted mostly with nitrogen or steam at pressures less than 1500 psia and high foam qualities. These studies include work by Friedmann and Jensen (1986), Falls (1988), Khatib (1988), Falls (1989), Persoff et al. (1989), Ettinger and Radke (1989), De Vries and Wit (1990), Radke and Gillis (1990), and Friedmann (1991). These are strong foams, Friedmann (1991), with liquid films or lamellae, that compose the foam, according to Friedmann and Jensen (1986), and are thought to be stable enough to survive movement from pore to pore. As a result, according to Rossen and Gauglitz (1990), foam generation and (according to Falls 1989; Rossen 1990a; and Rossen 1990b) foam propagation depends on exceeding a minimum pressure gradient for mobilizing lamellae.

The second group of studies done by Yang and Reed (1989), Chou (1990), and Kuhlman et al. (1990), were performed at higher pressures and lower foam qualities. In these weak foams, according to Holm (1968), where the lamellae do not move from pore to pore but break and reform at fixed locations, there may be no minimum pressure gradient for either generation or propagation (Yang and Reed (1989)).

A.2.3.1: Foam Generation Mechanisms

The fundamental pore-level mechanisms of foam generation were investigated by Ransohoff and Radke (1988) in a set of visual and parametric experiments. By visual
experiments of the primary mechanisms of foam generation in bead packs and by parametric experiments of the effects of gas velocity, fractional flow, bead size, and surfactant type on the relative importance of the generation mechanisms were determined. By these experiments, the following mechanisms responsible for the primary foam generation were introduced:

1. snap off,
2. lamellae division, and
3. leave behind.

Snap-Off, according to Ransohoff and Radke (1988), is a downstream mechanism in which bubbles are generated only at the exit of a constriction. For bubble generation to occur by downstream snap-off, several requirements must be satisfied. First, the porous media should be a water-wet system and sufficient surfactant solution must be available at the bubble generation site. Second, the wetting phase should backflow to generate a collar at the pore constriction. Third, a sufficient pressure drop should be present so that the non-wetting phase can invade the bubble generation site. Huh et al. (1989) observed two different snap-off mechanisms. Injection of CO₂ into the porous media saturated with surfactant solution resulted in downstream snap-off. Simultaneous injection of CO₂ and a surfactant solution, or the injection of a surfactant solution slug into a CO₂ saturated zone resulted in the bubble generation by upstream snap-off. The size of the bubbles generated by upstream snap-off is usually larger than the bubbles generated by downstream snap-off. Snap-off is believed to be responsible for the generation of strong foams in porous media.
Lamella Division, According to Ransohoff and Radke (1988), occurs wherever a lamella flows into two or more channels downstream of a branch point in the flow field.

According to Ransohoff and Radke (1988), the Leave-Behind mechanism is also responsible for bubble generation in which separate gas bubbles do not form, and only lamellae are generated. These lamellae are usually generated in a direction parallel to the flow path, and therefore do not contribute to any pressure drop or mobility reduction. The lamellae reduce sweep efficiency by obstructing crossflow. As gas invades a previously liquid-saturated region, it percolates through the many interconnected flow channels. Often two gas fronts approach the same liquid-filled pore space from different directions. When this happens, the liquid in the pore space is squeezed into a lamellae by the two fronts. If sufficient surfactant is present in the liquid phase, these lamellae may be stable; if not, they rupture. This mechanism does not require the two gas fronts to converge simultaneously; they can arrive at different times and squeeze down the lamellae as the local capillary pressure increases. Leave-behind leads to the formation of a large number of lamellae, blocking gas pathways. Leave-behind occurs below a critical velocity and generates a relatively weak foam.

Foam generation mechanisms were also observed by Huh et al. (1989). Bubble generation was observed by upstream and downstream snap-off at the bubble generation site and bubble subdivision at branching pores. According to Chambers and Radke (1991), generation mechanisms include snap-off, leave behind, and division. Lamellae leave behind and division are purely geometric in origin while snap-off is based on
capillarity. Division requires preexisting lamellae. Snap-off has been classified as neck constriction, preneck constriction, and rectilinear. Neck constriction snap-off occurs as gas entered the sites that were almost completely liquid filled. Preneck constriction snap-off occurs as wetting liquid induced a high liquid pressure gradient near the front of the bubble. Rectilinear snap-off occurs in relatively straight pores when the local capillary pressure falls and liquid invades to establish the critical corner saturation. In steady foam flow, rectilinear snap-off appears to be a dominant bubble generation mechanism. Generation mechanisms depend on pore-space geometry and topology, local capillary pressure, gas and liquid flows, and mode of injection (i.e., drainage versus imbibition). Surfactant serves a nonessential role in lamellae generation. The two minimum requirements for lamellae division are mobile lamellae and branching in the flow paths.

A.2.3.2: Foam Propagation Mechanisms

Mechanisms associated with foam propagation in porous media were investigated by Owete and Brigham (1987) in both homogeneous and heterogeneous micromodels using air and surfactant solution. Results showed that the displacement of aqueous surfactant solution by air in the homogeneous porous media could be described as modified channel flow. The liquid formed a network of interconnecting films around the matrix grains and between pores. Air was propagated as long bubbles flowing and extending across several pore lengths. Liquid and air were trapped in some pores. In the heterogeneous porous media, foam of various sizes was generated; small bubbles at high surfactant concentration and large bubbles at lower concentrations. Liquid flowed
through small pores while maintaining a continuous network through the lamellae. In the heterogeneous model, the propagation of films similar to the mechanisms in the homogeneous models was observed at low surfactant concentrations. A homogeneous fluid flow mechanism was proposed by Fried (1961), Marsden and Khan (1966), Raza and Marsden (1967), and David and Marsden (1969). According to these researchers, foam flows as a body; the gas and liquid flow at the same rate, and the foam behaves as a single fluid with high apparent viscosity.

Flowing of gas through porous media by breaking and reforming films, and transportation of the liquid as a free phase through the film network was suggested by Bernard et al. (1965), Holm (1968), and Mast (1972). Bernard and Holm (1964) and Marsden and Khan (1966) suggested that Darcy's law could be applied to liquid phase flow, while Kolb (1964), Nahid (1971), and Mast (1972) suggested that Darcy's law could be applied to both flowing liquid and gas phases in porous media.

A.2.3.3: Foam Destruction Mechanisms

According to the results obtained by Hirasaki (1989), the mechanisms recognized for steam foam destruction are: evaporation and condensation, coalescence at a limiting capillary pressure, and coalescence from the action of an oil phase. The evaporation and condensation processes can be retarded by the addition of a small amount of noncondensable gas. Coalescence increases with capillary pressure, and the capillary pressure may approach a limiting value as the quality is increased. High oil saturations promote coalescence and the oil saturation may have to be reduced by the steam from the
breaking foam for the foam front to be propagated. According to Chambers and Radke (1991), foam lamellae in porous media are generated and terminated at specific locations designated as generation and termination sites. Termination mechanisms, while mentioned as being based on capillarity in origin, have been identified as capillary suction coalescence and gas diffusion coalescence. Capillary suction coalescence is responsible for the breaking of flowing lamellae while gas diffusion coalescence is responsible for the breaking of trapped or static lamellae. Pore geometry, local capillary pressure, and gas and liquid flow rates are believed to be the parameters that affect the frequency of the coalescence events. The primary role has been assigned to surfactant. No foam lamellae, flowing or static, can exist without surfactant. Bubble size has been mentioned to be about the size of the pore channels.

A.2.4: Foam Flow through Porous Media

According to Holm (1968) and Owete and Brigham (1987), foam flow in porous media is controlled by bubble snap-off, coalescence, movement, and trapping. If films are unstable, foam propagates in porous media by breaking and reforming thin films. According to Sayegh and Girard (1989), the most important variables affecting the foam flow process in porous media may be considered as reservoir fluids, geometrical characteristics of the porous media, rock chemical composition and petrophysical properties, and physical conditions such as pressure and temperature. According to Holm (1968), foam movement in porous media consists of simultaneous movement of its
constituent phases: liquid (surfactant solution) as the lamellae and gas as the bubbles that continuously break down and reform. Therefore, the properties of the lamellae, such as strength, thickness, stability, and drainage rate, will affect the process of bubbles breaking down and reforming; thus, the apparent viscosity of the foam and at last the movement of the foam through porous media.

In general, the more stable the lamellae, the less mobile the foam will be through porous media; hence, it is possible to use foam in gas flooding to control the injected gas mobility. It has not been possible to make a quantitative description on foam rheology in porous media because of the complexity of the process. There are different results obtained by the experiments conducted on foam flow through porous media, indicating the complexity of the process. Huh and Handy (1986) report increasing foam mobility with increasing liquid velocity, while Nahid (1971) and Sanchez and Schechter (1986) report the opposite. Sanchez and Schechter (1986) and Treinen et al. (1985) observe hysteresis in foam mobility, whereas Huh and Handy (1986) do not. Both Huh and Handy (1986) and Sanchez and Schechter (1986) show that foam mobility (plotted as foam relative permeability) varies with the liquid saturation in the core, while De Vries and Wit (1988) find a constant liquid saturation in the porous medium. Friedmann and Jensen (1986) increased the flow rate in the absence of oil and obtained foam with a finer texture, while in the presence of oil they found a maximal oil saturation above which foam could not form. Isaacs et al. (1988) conducted high temperature experiments in porous media and found an optimal surfactant concentration beyond which no additional mobility reduction could be achieved. They also found that the optimal surfactant
concentration was higher in the presence of oil. The dependence of foam rheology upon foam quality and texture (bubble size and its distribution) was indicated by Fried (1961) and Hirasaki and Lawson (1985). Armitage and Dawe (1989) conducted foam flow experiments using micromodels, and found no dependency of bubble size upon the surfactant concentration while above (CMC). There also was no dependency on the flow rate, except at very high flow rates when small bubbles were generated in the upstream pore throats due to interfacial instabilities. They also found the bubble size to be linearly dependent upon the wetting fluid viscosity at a low flow rate. Khatib et al. (1988) conducted experiments investigating the effects of capillary pressure on foam flow through porous media and found the stability of foam lamellae was limited by capillary pressure. At constant gas velocity, by increasing the fractional flow of gas in the foam, the capillary pressure in a porous medium first increased, and then approached a limiting capillary pressure. By increasing the gas fractional flow after the limiting capillary pressure had been attained, coalescence coarsened foam texture, the liquid saturation remained constant, and the relative gas mobility became proportional to the ratio of gas-to-liquid fractional flow. The limiting capillary pressure varied with the surfactant formulation, gas velocity, and permeability of the medium. According to Manlowe and Radke (1988), there is no experimental data on foam rheology in porous media in the presence of an oil phase. A clear theoretical understanding of the mechanism of foam coalescence in the presence of oil also does not exist. However, it is generally agreed that oil weakens foam. Manlowe and Radke (1988) investigated foam/oil interactions in porous media using etched-glass micromodels containing residual oil. They observed that
foam decayed as a result of breakage of pseudoemulsion films (water films between oil and gas). Foam collapsed whenever the thin aqueous films separating gas bubble and oil, ruptured. Chou (1991) conducted coreflood experiments and found that foam was readily formed by co-injecting gas and surfactant solution whenever the core was presaturated with surfactant, regardless of flow rate or pressure gradient. He concludes that foam generation in a porous media strongly depends on the initial saturation of the core, and that foam generation is significantly delayed whenever the core is not presaturated with surfactant solution. He also concludes that the flow rate is not a critical parameter for foam generation in porous media. Another conclusion by Chou is that foam is formed during drainage, not imbibition, and that increasing capillary pressure does not necessarily destabilize foam. On the other hand, Rossen et al. (1991) claim that foam stability depends strongly on capillary pressure.

A.2.5: Modeling Foam Mobility in Porous Media

There are a variety of empirical and theoretical models of foam mobility in the literature suggested by Falls (1988) & (1989), Friedmann (1991), Chou (1990), Mahmood et al. (1986), Fisher (1990), and Rossen et al. (1991). Most of them account for the fact that foam does not affect the relation between water mobility and water saturation, which was first observed by Bernard (1965). Since foam affects water mobility indirectly by altering water saturation but directly affects gas mobility, predicting foam mobility is more precisely a matter of predicting gas mobility in the presence of foam.
There are three approaches in the literature to modeling gas mobility in foams. First there are empirical expressions for gas mobility as a function of flow rates, surfactant concentration, and other factors. These empirical expressions have been used by Mahmood (1986), Kular (1989), and Islam and Farouq Ali (1990). The second approach includes models that explain the breaking and reforming processes that control weak foams (Chou (1990)). In the third approach, population balance models have been used by Falls (1988 & (1989), Friedmann et al. (1991) and Chang (1990) for strong foams.

As a working hypothesis for strong foam at steady state, Rossen et al. (1991), Persoff et al. (1989), and Ettinger and Radke (1989) agree on the implications of the limiting capillary pressure concept, explained by Khatib et al. (1988). According to Rossen et al. (1991), the minimum pressure gradient for flow of a foam with a given texture is somewhat lower than estimated by previous investigators.

A.2.6: Simulation Work on Foam Rheology in Porous Media

Based on observations during a series of experiments on a scaled-model, a semi-analytical model has been proposed by Mahmood (1986) that predicts the oil recovery and pressure history from two-dimensional systems undergoing gas/surfactant injection. The model is based on the concept of a combination flood, in which gas/foam and surfactant solution flow in separate gravity tongues. The gas/foam displacement is assumed to follow the Buckley Leveret theory, whereas the surfactant displacement follows the Dietz model. A combination of these two theories has been used because the
displacements through the tongues have been considered mutually dependent.

To incorporate the mobility dependence of a foam on its texture in a mechanistic simulator, Falls et al. (1988) coupled the usual conservation equations with balances on the densities of flowing and stationary bubbles in the foam. Models for the critical capillary pressure and rate of generation of foam by capillary snap-off have been developed. These models together with one for gas mobility as a function of foam texture have been incorporated into a one-dimensional, finite-difference formulation of the mass-balance and population-balance equations. The simulator has been used to investigate the generation and flow of foam in a bead pack with changes in permeability. Falls (1989) developed a theory to describe the apparent viscosity of foams in smooth capillaries and extended it to account for (1) the capillary pressure imposed by the porous medium and (2) constricted flow paths. This theory has been used to correlate the data obtained from mobility measurements of aqueous foams of known texture in homogeneous bead packs.

Ettinger and Radke (1989) presented a simple one-dimensional foam population-balance model to quantify the flow and texture behavior agreement between the proposed model and observation was adequate. The two-dimensional simulator developed by Chang (1990) has the possibility to model many of the processes associated with channel blockage by foam and diversion of flow into the bypassed oil matrix. Based on published data for foam flow, Fisher (1990) developed two- and three-phase steady-state foam mobility models which exploit the dominant role of the foam coalescence mechanism. The mobility models have been used in a finite difference, three-phase, multi-component
The simulator has been applied to show that it can reproduce the generic transient foam behavior observed in core floods.

Chou (1990) presented a statistical network model and percolation theory to describe the behavior of foam in porous media based on pore geometry and the assumption that foam lamellae are generated by snap-off in pores with an aspect ratio greater than some critical value. The probability of snap-off and the percolating conductivity of the network have been calculated, approximated by the Bethe tree, which relates to two-phase permeabilities. The theory predicts that gas relative permeability is greatly decreased by foam and approaches zero at the trapped gas saturation corresponding to the minimum gas saturation below which the gas channels become discontinuous. The theory is able to describe gas and water relative permeabilities quantitatively, with or without foam.

Islam and Farouq Ali (1990) have presented a mathematical formulation that provides one possible representation of foam behavior in a porous medium. This formulation explains the blocking mechanism of foam in the presence of oil and water. The mathematical model has been tested against experimental results, showing good agreement. Friedmann et al. (1991) simulated high-temperature surfactant foams by modifying gas-phase mobility in a conventional thermal simulator. Both surfactant-alternative-gas (SAG) and gas/liquid-coinjection processes were modelled. Foam generation by leave behind and snap-off as well as foam coalescence and trapping mechanisms were incorporated in the model by an equation for the number density of foam bubbles; gas-phase relating permeability and apparent viscosity were modified
according to the bubble density. Pressure and saturation data of laboratory corefloods were successfully history matched with simulation results. Rossen et al. (1991) presented a model based on foam stability dependence on capillary pressure. In at least some conditions, capillary pressure, and therefore liquid saturation and mobility, would be maintained uniform and constant, independent of gas and liquid flow rates.

A.2.7: The Use of Foam for Mobility Control

Gas injection is often considered for enhanced oil recovery (EOR) because the residual oil saturation to gas may be less than the saturation to water. However, the high mobility of gas that results in early breakthrough can lead to low sweep efficiency; this would cause it to be uneconomical to continue production. One way of reducing the gas mobility is the use of foam. To achieve and maintain mobility control in oil reservoirs, the foam should remain stable against collapse. According to Armitage and Dawe (1989), foam has two advantages over other conventional EOR techniques. First, its ability to improve the sweep efficiency of the gas flood by effectively increasing the gas phase viscosity and hence reducing its mobility. It therefore provides a favorable mobility ratio between displaced and displacing fluids leading to reduced viscous fingering, gravity override, and channelling through high permeability zones. Second, foam flooding has the possibility, providing a suitable gas injection composition, of being multicontact miscible and hence eliminating total capillary resistance effects, a major cause of oil entrapment.
There are also some limitations on the application of foam. Experiments by Wellington (1985) and Wellington and Vinegar (1987) indicated the deleterious effect of oil on foam. According to Kuhlman (1990), three problems limit the application of foam. The first of these problems is that surfactant adsorption limits foam propagation. The second problem is the large pressure gradient observed in some foams. According to Irani and Solomon (1986), laboratory pressure gradients can be 10 to 100 psi/ft, while gradients greater than 1-2 psi/ft are not practical in a reservoir-wide application. The third problem was observed by Irani and Solomon (1986) as the decrease in oil recovery because of large mobility reduction. The three problems could be corrected if a surfactant that exhibits low adsorption was a weak foamer and emulsifier, but could still reduce gas mobility.

A.2.8: Flow Visualization

To facilitate a better understanding of foam rheology in porous media, glass beads in glass tubes or glass etched micromodels were used to visualize the flow. Flow visualization experiments are usually accompanied by a VCR system so that future review of the experiment be possible. Glass tube flow visualization has been reported by Fried (1961) Radke and Ransohoff (1986), Gauglitz et al. (1987), Hanssen (1988), Khatib et al. (1988), Falls et al. (1989), Hanssen and Dalland (1990), Llave et al. (1990), Brock and Orr (1991). Glass micromodel flow visualization has been reported by Koplik and Lasseter (1982), Bahralolom et al. (1985), Morrow et al. (1986), Bahralolom and Orr (1986), Owete and Brigham (1987), Martin and Kovarik (1987), Huh et al. (1988),
Armitage and Dawe (1989), Chang et al. (1990), Kuhlman (1990), Manlowe and Radke (1990), and Hornbrook et al. (1991).

Some visualization work has been performed that may be classified as neither glass tube flow visualization nor glass micromodel flow visualization. These have been reported by Mahmood et al. (1986), Suffridge et al. (1989), Llave and Olsen (1990), Schramm et al. (1990) and Stern (1991).
B: Introducing the New Evaluation Tool

B.1: Introduction

One flow experiment is usually compared with another based on the pressure drop across a micromodel or core. An average pressure drop ($\Delta P_{\text{ave}}$) for an experiment at specific conditions (i.e., flow rate, surfactant concentration, ... etc.) is often used to evaluate the quality of foaming, stability of the generated foam, and the uniformity of the flow front. In this work the average pressure drop for a WAG run sometimes was larger than that of the corresponding SAG run. Could this be interpreted as better foaming in WAG? Higher average pressure drop for WAG has also been observed by Kovaric and Heller (1989), and Chang and Martin (1992). The average pressure drop does not tell us anything about how the displacing fluid moves through the porous media at any moment. As an example, consider the pressure drop variations shown in figures B.1.1a through B.1.1d. All of these pressure drop variations have the same average value, thus would be evaluated as being equal if $\Delta P_{\text{ave}}$ is used as the evaluation tool. It can hardly be assumed that these pressure drop variations are an indication of the same flow patterns.

The pressure parameter ($P_P$), introduced in section B.4, will be used as an evaluation tool to compare the quality of foaming and uniformity of the flow front at different conditions. To introduce the new evaluation tool, two basic concepts, uniform flow front and bubble analogy, need to be reviewed.
Fig. B.1.1: Different pressure drop variations with the same average value.
B.2: Uniform Flow Front

Consider point \( A_i \), as a passage in a porous media as indicated in Figure B.2.1. Assume that \( m_{ij} \) is the mass of fluid passing through an unit cross sectional area (area open to flow) at point \( A_i \) in a period of time, \( \Delta t_j \). The subscript \( i \) refers to possible passages that may be open to flow, and the subscript \( j \) refers to the time interval in which fluid is flowing through a passage. Also assume that fluid may flow through point \( A_i \) for a specific time interval while, flow is stopped at all other points across the porous media (e.g. if \( m_{11} > 0 \), then \( m_{21}, m_{31}, \ldots = 0 \)). Notice that in general, flow at a point may be different at different time intervals, i.e. \( m_{11} \neq m_{12} \).

The flow front is uniform if the least possible amount of mass per unit cross sectional area, \( m_{ij} \), at the shortest possible time interval, \( \Delta t_j \), flows through any point before it is stopped at that point and started at a different point (i.e., flow is stopped at point \( A_i \) and diverted towards a different point). However, flow front will be uniform if there is flow at all points, at the same time, but at slightly different velocities.
Fig. B.2.1: Flow front in a porous media is uniform if the least possible amount of mass and at the shortest possible time interval flows through any point such as (A) before flow stops temporarily at that point and starts at a different point.
**B.3: Bubble Analogy**

When foam flows through porous media, each gas bubble feels a different resistance depending on the relative sizes of gas bubbles and passages. Consider a gas bubble flowing through a porous media as it approaches a restriction (i.e., throat). When this gas bubble is far from the throat (Figure B.3.1), it has minimal influence or restrictive effect on fluid flow through the throat. As the gas bubble approaches a throat its restrictive effect on fluid flow increases. When the bubble reaches the throat, (Figure B.3.2), it will have the most restrictive effect on fluid flow through the throat and may stop the flow of fluid through that throat. After this gas bubble has passed the throat, the throat will again become open to flow of fluid. Depending on how often and how fast a gas bubble approaches a throat, the degree of restriction to fluid flow through the throat and the rate at which this restriction is applied, change from time to time. A simple analogy comparing a gas bubble in a pore throat to a valve in a pipe is shown in the following:

1. A fully opened valve corresponding to a gas bubble far from the throat with no restrictive effect on fluid flow through the throat.

2. A partially opened valve corresponding to a gas bubble close to the throat.

3. A fully closed valve corresponding to a gas bubble at the throat.
Fig. B.3.1: Gas bubble does not have any restrictive effect on the pore throat.

Fig. B.3.2: Gas bubble has plugged the pore throat.
B.4: Introducing the Tool

The above two concepts are used in a simple model to understand how the displacing fluid has been moving through the porous media. Indicated in Figure B.4.1 is a piping system comprised of a pump, uniform valves, and a differential pressure transducer. Assume that all valves except one (valve 1) are closed and a liquid is pumped through the branches. The pressure drop $\Delta P_1$ shown in Figure B.4.2 is due to two contributions: the viscosity of the liquid and the resistance of the piping system in which the liquid is flowing. Assuming a constant viscosity, a higher pressure drop is an indication of a larger resistance in the piping system to the flow of liquid. If valve 1 is partially closed while the pump is running, pressure drop will increase to $\Delta P_2$ corresponding to the degree to which the valve has been closed. The height of $\Delta P_1 \Delta P_2$ will be an indication of the increase in resistance of the piping system and the slope of $\Delta P_1 \Delta P_2$ an indication of how fast the valve closed. If the valve is again opened, pressure drop will decrease to $\Delta P_3$ corresponding to the degree to which the valve has been opened. Another closing and opening of the valve will increase the pressure drop to $\Delta P_4$ and decrease it to $\Delta P_3$ respectively, corresponding to the degree that the valve has been closed or opened. If the heights of $\Delta P_1 \Delta P_2$, $\Delta P_3 \Delta P_4$, etc. are small, resistance change of the system is small before one valve has been closed and another one has been opened. A smaller slope indicates that closing one valve and opening another one has occurred at a slower rate. Assuming a homogeneous piping system, it is not necessary to close the same valve that has been opened. When pressure drop is increased by closing valve 1, it can be decreased by opening a different valve such as valve 2. If all
valves are closed and opened irregularly and simultaneously, then changes in the pressure drop will also be irregular (Figure B.4.3). The value of the pressure drop indicates the resistance of the piping system (how many and to what degree each valve has partially closed or opened) at any moment.

In a porous media, gas bubbles approach and pass the throats irregularly (i.e., at different frequencies and speeds of closing passages), hence alternatively restricting the flow of fluid through the passages, creating an irregular changes in the pressure drop. Considering any of the lines $\Delta P_1\Delta P_2$, $\Delta P_2\Delta P_3$, $\Delta P_3\Delta P_4$, and $\Delta P_4\Delta P_5$, the smaller the lengths of these variations the less the amount of fluid passing through a point before flow is stopped at that point and started at another point in porous media. The larger the number of variations in a certain time interval, the larger the number of passages that have been opened to the flow of fluid over that time interval. On the other hand, the average value of a variation is an indication of the resistance of the system at the time the variation was occurring. Notice that each variation such as $\Delta P_1\Delta P_2$ or $\Delta P_2\Delta P_3$ has a minimum and maximum point. In two phase flow through porous media, a change in pressure drop is due to the combination of the effects at numerous points at the same time.

In summary, a pressure drop variation curve is an indication of the flow pattern. The smaller the height of the variations, the larger the average value of the variations, and the larger the number of these variations in a certain time interval, indicate the existence of a more uniform flow front. Fortunately, the effects of the heights of the variations, the average value of the variations, and the number of variations per unit time
interval may be formulated in an equation that creates a unique trend. This new equation or tool will be referred to as the **Pressure Parameter**, \( P_p \).

\[
P_p = \frac{t}{N} \sum_{k=1}^{N} \left[ -\frac{\Delta P_{\text{max}_k} - \Delta P_{\text{min}_k}}{\frac{1}{2} (\Delta P_{\text{max}_k} + \Delta P_{\text{min}_k})} \right]
\]

Where \( N \) is the number of variations per time interval of \( t \). For good foaming and creation of uniform flow front, the number of variations per unit time is relatively large, the lengths of variations are small, and the value of the average of any variation is relatively large, hence the value for pressure parameter \( (P_p) \) is relatively small. Notice that the value of \( P_p \) for the pressure drop variations shown in figures B.1.1a through B.1.1d are not the same, therefore they will not be evaluated equally if the \( P_p \) is used as the evaluation tool. Using average pressure drop \( (\Delta P_{\text{ave}}) \) would lead to an equal evaluation of the pressure drop variations indicated in figures B.1.1a through B.1.1d. The \( P_p \) can be calculated for any arbitrarily selected time interval, \( t \); however, \( t \) should be small enough to show changes in \( P_p \) throughout the run.
Fig. B.4.1: Piping system representing bubble effects in porous media.

Fig. B.4.2: Pressure drop variation due to single valve operation.

Fig. B.4.3: Pressure drop variation due to irregular multi-valve operation.
C: Experimental Apparatus and Procedure

C.1: Apparatus

Indicated in Figure C.1.1 is the schematic of the apparatus (Chang, 1991). The apparatus was originally designed by Campbell (1983) and has been used and modified by Bahralolom (1985), Cochrane (1990), and Chang (1991) since then. The micromodel is placed in a high pressure cell filled with glycerine. A hand pump is used to increase the glycerine pressure to above the test pressure. Three ISCO constant flow rate pumps (model 314) are used to inject liquid, gas, and oil into the micromodel. Back pressure is supplied by a nitrogen vessel (with a capacity of one gallon). A differential pressure transducer (Honeywell STD-120) is used to measure the pressure drop across the micromodel. Four pressure transducers measure the pressure of liquid (brine or surfactant solution), CO$_2$, micromodel, and the back pressure vessel. The micromodel, liquid, and nitrogen vessel pressure transducers are Validyne model DP15 differential pressure transducers. The CO$_2$ pressure transducer is a Validyne model AP-10 absolute pressure transducer. A foam generator is used when an injected pregenerated foam is desired. A sight glass in the by-pass line is used to assure the stability of flow through the by-pass line before it is diverted through the micromodel. Pressure drop across micromodel is recorded by a strip chart recorder (Houston Instrument model B5117-2). A camera (Panasonic model VW-D 5000 with a 380 lines of horizontal resolution, a 12X power servo-control zoom lens with a Panasonic 1.5X teleconversion lens at the rear, and three 72 mm diopters at the front), VCR (Panasonic, model AG-1960 S-VHS), and color
monitor (Sony Trinitorn model KV-2095-R) is used to film the events during the run for future review. The whole system except the camera, VCR, monitor, chart recorder, glycerine hand pump, and the oil pump are enclosed in an air bath kept at the test temperature. The apparatus has been explained in more details by Campbell (1983), Bahralolom (1985), Cochrane (1990), and Chang (1991).
Fig. C.1.1: Schematic of flow visualization apparatus.
(from Chang 1991)
C.2: Experimental Procedure

Indicated in Figure C.2.1 is the flow diagram of the apparatus (Chang, 1991). First the micromodel was saturated with either brine, surfactant solution, or oil. Either pure CO₂, brine, surfactant solution, brine alternating with CO₂ (WAG), surfactant solution alternating with CO₂ (SAG), brine alternating with CO₂ through foam generator, or surfactant solution alternating with CO₂ through foam generator were injected into the micromodel.

The micromodel was saturated and partially pressurized the night before the test so that temperature equilibrium could be reached over night. Prior to the start of each run, the injection fluids were put in communication with the presaturated micromodel and back pressure vessel step by step. The liquid and gas pumps were turned on to inject the two phases through the by-pass line. The chart recorder was turned on to record the pressure drop across the micromodel. The camera and monitor were also turned on. About an hour after the gas-liquid interface appeared in the sight glass, the chart speed was increased. Flow was diverted through the micromodel, and the timer started. After a couple of minutes, the chart speed was reduced to the normal speed (4 inches/hour). This helped to determine the constant pressure drop across the micromodel during single liquid phase flow through the micromodel. This is a short period of time beginning at the time of diverting flow towards the micromodel (when both sides of the differential pressure transducer sense the flow of the single phase liquid). The purpose of determining this constant pressure drop at the beginning of each run was to compare this to the average pressure drop after foam had been generated in the micromodel. This
difference is an indication of the resistance of the foam in the system.

The camera was focused on the micromodel inlet to record the entrance time. The entrance time corresponds to the first interface appearing at the inlet. The camera was then focused on different points to view the displacement before breakthrough. The breakthrough time corresponds to when the first interface passed the micromodel outlet. After breakthrough, the camera was focussed on different points during the run to record various events.

Two micromodels with different patterns were used. Indicated in Figure C.2.2 is the modified layered (MLAY) micromodel, and in Figure C.2.3 is the modified heterogeneous (MHET) micromodel. The MLAY micromodel has already been used by Martin and Heller (1990). The MHET micromodel has already been used by Huh et al. (1989) and Kovaric and Heller (1989). The characteristics of the two micromodels are given in Table 1. The MHET micromodel has been referred to as MDH by previous investigators.

The experiments have been run mostly at 1.0 cc/hr and for a period of about 2 hours, therefore increase in back pressure during the run period has been negligible (the capacity of the back pressure vessel is one gallon). Base conditions for the tests were temperature of 101° F, pressure of 2100 psig, Gas-liquid ratio of 4/1, surfactant active concentration (by weight) of 2500 ppm, and total flow rate of 1.0 cc/hr. The surfactant Chaser CD1045 was used. This was supplied by Chevron Chemical Company as 46.7 wt% active.

The recorded pressure drop across the micromodel was analyzed and presented
in four plots. First, the variation of pressure parameter versus pore volume injected. Pressure parameter was calculated at arbitrary time interval of about 6 minutes. The calculated pressure parameters were used to plot the variation of pressure parameter versus pore volume injected. Second, all maximum and minimum points on the recorded pressure drop were used to obtain the average pressure drop for each time interval. The calculated average pressure drops for time intervals were used to plot the variation of the pressure drop across the micromodel versus pore volume injected. Third, the average of the pressure parameters for all time intervals was used as an averaged pressure parameter for each test. Fourth, the average of the pressure drops for all time intervals was used as an averaged pressure drop for each test. The analyzed pressure drop data corresponding to this study is presented by Salehpoor (1993).
Fig. C.2.1: Flow diagram of flow visualization apparatus. (from Chang 1991)
Fig. C.2.2: Modified layered micromodel (MLAY) shown in actual size. Pore space is dark.

Fig. C.2.3: Modified heterogeneous micromodel (MHET) shown in actual size. Pore space is dark.
D: Results and Discussion

D.1: General Reminders

The rheology of foam in micromodels (particularly in the case of the MLAY) when compared to rheology of foam in an actual reservoir is not the same. The relative dimensions of the injected slugs and of the micromodel, pore structures, and matrix composite of the micromodel are significantly different from an actual field.

While liquid and gas were injected simultaneously at a controlled rate, the alternating slugs of liquid and gas entered the micromodel. The relative lengths of the liquid and gas slugs could not be controlled. The lack of control over lengths of the liquid and gas slugs might have had effects on the results particularly when verifying the effect of gas-liquid ratio. Sometimes fluid flow was established in only one path, as was observed by Falls et al. (1989) in homogeneous bead packs. A single path reduces the pressure drop across the micromodel, causing inconsistency in the results when fluid flow is not established in only one path.

Although this work does not suggest the use of an averaged value as a comprehensive tool to compare the data corresponding to different conditions, both the pressure drop and the pressure parameter have been used as an average for different runs. The emphasis is on looking at comparing the variation of the pressure parameter versus time (or pore volumes injected) at different conditions. For each run both pressure parameter and pressure drop have been used as evaluation tools for analyzing the recorded pressure drop across the micromodel versus time.
The conclusions of this work are based on interpreting the data, visual observations, and the interpretations on the way it might occur in a real field. While a low value of pressure parameter is an indication of a uniform flow front, the effect of oil has been explained based on observations.
D.2: Results at the Absence of Surfactant

D.2.1: Results with brine

A series of tests were done without surfactant to aid in determining the effects of adding surfactant to the brine solution. The effects of flow rate, gas-liquid ratio, and in situ generation versus pregeneration were tested. There are two general observations to mention. First, without the presence of surfactant, whenever gas bubbles came in contact with each other they coalesced immediately. As a result, small bubbles and in general bubbles close to each other were not observed. The flow was in the form of relatively large slugs which extended over many pore bodies. Second, arrival CO₂ avoided entering pores which were already occupied by trapped CO₂ unless all nearby path choices were occupied by trapped CO₂ (see Figure D.2.1). If all pores were occupied with trapped CO₂, arrival CO₂ might have entered any of the surrounding pores and would have coalesced with trapped CO₂ in that pore. As a result, bubble generation was significantly reduced and flow of fluid (CO₂) was established in one path. This single path might change from time to time, however, fluid (CO₂) was often flowing in only one path. When bubbles touched each other in this path, they coalesced, sometimes generating CO₂ slugs extending from micromodel inlet to outlet. During the time CO₂ flowed as a single phase through one path, the pressure drop was close to zero.

After gas breakthrough occurred, when pure CO₂ was injected into the micromodel initially saturated with brine, CO₂ usually followed a single path accompanied by a relatively small constant pressure drop across micromodel. If the flow
path changed, for a short period of time flow of fluid (CO\textsubscript{2}) would be established in more than one path. Multipath flow was accompanied by an increase in the average pressure drop and fluctuation in pressure drop across the micromodel. After a short time, flow would be reestablished in a single path. This might be the previous single path, or a different one. When brine alternating with CO\textsubscript{2} was injected into the micromodel saturated with brine, flow was establishing through multiple paths more often than when only pure CO\textsubscript{2} was injected. This resulted in brine alternating with CO\textsubscript{2} having a better sweep efficiency than injecting pure CO\textsubscript{2}.

The high average pressure drop across the micromodel when injecting brine alternating with CO\textsubscript{2} was not due to good foaming. This fact has also been pointed out by Kovarik and Heller (1989). When CO\textsubscript{2} entered a pore saturated with brine, the invasion occurred in a relatively short time. This would create a larger resistance accompanied by a large fluctuation in pressure drop across the micromodel. This might explain larger pressure drop in WAG than in SAG.

The fact that CO\textsubscript{2} enters a pore saturated with brine suddenly, might be due to the point that CO\textsubscript{2} seemed to avoid entering pores that were already occupied by CO\textsubscript{2}. This caused the pressure to increase until the resistance to flow was overcome and the advancing CO\textsubscript{2} not to move into many of the surrounding pores. At 2100 psig, CO\textsubscript{2} is a relatively incompressible fluid, thus forcing its movement into only one pore to occur suddenly.

In the absence of surfactant, bubbles are stable if they are separated from each other and unstable and if they come into contact with each other. This makes it difficult
to predict and expect consistency in the results when the runs at different conditions are compared to each other.

Keeping the bubbles relatively far from each other will prevent them from coalescing. This will create a larger resistance against the flow which is accompanied with a reduction in mobility. In order for the bubbles to remain separated from each other, CO₂ must be injected at the shortest possible time interval, followed by a longer time interval (enough so that alternatively injected gas bodies are well separated from each other) of injecting brine, assuming gas and liquid are injected at the same flow rate. As an example, injecting one second of CO₂ followed by injecting one minute of brine will work much better than injecting one minute of CO₂ followed by injecting sixty minutes of brine, even though the amount of injected CO₂ and brine in a sixty and one minutes time interval will be the same for both cases. In the first case, the injected CO₂ exists as a large number of small bodies in porous media, creating a large resistance and pressure drop. In the second case, the injected CO₂ exists as a large single body. Even though this large single body may undergo subdivision, the generated smaller bubbles will soon coalesce, therefore a large resistance against the flow will not be created. Referring to section B.3, in the first case there will be numerous valves (corresponding to the existence of numerous bubbles) in the system; hence creating a large resistance and pressure drop. In the second case there will be only one valve (corresponding to the single large gas body); hence creating a low resistance and pressure drop.

Verifying the effect of shortening the injection time interval for CO₂ and brine on pressure drop across porous media, and thus on mobility reduction, is suggested as future
work. As mentioned, particularly in a WAG run, flow may be established in only one path after breakthrough, causing reduction in pressure drop across porous media. This effect may be eliminated by keeping the magnitude of the total flow rate well below the pore volume of the porous media so that gas breakthrough time be reasonably long.
Fig. D.2.1: CO2 avoided entering pores which were already occupied by trapped CO2.
The results at different flow rates for in situ generated foam are presented in figures D.2.2(a,b,c,d). The variations of pressure parameters (Figure D.2.2a) have large values. This indicates a non-uniform flow front. The fluctuation in these variations also indicates that the uniformity of flow front changes from time to time. The variations of pressure drop (Figure D.2.2b) corresponding to 0.5 and 4.0 cc/hr have large values and more fluctuations, while those at 1.0 and 2.0 cc/hr have lower values. In fact, as flow rate increased from 0.5 cc/hr to 1.0 and 2.0 cc/hr, the corresponding average pressure drop decreased, which is unexpected. At higher flow rates, more gas is injected into the micromodel per unit time. As a result, larger CO₂ slugs broke through from inlet to outlet for a longer time interval; resulting in reducing the pressure drop corresponding to the flow of CO₂ in only one path and for a longer time interval. This might explain reduction in pressure drop across the micromodel with an increase in flow rate. The unexpected variation of pressure drop across the micromodel versus flow rate supports the concept that conclusions based on the pressure data only may be misleading; hence flow visualization is important. Average pressure parameter and pressure drop (figures D.2.2c and D.2.2d) also do not have the same trend in predicting the uniformity of flow front at different flow rates. Please be reminded that a lower average pressure parameter and a larger pressure drop indicates a more uniform flow front.
Fig. B.2.2a: Pressure parameter is compared at different flow rates. The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected.
EFFECT OF FLOW RATE

Fig. D.2.2b: Pressure drop is compared at different flow rates. The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected.
Fig. D.2.2c: Average pressure parameter is compared at different flow rates. The MLAV micromodel was saturated with brine and then brine alternating with CO₂ was injected.
**Fig. D.2.2d:** Average pressure drop is compared at different flow rates. The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected.
When the foam generator was used, foam was not generated but slugs of CO₂ and brine entered the micromodel. These slugs were similar to those from injecting brine alternating with CO₂ without using the foam generator. The results are presented in figures D.2.3(a,b,c,d). The results shown in figures D.2.3d and D.2.3b in which the pressure drop across the micromodel was decreased with increasing flow rate were unexpected. Looking at Figure D.2.3a, the fluctuation in pressure parameter indicates no trend in the uniformity of flow front. However, the consistent increase in pressure parameter with increasing flow rate (Figure D.2.3c) should not be interpreted as a more uniform flow front at lower flow rates, because of bubble instability and the fact that we can not rely on any average value to compare tests at different conditions.
Fig. D.3.3a: Pressure parameter is compared at different flow rates. The MINAY micromodel and foam generator were both saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator.
EFFECT OF FLOW RATE (PREGENERATION)

Fig. D.2.3b: Pressure drop is compared at different flow rates. The MLAY micromodel and foam generator were both saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator.
Fig. D.2.3c: Average pressure parameter is compared at different flow rates. The MLAY micromodel and foam generator were both saturated with brine and then brine alternating with CO\textsubscript{2} was injected into the micromodel through the foam generator.
Fig. D.3.3d: Average pressure drop is compared at different flow rates. The MLAY micromodel and foam generator were both saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator.
A number of tests were done varying the gas-liquid ratio (G/L). The results for in situ foam generation are presented in figures D.2.4(a,b,c,d). When G/L was infinite, pure CO₂ injection, flow was established in one path after breakthrough. As a result, pressure drop variation across the micromodel became flat and almost zero. The pressure parameter and pressure drop variations corresponding to this time interval are indicated as a dashed line in figures D.2.4a, D.2.4b, D.2.5a, and D.2.5b. More separation in bubbles is expected at lower G/L ratios. This separation will keep bubbles from coalescing and increases the resistance of the micromodel against the flow. This expectation was not always satisfied because of the following two effects:

1. The initial saturation (brine) changes the G/L ratio in the micromodel.
2. The length of the entering slugs are comparable to the length of the micromodel.

The fluctuations at different G/L ratios in Figure D.2.4a are due to bubble instability and indicate that a uniform flow front was not achieved. In Figure D.2.4b, the variation of the pressure drop corresponding to G/L ratios of 4/1 and 1/1 are almost the same for about the first two pore volumes injection. This fact is not indicated in Figure D.2.4d in which each run is represented by an average pressure drop. Thus, more detailed information about the flow pattern is given when looking at the variation of the data versus time or pore volumes injected. When each run is represented by an average (average pressure parameter or pressure drop), no information about the dynamic flow pattern is obtained.
Fig. D.2.4a: Pressure parameter is compared at different gas-liquid ratios. The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected.
EFFECT OF G/L RATIO

Fig. D.2.4b: Pressure drop is compared at different gas-liquid ratios. The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. The average pressure drop corresponding to injecting only brine (G/L=0.0) was about 0.0028 psi.
Fig. D.2.4c: Average pressure parameter is compared at different gas-liquid ratios. The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected.
The micromodel was saturated with brine and then brine alternating with CO2 was injected. Average pressure drop is compared at different gas-liquid ratios.
Foam was not observed when the foam generator was used, only slugs of CO₂ and brine entered the micromodel. The results are presented in figures D.2.5a through D.2.5d. The foam generator affected the frequency of CO₂ appearance at the micromodel inlet. As a result, sometimes CO₂ did not enter the micromodel for a relatively long time. The corresponding pressure drop variation was without fluctuation and had very low values. The variations corresponding to this time interval is indicated by a dashed line in figures D.2.5a and D.2.5b. The variations of pressure parameter at different G/L ratios (Figure D.2.5a) indicates non-uniform flow front. This may also be understood by the variations of pressure drop in Figure D.2.5b. The linearity in Figure D.2.5c is not representative because the single phase flow (dashed line) has not been considered in calculating average pressure drop at 1/4 and 4/1 G/L ratios.

The same as with in situ generation, in the case of pregeneration only slugs of brine and CO₂ entered the micromodel. The different trends in the pressure drop variations in figures D.2.5d and D.2.4d is due to bubble instability which makes predicting the results inaccurate. Figures D.2.6a and D.2.6b compare foam in situ generation versus pregeneration in the absence of surfactant. There was no evidence that the foam generator consistently changed the lengths of the slugs entering the micromodel. Different variations for in situ and pregeneration are due to bubble instability which may cause inconsistency in the results of tests at different conditions.
Fig. D.3.5a: Pressure parameter is compared at different gas-liquid ratios. The KLAY micromodel and foam generator were both saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator.
EFFECT OF G/L (PREGENERATION)

Fig. D.2.5b: Pressure drop is compared at different gas-liquid ratios. The MEAY micromodel and foam generator were both saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator.
Fig. D.2.5c: Average pressure parameter is compared at different gas-liquid ratios. The MLAY micromodel and foam generator were both saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator.
Fig. D.2.5d: Average pressure drop is compared at different gas-liquid ratios. The MLAY micromodel and foam generator were both saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator.
Fig. D.2.6a: Average pressure parameter is compared for foam generation by in situ and pregeneration. In Situ: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. Pregenerated: The MLAY micromodel and foam generator were saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator.
Fig. D.2.6b: Average pressure drop is compared for foam generation by in situ and pregeneration. In Situ: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. Pregenerated: The MLAY micromodel and foam generator were saturated with brine and then brine alternating with CO₂ was injected into the micromodel through the foam generator.
D.2.2: Effect of Salinity

While the effect of salinity was not originally included in the scope of this work, there were some experiments conducted with distilled water. A comparison of the corresponding data with those conducted with brine are reviewed here. Distilled water and brine are compared at 1.0 cc/hr, 2.0 cc/hr, and 4.0 cc/hr. The results are presented in figures D.2.7(a,b) through D.2.9(a,b).

According to Adamson (1982), surface tension of aqueous electrolyte solutions rises with concentration. When distilled water is used, it may be expected to have a lower surface tension, thus a lower pressure drop across the micromodel. Comparing figures D.2.7b and D.2.8b, the pressure drop for distilled water is consistently higher than for brine. However, as it has already been explained consistency is difficult to be interpreted in the absence of surfactant.
EFFECT OF SALINITY (1.0 cc/hr)

Fig. D.2.7a: Pressure parameter is compared for different initial saturation and injection fluid salinity. #1: The MLY micromodel was saturated with brine and then brine alternating with CO₂ was injected. #2: The MLY micromodel was saturated with distilled water and then brine alternating with CO₂ was injected. #3: The MLY micromodel was saturated with distilled water and then distilled water alternating with CO₂ was injected.
EFFECT OF SALINITY (1.0 cc/hr)

Pore Volume Injected (PV)

Pressure Drop (psi)

Fig. D.2.7b: Pressure drop is compared for different initial saturation and injection fluid salinity. #1: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. #2: The MLAY micromodel was saturated with distilled water and then brine alternating with CO₂ was injected. #3: The MLAY micromodel was saturated with distilled water and then distilled water alternating with CO₂ was injected.
Fig. 6.2.8a: Pressure parameter is compared for different initial saturation and injection fluid salinity. #1: The NLAY micromodel was saturated with distilled water and then distilled water alternating with CO₂ was injected. #2: The NLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected.
EFFECT OF SALINITY (2.0 cc/hr)

Fig. D.2.8b: Pressure drop is compared for different initial saturation and injection fluid salinity. #1: The MLAY micromodel was saturated with distilled water and then distilled water alternating with CO₂ was injected. #2: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected.
Fig. D.2a: Pressure parameters are compared for different initial saturation conditions. 1: The MIAY micromodel was saturated with distilled water and then brine alternating with CO$_2$ was injected. 2: The MIAY micromodel was saturated with brine and then brine alternating with CO$_2$ was injected.
Fig. D.2.9b: Pressure drop is compared for different initial saturation conditions. 

1: The MLY micromodel was saturated with distilled water and then brine alternating with CO₂ was injected. 
2: The MLY micromodel was saturated with brine and then brine alternating with CO₂ was injected.
D.3: Results in the Presence of Surfactant

When surfactant was present, the generated bubbles generally remained stable. It was much easier to evaluate and compare the results for these sets of experiments. However, conclusions were based on both the analysis of the recorded data and observations. The effects of flow rate, gas-liquid ratio, in situ foam generation versus pregenerated foam, surfactant concentration, initial saturation, and oil on the formation of foam and uniformity of flow front will be discussed in this section.

When surfactant solution alternating with CO₂ (SAG) was injected into the micromodel, bubbles were observed to penetrate various pores and channels even when already occupied by bubbles. Bubble stability and population density was much higher compared to WAG. Therefore SAG is distinguished from a WAG in two ways. First, more bubbles are generated in SAG than in WAG. Second, the generated bubbles are generally stable in SAG while they are unstable in WAG.

In contrast to WAG, bubbles travel more smoothly when passing from a pore throat into a pore body saturated with surfactant solution. The reason for smooth passage may be due to CO₂ being able to enter numerous pores and channels simultaneously. Therefore the disturbance to the CO₂ body is distributed over the front, hence any movement at any point of the front of the moving CO₂ body will be smoother.
D.3.1: Surfactant Molecular Structure

The molecular structure of surfactants consists of two parts, a hydrocarbon tail and a polar or charged head. The tail has affinity to oil while the head has affinity to water. When surfactant is added to a two phase system (such as water and CO₂), surfactant molecules will orient themselves at the interface of the two phases such that the tail is in CO₂ and the head in water. Surfactant molecular structure has been mentioned by Shaw (1966) in saying: "Materials such as short-chain fatty acids and alcohols are soluble in both water and oil (e.g. paraffin hydrocarbon) solvents. The hydrocarbon part of the molecule is responsible for its solubility in oil, whilst the polar -COOH or -OH group has sufficient affinity to water to drag a short-length non-polar hydrocarbon chain into aqueous solution with it. If these molecules become located at an air-water or oil-water interface, they are able to locate their hydrophilic head groups in the aqueous phase and allow the lipophilic hydrocarbon chains to escape into the vapor or oil phase. This situation is energetically more favorable than complete solution in either phase. The strong adsorption of such materials at surfaces or interfaces in the form of an oriented monomolecular layer (or monolayer) is termed surface activity. Surface-active materials (or surfactants) consist of molecules containing both polar and non-polar parts (amphiphilic). Surfactants are classified as anionic, cationic or non-ionic according to the charge carried by the surface-active part of the molecule."
D.3.2: The Role of Surfactant in Foam Stability

Three intermolecular forces acting across thin films have been recognized by Hunter (1987) in saying: "The forces which act across the film are: (a) the van der Waals force; (b) the electrostatic (or coulombic) interaction due to double layer overlap; and (c) the steric forces caused by the free energy increase which occurs when neutral or charged molecules are forced into unfavorable density or conformational situations." Coulombic forces are long range but van der Waals and steric forces are short range forces.

When CO$_2$ is introduced into a brine surfactant solution, surfactant molecules will locate at the interface as indicated in Figure D.3.1. When a gas bubble propagates through the liquid, at any time the surfactant molecules will be at its interface with the liquid. Because of the charged head (in case of ionic surfactant) the bubble may be considered as a body with an electric charge uniformly distributed over its surface. At larger separations coulombic forces are the dominant interacting forces between two bubbles. As bubbles have similar charges on their surfaces, the corresponding coulombic force will be a repulsive force. As a result, two bubbles repel each other and remain stable. At any smaller separation, when van der Waals and steric forces are significant, if the resultant intermolecular force between two bubbles (across thin film) is a net repulsive force, the bubbles will be kept far from each other and thus remain stable. In case of a nonionic surfactant, the head is polar instead of charged. In this case the head may be considered as a dipole. The same orientation of surfactant molecules at the interfaces causes a repulsion between two gas bubbles; hence they remain stable (Figure
D.3.2).
Fig. D.3.1: Surfactant molecules will locate at the interface in a two phase system.

Fig. D.3.2: Orientation of surfactant molecules with uncharged head groups at the interface.
According to Israelashvili (1992) the amounts of the interaction energies for ion-ion and dipole-dipole interactions are different and depend on the media in which the interaction takes place. As a result, different surfactants and also different media may result in different foam stability. As an example, a nonionic surfactant with a large head group such as Ethoxylated alcohols (e.g., dodecyl hexaoxyethylene glycol monoether) will keep the bubbles further from each other compared to a small head group such as Amine oxides (e.g., decyl dimethyl amine oxide); hence they may work better. On the other hand, a mixture of surfactants with opposite charges may not result in foam stability. This is because of locating the opposite charges in the same interface, thus vanishing a net repulsive force between the bubbles.

Based on this mechanism for foam stability, the following important conclusions may be drawn. First, conditions that can separate the head and the tail will result in foam destabilization since the molecular alignment at the interface will be destroyed and CO₂ (gas) bubbles will not repel each other any more; however, separating the tail and the head will not occur under realistic conditions. Second, conditions that cause the tail or the head to leave a phase (gas or liquid) will result in foam destabilization. This eliminates the molecular alignment at the interface, thus gas bubbles will not repel each other. It should be noted once the whole surfactant molecule is in one phase, nothing prevents this molecule from leaving the interface region and moving through that phase. Third, conditions that cause the physical removal of either of the two immiscible phases will result in foam destabilization. Examples are evaporation of the liquid phase and drainage of the liquid phase due to gravity. Oil destroys foam in short time by the
second mechanism which is discussed in section D.3.11.

Colloidal stability due to separation, because of a net repulsive force, may be found in the literature. According to Glasstone (1946): "The electrical properties of colloids, and other related phenomena, can be most clearly understood by a more detailed consideration of the electrical condition of a surface. It was suggested by H. von Helmholtz (1879) that an electrical double layer, of positive and negative charges, is generally formed at the surface of separation between two phases. According to modern views, at a solid-liquid interface, this double layer is made up of a layer of charges, i.e., ions in aqueous solution, which are firmly held to the solid, and a more diffuse mobile layer, extending into the solution. The resultant (net) charge of the diffuse layer is equal in magnitude but of opposite-sign to that of the firmly held, or fixed, layer....It is probably the presence of electrical double layers surrounding all the particles that accounts for the stability of a colloidal system; the mutual repulsion of these layers prevents the particles from approaching sufficiently closely for them to coalesce. When an ion of opposite charge to that of the colloidal particle is adsorbed, the double layer (electrokinetic) potential is decreased. As a result, the mutual repulsion of the particles is diminished and coalescence, with consequent precipitation, becomes possible."

According to Shaw (1966): "Particle aggregation is caused by the universal van der Waals attractive forces which operate between the atoms of the various particles. Stability against particle aggregation (flocculation) is a consequence of repulsive interactions between similarly charged electrical double layers around the particles
and/or particle-solvent affinity....Ideally, lyophobic sols are stabilized entirely by electrical double layer interactions, and are sensitive to flocculation by relatively small amounts of added electrolyte. The added electrolyte causes the double layers around the particles to be compressed (this is a non-specific effect), and the sol flocculates when the range of the double layer repulsive interactions is sufficiently reduced for the particles to approach close enough for van der Waals attractive forces to predominate.

According to Adamson (1982): "The action of antifoam agents in preventing foaming can be analyzed qualitatively along lines similar to the preceding material. First, of course, the agent should be able to displace the foam producing surfactant from the interface. The agent should then insert its own poor foam stabilizing characteristics into the system....There are many situations where van der Waals attraction is balanced by electrical double layer repulsion. An outstanding example is that of the flocculation of lyophobic colloids. A sol consisting of charged particles experiences both the double layer repulsion and the van der Waals attraction effects, and the balance of these determines the ease and hence the rate with which the particles can approach sufficiently close to stick together."

According to Hirtzel and Rajagopalan (1985): "van der Waals forces play an important role in many particle-particle or particle-surface interactions. Usually, these van der Waals forces are attractive in nature; however, it is also possible that the van der Waals interactions between two different materials immersed in a liquid medium can be repulsive....The possibility that the van der Waals interactions between different particles or molecules in a liquid can be attractive, repulsive or zero was suggested in
Hamaker's paper on London-van der Waals forces."

According to Hunter (1987): "When two colloidal particles (or two charged interfaces, in general) approach one another so that their electrical double layers begin to overlap the result is usually a repulsive force, which tends to oppose further approach....The systems of most concern to us here are what are called lyophobic or irreversible colloidal systems, for which the free energy is lowest when the particles are all condensed together into one large lump. Such systems can remain as individual particles for an appreciable time only if some mechanism prevents aggregation during a collision. There are two ways in which that can be done: (a) The particles can be given an electric charge (either positive or negative) and if all have the same charge they will repel one another more or less strongly when they approach. (b) The particles can be coated with an adsorbed layer of some material (say a polymer), which itself prevents their close approach. Mechanism (a) is referred to as electrostatic stabilization and mechanism (b) as steric stabilization, where the term stability refers to the aggregation behavior. Soap films are very easily formed by bubbling gas through surfactant solution and are stabilized by the repulsive forces between layers of surfactant molecules adsorbed at the air-solution interface. These repulsive forces are often sufficiently strong to prevent drainage of the water layer by combined action of attractive van der Waals forces and gravitational forces. For films with a water-layer thickness greater than about 10 nm the dominant force is, for the case of ionic surfactants, due to double-layer repulsion; it is usually balanced by hydrostatic pressure."

According to Khatib et al. (1988): "The behavior of soap films is described
qualitatively by Derjaguin-Landau-Verwey-Overbeek (DLVO) theory, the classic theory of colloid stability. When gas/liquid interfaces are present, ionic surfactant molecules from an aqueous solution adsorb preferentially at the interfaces, thereby creating charged surfaces. The overlap of the electric fields from these charged layers imparts stability to a foam lamella. Long-ranged, attractive van der Waals forces tend to destabilize the system. DLVO theory considers how double-layer repulsion balances against the van der Waals forces. Films that are stable to small perturbations result only when the repulsive forces are stronger than the attractive ones."

According to Edwards et al. (1991): "Thin liquid films (<100 nm) formed between two fluid phases, or, equivalently, a solid and a fluid phase, may become unstable to small disturbances owing to net attractive (dispersion) forces within the film of fluid."

According to Heller and Kuntamukkula (1987), Ransohoff and Radke (1988), and Chambers and Radke (1991) no foam or lamellae is stable unless surfactant is present. According to Heller and Kuntamukkula (1987) drainage of the continuous liquid and mass transfer across the foam lamella are the mechanisms which contribute to foam decay. According to Hirasaki (1989) steam foam is destroyed by evaporation and condensation mechanisms. Notice that drainage of the continuous liquid, evaporation, and condensation will result in the physical removal of one of the two foam constituent phases.
D.3.3: Effect of Surfactant on the Average Bubble Size

According to Chambers and Radke (1991) and Ransohoff and Radke (1988) the size of the bubbles is generally on the order of the size of the pore channels; however, bubble size depends also on the amount of available surfactant. Consider a gas bubble dispersed in a liquid as indicated in Figure D.3.3. This gas bubble has a certain surface in contact with the liquid. If this gas bubble is divided into two smaller bubbles, at constant pressure and thus constant mass density, the total amount of the gas volume remains constant; however, the total surface area corresponding to the two smaller gas bubbles is larger than that corresponding to the primary large gas bubble. As a result, bubble division is accompanied with an increase in the total surface area or the ratio of the surface area to the gas volume. If free surfactant molecules are available, they will locate in the newly generated lamella. As a result, the generated bubbles will remain stable. Further division of the gas bubbles is accompanied with the generation of more lamella which requires the consumption of more free surfactant molecules. This division and the generation of new bubbles continues while free surfactant molecules are available. A surfactant molecule is free if it is not presently located in the gas-liquid interface and can be located in the newly generated lamella. As the amount of free surfactant molecules vanish, further generated lamella will not be furnished with surfactant molecules, therefore the newly generated bubbles will be unstable. From that point on, the generated bubbles coalesce and further reduction in the average bubble size is stopped. As a result, higher surfactant concentrations and smaller gas-liquid ratios could result in a smaller average bubble size. Therefore the amount of free surfactant
molecules together with the permeability of the porous media are controlling factors on the average bubble size. The effect of the amount of available surfactant on the average bubble size is experimentally confirmed when the effect of G/L ratio on a pregenerated foam is discussed in section D.3.7.
Fig. D.3.3: Bubble division is accompanied with increase in total surface area.
D.3.4: Foam High Apparent Viscosity

The high apparent viscosity of foam was realized by Fried (1961) in saying: "Foams exhibit markedly greater viscosities than the separate viscosities of the gaseous and liquid phases of which they are constituted....The results of the brief study of foam properties indicated that surfactant foams exhibit viscosities considerably higher than those of the aqueous solutions from which they are generated. Although bulk foams may demonstrate apparent viscosities over 100 times greater than the aqueous liquid...."

According to Manlowe and Radke (1988) the apparent viscosity of foam may be up to 1000 times greater than its constituent phases, liquid and gas. According to Ettinger and Radke (1989): "Flowing foam can exhibit effective flow resistances in porous media that are several orders of magnitude larger than that of water."

While, in general, viscosity is a property of fluids, the apparent viscosity of foam has been mentioned to be geometry dependent. According to Heller and Kuntamukkula (1987): "There is, in fact, experimental evidence in some of these papers that the apparent viscosity values, unlike those measured in simpler fluids, are geometry dependent."

Foam viscosity in this work is distinguished from the foam apparent viscosity in the literature in that the foam apparent viscosity is geometry dependent, while foam viscosity is a property of the fluid (foam) itself. This work explains the origin of the high viscosity of the foam as a fluid property, independent of the way it is measured.

It is a well established concept that the interfacial viscosity of surfactant adsorbed interfaces is much more than the viscosities of the two constituent phases. According to
Edwards et al. (1991), Plateau in 1869 mentioned a difference in interfacial viscosity and the two constituent phases by saying: "The superficial layer of liquids has a proper viscosity, independent of the viscosity of the interior of the mass. In some liquids this superficial viscosity is greater than the internal viscosity, and often much greater, as in water and, especially, in solution of saponine; in other liquids, on the contrary, it is less than the internal viscosity, and often much less, as in oil of turpentine, alcohol, etc."

According to Edwards et al. (1991): "Surface shear viscosity is negligible for a surfactant-free interface; its magnitude increases monotonically with adsorbed surfactant concentration, normally until the critical micelle concentration (CMC) is reached, at which point a more complex behavior ensues...the magnitude of the interfacial dilatational viscosity for most adsorbed surfactant interfaces appears to be at least as large as the interfacial shear viscosity...Typically, for surfactant-adsorbed interfaces, surface viscous forces dominate bulk viscous forces (i.e. $Bo = \mu^*/\mu a \gg 1$) for spherical particle radii $a$ in the 100 micron range." 'Bo' is called Boussinesq number, $\mu^*$ is the surface shear viscosity, $\mu$ is the bulk viscosity and $a$ is a length scale.

Three techniques for measuring interfacial dilatational viscosity, i.e. surface wave methods, droplet deformational methods, and the maximum bubble pressure method, and three basic types of surface viscometers for measuring interfacial shear viscosity i.e. canal viscometers, disk viscometers, and knife-edge viscometers have been reviewed by Edwards et al. (1991). High surface viscosity has been realized by Adamson (1982) in saying: "In addition to high elasticity and resilience as properties giving stability to foams, high surface viscosity appears also to be important."
The high viscosity of surfactant adsorbed interfaces is the basis for explaining foam high viscosity by this work. Indicated in figures D.3.4a and D.3.4b are bubbles with different sizes occupying the same spaces. In Figure D.3.4a the space has been occupied by a few of the large size bubbles. In Figure D.3.4b the same volume of CO$_2$ has occupied the space but as a larger number of small size bubbles. We may consider three distinguished phases in any of these spaces as CO$_2$, surfactant solution, and the lamella. According to Moelwyn-Hughes (1961) the interface is a phase, having properties different from those of the two constituent phases. It can easily be understood that the total surface area in Figure D.3.4b is much more than that in Figure D.3.4a. As the amount of any one of these phases increases in the mixture, the properties of the mixture approaches those of that particular phase. As the total amount of lamella (surface area) in Figure D.3.4b is much more that in Figure D.3.4a, the corresponding viscosity is much more in Figure D.3.4b.
Fig. D.3.4: Foam viscosity depends on the bubble size. Foam with smaller bubble size has higher viscosity.
In summary, the smaller the bubble size, the larger the ratio of total surface area to gas volume and the higher the viscosity of the foam. This is most apparent in Figure D.3.17 when comparing pressure drop across the micromodel for in situ (large bubble size) and pregenerated (small bubble size) foams. The pregenerated foam had an average bubble size much smaller (therefore a larger ratio of total surface area to gas volume) than that of the in situ generated foam, thus created a larger pressure drop across the micromodel due to higher viscosity.

Dependency of foam viscosity on the bubble size has been realized by Fried (1961) in saying: "If the foam is too stable, foam bubbles may redivide into progressively smaller particles while they are passing through pore constrictions. It was shown that such redivision, which does reduce the pressure drop required to move the bubbles through a constriction of given size, can increase the viscosity of the dispersed medium to a point where the sand is blocked to flow... Presumably, for a given size of capillary, flow resistance should increase as bubble size decreases in a foam of given expansion factor. This was qualitatively verified by the study but not quantitatively correlated." The expansion factor has been mentioned as the ratio of foam density to liquid density or the ratio of the volume of foam to the volume of liquid in the foam.

According to Hirasaki and Lawson (1985): "Measurements and theory presented here show that the most important variable affecting foam viscosity in uniform, smooth capillaries is foam texture (bubble size). Foam of finer texture has more lamellae per unit length and, as a result, greater resistance to flow. This is true both for flow of bulk foam and series of lamellae." Falls et al. (1988) agreed on the dependency of foam
viscosity on the bubble size in saying: "On the other hand, when all the gas phase is discontinuous, not only can its relative permeability be smaller, but it appears to have a larger viscosity.... The apparent viscosity of foam in porous media depends strongly on the texture of the foam. The finer the texture, the larger the number of lamellae that must be transported through the system.... If the ratio of bubble size to average pore size diminishes two-fold, the apparent gas viscosity increases by an order of magnitude."

According to Ettinger and Radke (1989): "The most important property of $\mu_c$ is that it increases with increasing texture so that smaller bubbles produce larger flow resistances.... The viscous resistance of flowing foam is linearly proportional to bubble density.... A proposed population-balance model for foam flow represents our new bubble-size and pressure profile data adequately. The main premise of the model, is that finer textured foam leads to larger flow resistance." In this paper $\mu_c$ and bubble density were defined as the effective or apparent viscosity and the number of bubbles per available flowing volume respectively.

According to Marsden et al. (1967) mobility seemed to be more strongly affected by bubble size rather than quality or foamer concentration. According to Falls et al. (1989): "The influence of texture on the foam viscosity of bulk foams (i.e., foams in which the average bubble size is much smaller than the dimensions of their physical boundaries) has long been recognized but has been ignored by most researchers who have studied foam in porous media.... Nevertheless, for the range of bubble sizes shown, both theory and experiment show the apparent viscosity to be a strong function of foam-bubble size." Lee et al. (1991), found that the apparent viscosity of CO$_2$ foam depended
on surfactant type, surfactant concentration, foam quality, flow rate to a minor extent, and the permeability to a large extent such that foam apparent viscosity is greater in rocks of higher permeability.

There are also significant differences in describing the apparent viscosity of foam. Using capillary tubes, Patton et al. (1983) concluded the dependence of foam apparent viscosity on capillary length, while Hirasaki and Lawson (1985) concluded no dependence on capillary length. According to Fried (1961), foam apparent viscosity increased in proportion to the capillary radius, while Hirasaki and Lawson (1985) showed it increased with the 2.0 to 2.5 power of the capillary radius, and Raza and Marsden (1967) concluded its proportionality to the fourth power of the capillary radius.

In this work, high viscosity of CO₂-foam is explained based on the high interfacial viscosity of the CO₂-surfactant solution and the existence of a large ratio of total surface area to gas volume in the foam. Also due to repulsion between the bubbles, bubbles should be oscillating. This could also contribute to increasing viscosity of foam.

Dependency of bubble size on the pore channel size has been pointed out in the literature. According to Chambers and Radke (1991): "Foam mobilities measured in porous media are many orders of magnitude smaller than that of the constituent gas....This mobility reduction is achieved primarily because the gas phase is dispersed into bubbles, which are generally about the size of the pore channels." According to Ransohoff and Radke (1988): "In other words, the size of the bubbles is generally on the order of the size of the pore channels." Therefore the average bubble size is a function
of permeability such that the average bubble size generated in low permeability zones will be smaller than that generated in high permeability zones. As a result, the viscosity of the CO₂-foam generated in a low permeability zone should generally be higher than the viscosity of the foam generated in a high permeability zone.

The viscosity of the foam generated in a low permeability zone may be similar to that of the foam generated in a high permeability zone if two criteria are satisfied. First, the amount of surfactant is insufficient, thus surfactant molecules can not furnish the newly generated lamella. As a result the newly generated bubbles coalesce and further reduction in the average bubble size is stopped. In this case the critical average bubble size, which depends on the amount of available surfactant, may be much greater than the pore channel size of the low permeability zone. Second, the average bubble size in the high permeability zone, corresponding to the permeability of the zone, is similar to the critical average bubble size in the low permeability zone that was limited by surfactant concentration.

In other words, if the critical average bubble size corresponding to a surfactant concentration or gas-liquid ratio is larger than the pore channel size of the low permeability zone but equal to the pore channel size of the high permeability zone, the average bubble size in low and high permeability zones will be the same. This unique average bubble size in the low and high permeability zones is the pore channel size of the high permeability zone. As a result, the viscosity of the foam generated in the low and high permeability zones will be the same. The effect on the average bubble size by the amount of available surfactant was discussed in section D.3.3. Viscosity dependency
of stable foams on the local permeability is an important parameter which has to be considered when analyzing the effect of heterogeneity.
D.3.5: Effect of Initial Saturation

In most of this study the micromodel was saturated with the same liquid as the aqueous solution used in the displacement test, e.g. brine or surfactant solution. In these series of tests the aqueous solution used to saturate the micromodel differed from that injected as the displacing liquid. In the first set, the micromodel was saturated with surfactant solution and brine alternating with CO$_2$ (WAG) was injected. This was done at injection flow rates of 1.0 and 4.0 cc/hr. In the second set, the micromodel was saturated with brine and surfactant solution alternating with CO$_2$ (SAG) were injected. This was done at injection flow rates of 1.0 and 4.0 cc/hr also.

In the first set, the initial stability of bubbles would vanish as the surfactant molecules available in the micromodel were washed out by brine or carried out by the initially generated lamella. In the second set, good foaming was not expected until the injected surfactant solution had brought surfactant molecules into the micromodel. These expectations were satisfied by observations. In the first case bubble stability was observed at the beginning of the displacement; however coalescing of the generated bubbles soon started behind the displacing fluid front. In the second case bubble instability was observed at the beginning of the displacement; however, the generated bubbles soon remained stable behind the displacing fluid front. The results are presented in figures D.3.5(a,b) and D.3.6(a,b).

At 1.0 cc/hr, $\Delta P_{ave}$ (Figure D.3.5b) had higher but less stable values for the first case. This could be interpreted as having better foaming causing the higher $\Delta P_{ave}$. This was not what one would expect since it predicts bubble stability in brine and bubble
instability in surfactant solution. On the other hand $P_p$ (Figure D.3.5a) indicates lower values and less fluctuations, representing better foaming and more uniform flow front, for the second case.

At 4.0 cc/hr, pressure drop variations (Figure D.3.6b) for the two cases have almost the same values; however, the pressure drop variation for case two is smoother. The $P_p$ values (Figure D.3.6a) for case two are much lower and smoother, indicating a better foaming and more uniform flow front.

The difficulty in interpreting the results with the two different evaluation tools together with predicting bubble stability in brine when $\Delta P_{ave}$ is used, demonstrates the importance of employing more than one evaluation tool and observations.

In conclusion, when the micromodel was saturated with surfactant solution and then brine alternating with CO$_2$ were injected, the micromodel saturation rapidly shifted to brine. When micromodel was saturated with brine and then surfactant solution alternating with CO$_2$ were injected, the micromodel saturation rapidly shifted to surfactant solution.
Fig. D.3.5a: Pressure parameter is compared for different initial saturations. 
#1: The MLAY micromodel was saturated with surfactant solution and then brine alternating with CO$_2$ was injected. 
#2: The MLAY micromodel was saturated with brine and then surfactant solution alternating with CO$_2$ was injected.
INITIAL SATURATION EFFECT (1.0 cc/hr)

Fig. D.3.5b: Pressure drop is compared for different initial saturations. #1: The MLAY micromodel was saturated with surfactant solution and then brine alternating with CO₂ was injected. #2: The MLAY micromodel was saturated with brine and then surfactant solution alternating with CO₂ was injected.
INITIAL SATURATION EFFECT (4.0 cc/hr)

Fig. D.3.6a: Pressure parameter is compared for different initial saturations.
#1: The MLAY micromodel was saturated with surfactant solution and then brine alternating with CO₂ was injected. #2: The MLAY micromodel was saturated with brine and then surfactant solution alternating with CO₂ was injected.
INITIAL SATURATION EFFECT (4.0 cc/hr)

Fig. D.3.6b: Pressure drop is compared for different initial saturations. 

1: The MLAY micromodel was saturated with surfactant solution and then brine alternating with CO₂ was injected. 
2: The MLAY micromodel was saturated with brine and then surfactant solution alternating with CO₂ was injected.
D.3.6: Effect of Gas-Liquid Ratio (In Situ Generation)

The results of the effect of gas-liquid ratio are presented in figures D.3.7(a,b,c,d). The result of a pure CO₂ injecting can not be compared with those of SAG. In SAG we have two phase flow, while in injecting pure CO₂, it may flow as a single phase breaking through the micromodel. However the result of injecting pure CO₂ has also been included in figures D.3.7a and D.3.7b.

In case of injecting pure CO₂, flow was established in one path for relatively long time intervals, creating a small and relatively constant pressure drop across micromodel. Sometimes due to a disturbance, flow was established at several paths, and the pressure drop increased significantly. However after a while, flow was reestablished in a single path accompanied by a small relatively constant pressure drop. After about 3.5 pore volumes were injected, flow was established in one single path and remained unchanged until the end of the experiment. There is no pressure drop fluctuation in a single phase flow; therefore, pressure parameter is not defined for a single phase flow. Pressure parameter and pressure drop corresponding to the single phase flow interval have been identified by dashed lines in figures D.3.7a and D.3.7b. As the G/L ratio is increased (at the same total flow rate) the amount of the free liquid in the system is decreased, resulting in a better blockage in the system. However at higher G/L ratios, due to the lack of surfactant molecules, the newly generated lamella may not be furnished with surfactant molecules. Therefore, the generated bubbles may be unstable resulting in a larger average bubble size. According to Llave et al. (1990), higher foam qualities yielded larger foam bubble sizes in smooth capillary tubes.
In our case (1.0 cc/hr total flow rate) it was not possible to test the G/L ratio larger than 9/1 because of the uncertainty in pump performance at very low flow rates. However, a change in the average bubble size was not evident when foam was generated in the glass micromodel. Referring to Figure D.3.7a, notice that pressure parameters at 9/1 and 4/1 are almost equally smooth and have low values. This is an indication of a relatively good foaming and uniform flow front. The pressure parameters corresponding to a G/L ratio of 1/9 and 1/4 have larger values and more fluctuations. This is an indication of worse foaming and a less uniform flow front. This is because of fewer bubbles, due to insufficient amount of CO₂, and a larger amount of liquid. As a result, the change in the pressure drop when bubbles approached the throats was significant. The same conclusion is obtained by comparing the pressure drop in figure D.3.7b.
Fig. D.3.7a: Pressure parameter is compared at different gas-liquid ratios. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
Fig. D.3.7b: Pressure drop is compared at different gas-liquid ratios. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected. When only surfactant solution was injected (G/L=0), the corresponding pressure drop was about 0.003 psi.
Fig. D.3.7c: Average pressure parameter is compared at different gas-liquid ratios. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
Fig. D.3.7d: Average pressure drop is compared at different gas-liquid ratios. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected. When only surfactant solution was injected (G/L=0.0), the corresponding pressure drop was about 0.003 psi.
D.3.7: Effect of Gas-Liquid Ratio (Pregeneration)

The foam generator was filled with glass beads, 60-80 mesh. Surfactant solution alternating with CO₂ (SAG) was injected into the micromodel through the foam generator. The foam generated in the foam generator had a very small bubble size compared to that generated in the micromodel. This is due to the smaller pores and throats in the foam generator compared to that of the glass etched micromodel. Because of the large amount of lamella and the light refraction at the interface, the pregenerated foam appeared as a black fluid on the monitor screen. The difference between the sizes of the bubbles and that of the pore bodies and throats of the micromodel (MLAY) was such that foam could flow as a single phase (as the ease of propagation is concerned) through the micromodel.

Due to large ratio of total surface area to gas volume, a large amount of surfactant is required to support bubble generation in a pregenerated foam. As a result, the effect of the amount of available surfactant on the average bubble size becomes significant in pregenerated foam. Two runs were conducted injecting a pregenerated foam. The results are presented in figures D.3.8(a,b,c,d).

At a G/L ratio of 1/4 the larger amount of the available surfactant resulted in a smaller average bubble size. At a G/L of 4/1, the amount of the gas phase increased and the amount of surfactant molecules decreased. This caused the appearance of large bubbles in micromodel. The fact that the large bubbles did appear in a G/L ratio of 4/1 but did not appear in a G/L ratio of 1/4 supports the idea that the amount of available surfactant affects the average bubble size. The large bubbles created
fluctuation in pressure drop across the micromodel, hence increased the value of the pressure parameter.

Referring to Figure D.3.8a, pressure parameter at G/L ratio of 1/4 is lower and more smooth than that corresponding to the G/L ratio of 4/1. This is an indication of a more uniform flow front in the G/L ratio of 1/4. Referring to Figure D.3.8b, pressure drop for the G/L ratio of 4/1 is consistently higher than that corresponding to G/L of 1/4. This is interpreted as better foaming and more uniform flow front in G/L ratio of 4/1 if pressure drop is used as the evaluation tool. This is a contradiction in predicting better foaming and uniform flow front when pressure parameter and pressure drop are used separately as the evaluation tool. This contradiction also exists when pressure parameter and pressure drop are compared as an average in figures D.3.8c and D.3.8d. In both of these runs, 1/4 and 4/1 gas-liquid ratios, a bulk foam entered the micromodel and flowed as a single phase. There was no evidence of any difference in uniformity of flow front. The only difference was the propagation of a few large bubbles in the one corresponding to G/L ratio of 4/1. The contradiction in interpreting the results with two different tools together with the observation of the same uniform flow front in both gas-liquid ratios indicates the importance of employing the right evaluation tool and relying on observation before any conclusion is made.

When verifying the effect of G/L ratio is the objective, the initial saturation may be a source of inaccuracy. In case of in situ generation the micromodel is saturated with the liquid phase (surfactant solution). In case of a pregenerated foam injection, both the micromodel and the foam generator are saturated with surfactant solution. Therefore at
large value of G/L ratio, the initial saturation creates a significant inaccuracy. It should work better if the initial saturation is CO₂. However it is a more difficult task to saturate the micromodel or foam generator with CO₂.

The following points are in the literature concerning the effect of G/L ratio. According to Ransohoff and Radke (1988), increasing the fractional flow of the liquid, slightly increases the critical capillary number (above which a strong foam and below which a weaker foam is generated) while Lee and Heller (1988) believe mobility can be reduced by increasing the surfactant fraction at constant surfactant concentration. According to Khatib et al. (1988): "As the gas fractional flow is increased at a constant gas flow rate, the capillary pressure measured during a foam displacement approaches a limiting capillary pressure. At this pressure, foam coalescence manifests itself by causing the capillary pressure to drop abruptly and foam texture to coarsen." Llave et al. (1990) found a higher foam quality resulted in higher measured foam viscosities in smooth capillary tubes and yielded larger foam bubble sizes. According to Chou (1991), a wetter foam (lower gas fractional flow) may have a lower steady-state water saturation.

In summary, bubble generation is improved to a maximum as the G/L ratio is increased. When this maximum is reached, a further increase in G/L ratio results in a larger average bubble size (due to insufficient surfactant). This larger average bubble size may be well above the pore channel size.
**EFFECT OF G/L (PREGENERATION)**

![Graph showing pressure parameter vs. pore volume injected]

---

**Fig. D.3.8a:** Pressure parameter is compared at different gas-liquid ratios. The NLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator.
Fig. D.3.8b: Pressure drop is compared at different gas-liquid ratios. The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator.
Fig. D.3.8c: Average pressure parameter is compared at different gas-liquid ratios. The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator.
Fig. D.3.8d: Average pressure drop is compared at different gas-liquid ratios. The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator.
D.3.8: Effect of Surfactant Concentration

A number of tests were conducted at two different flow rates, 1.0 cc/hr and 4.0 cc/hr. The results are presented in figures D.3.9(a,b,c,d) and D.3.10(a,b,c,d). In all tests the same surfactant concentration was used to saturate the micromodel and to perform the displacement.

When bubbles touched each other, they coalesced when surfactant concentration was 100 ppm (active by weight) but they remained stable when the concentration was 200 ppm and above. However at concentrations of 200 ppm and above, sometimes a bubble stuck to a point on the glass surface. When another bubble reached that point, the two bubbles coalesced resulting in the stationary bubble growing. This growth in the size of the bubble would continue until it had a significant surface area in contact with the flowing bulk foam. The large bubble was then detached, and washed away by the flowing bulk foam. A new bubble then started growing at that point. The size of the bubbles when detached, and the frequency of detaching was constant. Sticking of bubbles to a point on the glass surface observation may be explained based on the fact that any point on the glass may somehow be charged and this charge may be opposite to the head of the surfactant molecule. This will cause the bubbles passing over that point to be attracted and stick to that charged point. When two of these bubbles are attracted to that point (Figure D.3.11) they coalesce.

At 1.0 cc/hr, considering pressure parameter, the variations corresponding to 500 and 2500 ppm are almost the same. This is in accordance with the same bubble stability that was observed at these concentrations. However, at 1000 ppm, flow was established
in one path causing reduction in pressure drop across the micromodel and increasing pressure parameter compared with the others (see figures D.3.9a and D.3.9c). The difference in pressure parameter variations corresponding to 300 and 1000 ppm (Figure D.3.9a) is not believed to be due to a change in foam stability because of change in surfactant concentration. The variations of pressure drop across the micromodel (Figure D.3.9b) for 500 and 2500 ppm are close to each other. This could be interpreted as the same bubble stability at these two concentrations, which was in accordance with the observation. The lower value for pressure drop at 1000 ppm (figures D.3.9b and D.3.9d) is due to establishing flow through one path. At 100 ppm the bubbles were as unstable as at 0 ppm, but the corresponding variations are consistently different. The lower value for pressure drop at 100 ppm may be interpreted as a reduction in surface tension. However, in section D.2.2, an increase in surface tension due to a higher salinity resulted in a lower value of pressure drop across the micromodel. This contradiction confirms that we can not rely only on analyzing the recorded pressure drop data but must include the visual observations.
Fig. D.3.9a: Pressure parameter is compared at different surfactant concentrations. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
Fig. D.3.9b: Pressure drop is compared at different surfactant concentrations. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
EFFECT OF CONCENTRATION (1.0 cc/hr)

Fig. D.3.9c: Average pressure parameter is compared at different surfactant concentrations. The NLAV micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
EFFECT OF CONCENTRATION (1.0 cc/hr)

Fig. D.3.9d: Average pressure drop is compared at different surfactant concentrations. The HLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
At 4.0 cc/hr The variations of pressure parameter (Figure D.3.10a) corresponding to 500, 1000, and 2500 ppm are almost the same in value and fluctuation. This is an indication of the same foaming and uniformity of flow front. The variation of pressure parameter corresponding to 200 ppm is not much different in value and fluctuation from those corresponding to 500, 1000, and 2500 ppm. This is an indication of the same bubble stability at 200 ppm compared to 500, 1000, and 2500 ppm. The variation of pressure parameter corresponding to 0 ppm (brine) has a much larger value and fluctuation. This indicates bubble instability and non-uniformity in flow front which is expected. Considering pressure drop across the micromodel (Figure D.3.10b) the variations corresponding to 200, 1000, and 2500 ppm are almost the same. This is an indication of the same bubble stability. The one corresponding to 500 ppm is higher than the others. This could be interpreted as a better stability at 500 ppm if pressure drop is used as the evaluation tool. At 0 ppm (brine) the variation is more fluctuating, however it has a value as high as the others. This could be interpreted as bubble stability at 0 ppm. The pressure parameter at 0 ppm is considerably larger and more fluctuating Compared with other concentrations (Figure D.3.10a). This indicates bubble instability and non-uniformity of flow front in brine. The pressure drop at 0 ppm has the same large value as those at other concentrations (Figure D.3.10b). This could be interpreted as the same bubble stability in brine and other concentrations. This difference in predicting bubble stability in brine demonstrates that pressure parameter distinguishes bubble stability while pressure drop does not.
EFFECT OF CONCENTRATION (4.0 cc/hr)

Fig. D.3.10a: Pressure parameter is compared at different surfactant concentrations. The HAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
EFFECT OF CONCENTRATION (4.0 cc/hr)

Fig. D.3.10b: Pressure drop is compared at different surfactant concentrations. The MILAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
Fig. D.3.10c: Average pressure parameter is compared at different surfactant concentrations. The NLAV micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
Fig. D.3.10d: Average pressure drop is compared at different surfactant concentrations. The MDAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
Fig. D.3.11: Two bubbles may come together at a point with opposite charge.
The conclusion of this work is that in case of the Surfactant CD1045, bubble stability remained unchanged at concentrations of 200 ppm and above when foam was generated in a glass etched micromodel. However, low surfactant concentration may result in a larger bubble size. The change in bubble size was not evident in the case of in situ generation in the micromodel. The bubbles generated in the micromodel are large in size corresponding to a low total surface area or lamella. Therefore the free surfactant molecules at 200 ppm have been sufficient to furnish the newly generated lamella.

In a pregenerated foam the average bubble size is very small corresponding to a large ratio of total surface area to gas volume, requiring a large amount of available surfactant to support bubble stability. At low surfactant concentration, at further steps of bubble division, the newly generated lamella might not be furnished with surfactant molecules. Therefore the divided bubbles do not repel each other efficiently and coalesce. As a result, average bubble size can not get smaller than a critical size at low surfactant concentration. In the case when sufficient surfactant is available the average bubble size is controlled by permeability of the porous media. When insufficient surfactant is available the critical bubble size may be bigger than the pore channel size and is a function of the surfactant concentration or, in general, the amount of available surfactant. The critical bubble size is the average bubble size below which further reduction is not achieved due to instability of the newly generated lamella.

Pregenerated foam was not tested at different surfactant concentrations; however, the effect of the amount of available surfactant on the average bubble size was
experimentally indicated when the effect of G/L ratio on a pregenerated foam was tested in section D.3.7.

Previous work by Huh et al. (1989) conducting micromodel experiments, found a better sweep efficiency with higher surfactant concentration. Lee and Heller (1988) conducted core flood experiments and concluded that mobility decreased with increasing surfactant concentration regardless of the type of surfactant and that the decrease of mobility continued well above the critical micelle concentration (CMC) of the surfactant solution. Llave et al. (1990) generated foam in a high permeability core and measured the corresponding apparent viscosity in a packed glass tube and a smooth capillary tube. They found that the measured apparent viscosity of foam was not dependent on surfactant concentration above the CMC of the system.

The above contradiction in the reported effect of surfactant concentration below and above CMC may be explained based on the effects of available surfactant molecules and permeability of the porous media on the bubble size, thus on the foam viscosity. The bubble size (thus foam viscosity and its capability to reduce the mobility) is a function of the total amount of surfactant available (concentration as well as G/L ratio) and the permeability of the porous media. As mentioned the effect of the amount of the available surfactant becomes significant in a low permeability porous media where there is a large total surface area corresponding to the small bubble sizes. In other words, G/L ratio and the permeability of the porous media should also be considered when the effect of surfactant concentration on foam viscosity or mobility reduction is evaluated.
D.3.9: Effect of Flow Rate (In Situ Generation)

The results are presented in figures D.3.12(a,b,c,d). Figure D.3.12d indicates a consistent increase in average pressure drop with an increase in flow rate. The increase in pressure drop is due to the increase in flow rate and would be affected by a change in foam. There is a way to determine whether foam is more effective at higher flow rates. Consider a piece of a porous rock indicated in Figure D.3.13. Assume that gas bubbles of the same size pass through the rock such that at any time the rock pore volume is occupied by \( n \) number of bubbles. Also assume that the bubble size is such that it can easily pass through the pore throat. If the bubble size is constant, the following conclusions can be made. First, the viscosity will be constant. Second, the permeability to the flow of bubbles will also be constant. Regarding these two facts, Darcy’s Law may be written as:

\[
\Delta P = \frac{Q L \mu}{K A}
\]

Where \( Q \) is the flow rate, \( L \) is the length of the rock, \( A \) is the cross sectional area of the rock, \( K \) is the permeability to flow, \( \mu \) is the viscosity corresponding to the flow of bubbles, and \( \Delta P \) is the pressure drop across the rock. This equation indicates that considering the above two conditions (constant viscosity and permeability), pressure drop across the rock is a linear function of the flow rate, with \( \mu L/KA \) as the slope of the line. In other words, if the bubble sizes remain unchanged when foam flows through the rock, the slope of the line should remain unchanged. This constant slope line is referred to as theoretical pressure drop variation versus flow rate. Any change in the slope of
the line will be due to change of viscosity or permeability. The values of the constant viscosity and permeability corresponding to the flow of bubbles of the same size, therefore the slope of the theoretical pressure drop variation versus flow rate is not known.

In Figure D.3.14, assume curve (a) represents the experimental pressure drop versus flow rate. A constant slope line such as (1) or (2) in Figure D.3.14, corresponds to the flow of bubbles at constant viscosity and permeability. In most cases this value is not known.

When the plot of flow rate versus pressure drop deviates from a straight line such as curve (a) or in other words the slope changes, so does the ratio of $\mu/K$. This assumes $L$ and $A$ remain constant in all cases. If the slope decreases with increasing flow rate then $\mu/K$ decreases and thus the inverse $K/\mu$ or mobility increases. Inversely if the slope increases with increasing flow rate, then $\mu/K$ increases and the mobility decreases. This is an average mobility that does not indicate how uniform the flow is. Thus combined with the pressure parameter we can have an indication of mobility and uniformity of flow.

In our tests, at 0.5 cc/hr fluid flow was established only in one path. At 1.0 cc/hr fluid flow was established mainly in two paths. At 2.0 cc/hr fluid flow was established mainly in two paths but it was slow in other paths. At 4.0 cc/hr fluid flow was almost uniform across the micromodel. This non-uniformity in flow pattern affects the pressure drop across the micromodel.

Change in the average bubble size at different flow rates was not evident. Figure
D.3.12d indicates that the curve of experimental average pressure drop plotted versus flow rate has almost a constant slope. However due to the non-uniformity of flow pattern, which affects the results, this constant slope can not be interpreted as the same foaming at different flow rates.

The pressure parameter (see figures D.3.12a and D.3.12c) indicates the largest value at 0.5 cc/hr (corresponding to an interstitial velocity of 6.75 ft/day). At 4.0 cc/hr, flow front across the micromodel was almost uniform and the corresponding pressure parameter (see Figure D.3.12a) has the lowest value and fluctuations which are indications of a more uniform flow front. Figures D.3.15a and D.3.15b compare WAG and SAG based on the average pressure parameter and pressure drop. As shown, see Figure D.3.15a, the average pressure parameter for SAG is lower than that of WAG; thus SAG and WAG are easily distinguished by pressure parameter. It is difficult to find a consistent trend in the results when SAG and WAG are compared by average pressure drop. Notice that at 0.5 and 4.0 cc/hr, pressure drop across the micromodel is larger for WAG than for SAG. This could be interpreted as a better foaming in WAG which is unexpected.
Fig. D.3.12a: Pressure parameter is compared at different flow rates. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
Fig. D.3.12b: Pressure drop is compared at different flow rates. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
The micromodel was saturated with surfactant solution and then surfactant solution alternating with CO$_2$ was injected.

Fig. D.3.12c: Average pressure parameter is compared at different flow rates.
Fig. D.3.12d: Average pressure drop is compared at different flow rates. The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
Fig. D.3.13: Foam flow through porous media. Pressure drop increases linearly with increase in flow rate if bubble size remains constant.

Fig. D.3.14: Comparing experimental and theoretical pressure drop versus flow rate.
Fig. D.3.15a: Average pressure parameter is compared for WAG and SAG. WAG: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. SAG: The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
Fig. D.3.15b: Average pressure drop is compared for WAG and SAG. WAG: The MLAY micromodel was saturated with brine and then brine alternating with CO₂ was injected. SAG: The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected.
D.3.10: Effect of Flow Rate (Pregeneration)

The foam generator was filled with glass beads, 60-80 mesh. Surfactant solution alternating with CO₂ (SAG) was injected into the micromodel through the foam generator. The pregenerated foam appeared as a black fluid as mentioned in section D.3.7 on the effect of gas-liquid ratio on a pregenerated foam. The results of this set of experiments are presented in figures D.3.16(a,b,c,d).

As the pregenerated foam had been flowing through the micromodel as a single phase (with high viscosity) there should not have been any pressure fluctuation. However sometimes relatively large bubbles (comparable to the pore size) appeared in micromodel, propagated through the bulk foam, and caused fluctuation in pressure drop when they approached and passed the pore throats. Fluctuations in pressure drop across the micromodel result in fluctuation in the pressure parameter. These fluctuations at different flow rates (see Figure D.3.16a) are not due to the non-uniformity of the flow front. These are due to the presence of the large bubbles propagating through the bulk foam. The appearance of the large bubbles might be due to the lack of free surfactant molecules required to support bubble division. These large bubbles appeared extensively at 1.0 cc/hr. At 2.0 cc/hr only a few of large bubbles appeared. At 0.5 and 4.0 cc/hr large bubbles did not appear. The appearance of large bubbles seemed to decrease with an increase in flow rate. However, At 0.5 cc/hr the initial saturation of the foam generator might have affected the ratio of the amount of gas and surfactant, thus foam generation was supported effectively by this excess surfactant molecules and the large bubbles did not appear.
Pressure drop at 1.0 cc/hr is less than that at 0.5 cc/hr, which is unexpected. This might be due to the larger bubble size, thus lower viscosity at 1.0 cc/hr. The presence of the large bubbles at 1.0 cc/hr has also caused a large average pressure parameter in Figure D.3.16c. Pressure drops for 0.5 and 1.0 cc/hr are distinguished in Figure D.3.16b when the variation of the pressure drops are compared. When average pressure drop is used, see Figure D.3.16d, these two different flow rates are not easily distinguished. This is the disadvantage of using average values to compare tests at different conditions.

The pressure drop corresponding to pregenerated foam was much larger than that of the in situ generated foam, see Figure D.3.17. This larger pressure drop may reasonably be explained due to an increase in foam viscosity. In other words, the foam generated in the foam generator (having small bubble sizes) had a higher viscosity than the foam generated in the micromodel (having large bubble sizes).

In summary, a promoted bubble generation at higher flow rates was clearly observed only when foam was generated in the foam generator which has a permeability closer to a real reservoir. However, to verify the effect of flow rate, it is necessary to use different surfactant concentrations at different flow rates such that the rate of injected surfactant be the same at different flow rates. This way, the effects of increasing flow rate and the total amount of existent surfactant will be isolated from each other. Notice that another variable (surfactant to gas ratio) will be created in this case. Testing the effect of flow rate at different surfactant concentration by observing the bubble size of a pregenerated foam is suggested as future work.
The following points may be found in literature concerning the effect of flow rate. According to Friedmann and Jensen (1986) foam with a finer texture was obtained by increasing the flow rate in the absence of oil. According to Ransohoff and Radke (1988), there is a critical flow rate (velocity) above which a strong foam is generated (by snap off and lamella division). Below this critical flow rate (velocity), a weaker foam is generated (by leave behind mechanism). According to Lee and Heller (1988), the effect of total velocity on mobility shows some shear-thinning behavior only under conditions of low surfactant availability and in most circumstances the apparent foam viscosity is almost unaffected by flow velocity. According to Huh et al. (1989), a better sweep efficiency was obtained with higher flow rates. Llave et al. (1990) conducted experiments in smooth capillary tubes and packed glass tubes and concluded that the generation of foam bubbles increased by increasing the pure gas (nitrogen) flow rate, displacing the surfactant solution. Chou (1991) conducted core flood experiments and found that the role of flow rate was not critical.
Fig. E.3.16a: Pressure parameter is compared at different flow rates. The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO2 was injected into the micromodel through the foam generator.
EFFECT OF FLOW RATE (PREGENERATION)

Pressure drop is compared at different flow rates. The micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator.

Fig. D.3.4.b: Pressure drop is compared at different flow rates. The micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator.
Fig. D.3.16c: Average pressure parameter is compared at different flow rates. The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator.
EFFECT OF FLOW RATE (PREGENERATION)

Fig. D.3.16d: Average pressure drop is compared at different flow rates. The MLEV micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator.
Fig. D.3.17: Average pressure drop is compared for foam generation by in situ and pregeneration. In Situ: The MLAY micromodel was saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected. Pregenerated: The MLAY micromodel and foam generator were saturated with surfactant solution and then surfactant solution alternating with CO₂ was injected into the micromodel through the foam generator.
By our discussion about the role of surfactant in foam stability in section D.3.2, one might expect the mechanism by which oil destroys foam. When foam is introduced to an oil phase, the tail that was already in CO₂ will locate in the oil phase because of its affinity to oil. This will make the whole surfactant molecule (head and tail) to locate outside CO₂. As soon as this happens, surfactant molecules will locate at brine-oil interface with the tail in the oil and the head in the brine. The oil surfaces become uniformly charged. As a result two oil bodies repel each other and remain separated in the surfactant solution. Stability of two oil bodies in surfactant solution (see Figure D.3.18) was confirmed experimentally and videotaped. CO₂ surfaces are not charged any more; hence they do not repel each other. As a result two CO₂ bodies will coalesce when they come to each other, resulting in foam destabilization.

A series of tests were performed to determine the effect of oil on foam. The modified heterogeneous (MHET) micromodel was used to test the effect of oil. The micromodel was saturated with Maljamar crude. The characteristics of this oil is given in Table 3. Brine, surfactant solution, pure CO₂, surfactant solution alternating with CO₂ (SAG), pregenerated foam, and brine alternating with CO₂ (WAG) were injected into the micromodel.

CO₂-CO₂ and brine-brine bodies coalesced suddenly whenever they touched each other in the oil phase because of not having surfactant molecules at their surfaces. The presence of surfactant molecules at the surfaces of two surfactant solution bodies could not prevent surfactant solution bodies from coalescing in the oil phase; however, this
coalescing occurred more slowly. The reason for this is the orientation of surfactant molecules at the interface such that the head is in the brine and the tail in the oil phase. This causes some repulsion between the two surfactant solution bodies, thus slowing coalescing (see Figure D.3.18). When two oil bodies came together in surfactant solution, they remained stable. This is again because of the orientation of the surfactant molecules at the interface, with the tail in oil and the head in brine, that causes the two oil bodies to repel each other (Figure D.3.18). Individual blobs of oil floating in surfactant solution has also been observed by Chang and Martin (1992).

In brief, whenever two identical bodies (such as oil-oil) came close to each other in a different phase in the presence of surfactant, there were two possible outcomes. If the heads were aligned inside the two approaching bodies, they coalesced. If the heads were aligned outside the two approaching bodies, they remained stable. This is indicated in Figure D.3.18. The stability and instability of two identical bodies at different situations (in agreement with the above argument) has been videotaped. As the sweep efficiency is concerned, the following may be pointed out:

1. When a single phase (i.e., brine, surfactant solution or CO₂) was injected, the highest sweep efficiency was obtained in injecting pure CO₂ and the lowest in injecting brine. In the case of injecting brine into the oil, only oil in the high permeability zone from inlet to outlet (the preferential path) was recovered; however, when injection flow rate was increased significantly much of the oil in the low permeability zones was recovered. In the case of injecting pure CO₂, oil remained as the wetting phase in the swept areas, while in the case of brine and surfactant solution wettability altered from
oil to brine and surfactant solution respectively.

2. When two phases (SAG and WAG) were injected, the higher sweep efficiency was obtained in SAG. The generated bubbles from SAG injection were not stable when in contact with oil, however foam was generated and was stable in oil swept areas. The stability of the foam was an indication that oil had been physically displaced. The sweep efficiencies of different injection modes may be compared to each other as the following:

\[ SAG > \text{CO}_2 > WAG > \text{Surfactant Solution} > \text{Brine} \]

In the case of SAG, almost all the oil was recovered; however, some oil was trapped in the lower permeability zones even though at the adjacent higher permeability zone foam was flowing.

3. When a pregenerated foam was injected, initially large slugs instead of a bulk foam entered the micromodel. This is because foam was destabilized by contacting oil. However, a fine texture foam soon started entering the micromodel and remained stable in oil swept zones. Again the foam stability in swept zones indicated that the oil had been physically displaced.

It can hardly be said that sweep efficiency was different in the SAG and pregenerated foam. The pregenerated foam was also observed to flow through a high permeability zone leaving oil at the adjacent low permeability zone. In both cases (SAG and pregeneration) foam flow through the preferential path was much faster than foam flow in the adjacent lower permeability zones. The preferential path is a high permeability zone connecting the micromodel inlet and outlet.

Wellington (1985) and Wellington and Vinegar (1987) found the deleterious effect
of oil on foam. Manlowe and Radke (1988), introduced the concept of a dynamically metastable foam in the presence of oil, based on the proposed pseudoemulsion film destabilization mechanism. Huh et al. (1989) believed that saturating the micromodel with crude oil changes the wettability to intermediate or oil wet. As a result, foam generation is greatly reduced due to the lack of surfactant solution at foam generation sites. According to Sanchez and Hazlett (1989), in the presence of surfactant, foam is formed in situ in an initially oil-wet porous medium. This is a result of wettability alteration of the hydrophobic solid to hydrophilic. Gas permeability reduction for the same surfactant concentration is essentially identical for both water-wet and initially oil-wet media. According to Hornbrook et al. (1991), the mechanism by which surfactant becomes the wetting phase in a porous medium of intermediate wettability in the presence of crude oil when a foam is the displacing phase is not fully understood.

The conclusion of this work is that CO$_2$ foam is destroyed when contacting an oil phase because the repulsion between CO$_2$ bodies has vanished. As a result, oil destabilizes foam no matter what is the surfactant concentration or the amount of the available surfactant.
Fig. D.3.18: Stability of the non-wetting phase depends on the orientation of surfactant molecules at the interface.
E: Miscellaneous Observations

There are a few observations which are mentioned here. These observations may find particular meaning in research on foams.

1. A small gas bubble, floating in the liquid, was moving parallel to a large CO₂ slug at a different speed (Figure E.1). The speed of the small bubble should be almost the same as that of liquid. This indicates that gas and liquid propagated at different velocities. The CO₂ slug probably continued to the injection point.

2. A large CO₂ slug was passing through the outlet port of the micromodel. A small bubble, seemed to be floating in liquid, close to the large slug was stationary (Figure E.2). This indicates that the lamella corresponding to the large slug was not moving. Had the lamella been moving, it should have created rotational speed in the liquid resulting in a rotation in the small bubble. This observation suggests that small bubbles (floating in the liquid) are carried by the liquid and propagate as a body. Large gas slugs (apparently in contact with the solid phase) propagated by lamella contraction at the back and lamella expansion at the front. These being the only parts of the lamella that are not stationary.

3. Sometimes the upstream side of the lamella of a moving gas bubble stuck to a point on the glass surface (Figure E.3). As a result the bubble was stretched and finally divided into two parts, the downstream part moving and the upstream side still stuck to the point (Figure E.4). This also happened when a fast motion in the front of the gas body could not be followed by the back of the body. The division has occurred because of the discontinuity of mass at the division point. Such a division is known as
bubble snap-off mechanism for bubble generation. Another bubble generation mechanism, known as bubble subdivision, was also observed to be due to the discontinuity of mass at the branching point.
Fig. E.1: CO2 slug and the small bubble propagate at different velocities.

Fig. E.2: The small bubble is stationary close to a propagating slug.
Fig. E.3: A propagating bubble is stuck at a point and is stretched.

Fig. E.4: Bubble is divided due to mass discontinuity at division point.
**Conclusions**

1. Interpretation of the data and conclusions in the research concerning foam flooding may be seriously affected by the way the data are analyzed. Even when the data are analyzed in the most possible reasonable way, visualization is of much importance at least when the research is at its developmental stages.

2. A new evaluation tool (pressure parameter, $P_p$), based on the concept of a uniform flow front, is introduced to analyze the recorded pressure drop data corresponding to different conditions.

3. In the absence of surfactant, fewer bubbles are generated in porous media and the generated bubbles are not stable.

4. Surfactant molecules will locate at CO$_2$-brine interface causing a repulsion between the generated gas bubbles, hence keeping them stable.

5. In the presence of surfactant, the average bubble size is controlled by the permeability of the porous media and the amount of available surfactant. In case of sufficient surfactant, the average bubble size will approach the pore channel size. In case of insufficient surfactant, the average bubble size may be bigger than the pore channel size.

When surfactant was present and bubbles were generated the following conclusions were made:

6. The high viscosity of foam is explained based on the high CO$_2$-surfactant solution interfacial viscosity, and the large ratio of surface area to gas volume. The
smaller the bubble sizes, the higher the viscosity of the foam. As a result, the foam generated in a low permeability zone (having smaller bubble size) will have a higher viscosity than the foam generated in a high permeability zone (having bigger bubble size).

7. The effect of oil in destabilizing foam is explained based on the vanishing of the repulsion between the gas bubbles at the presence of an oil phase.

As the effect of various parameters are concerned, when surfactant is present,

8. The average bubble size decreased with increase in flow rate. The effect of flow rate should be verified at different surfactant concentrations such that the total amount of surfactant remains the same at different flow rates.

9. Increasing gas-liquid ratio promotes foaming and improves the uniformity of flow front in the range that surfactant molecules can still furnish the newly generated lamellae. However larger ratios can result in a larger average bubble size because of insufficient surfactant molecules required to support further bubble division.

10. For an in situ generated foam in glass micromodel, foam was observed stable at surfactant concentrations of 200 ppm and above. However when foam is generated in a real porous media, the average bubble size is much smaller compared to that in the glass micromodel. Therefore at low surfactant concentrations the generated lamellae may not be supported by surfactant molecules, resulting in bubble coalescence. As a result of bubble coalescence, the average bubble size will be bigger than the pore channel size.

11. When the micromodel was saturated with surfactant solution and brine
alternating with CO₂ was injected, the surfactant molecules in the micromodel were soon washed out by brine and then the bubbles coalesced. When the micromodel was saturated with brine and surfactant solution alternating with CO₂ were injected, surfactant molecules were carried into the micromodel by the injected surfactant solution and the generated bubbles remained stable.
References:


Glasstone, S. Elements of Physical Chemistry. New York: D. Van Nostrand Company,


California regional meeting of the Oakland, CA, Society of Petroleum Engineers of AIME, Apr. 2-4, 1986.


Appendix A: Tables

Table 1- Micromodel Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>MLAY</th>
<th>MHET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (cm)</td>
<td>6.4</td>
<td>6.4</td>
</tr>
<tr>
<td>Width (cm)</td>
<td>4.5</td>
<td>4.8</td>
</tr>
<tr>
<td>Depth (cm)</td>
<td>0.0127</td>
<td>0.0127</td>
</tr>
<tr>
<td>Pore Volume (cc)</td>
<td>0.4</td>
<td>0.146</td>
</tr>
<tr>
<td>Pore body to throat ratio</td>
<td>4.5, 7.5, 9.0</td>
<td>&gt;14*</td>
</tr>
</tbody>
</table>

* From Kovarik and Heller (1989)

Table 2- Brine Composition

<table>
<thead>
<tr>
<th>Substance</th>
<th>grams</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>61.26</td>
</tr>
<tr>
<td>KCl</td>
<td>0.58</td>
</tr>
<tr>
<td>CaCl$_2$.H$_2$O</td>
<td>9.44</td>
</tr>
<tr>
<td>MgCl$_2$.6H$_2$O</td>
<td>5.19</td>
</tr>
<tr>
<td>Na$_2$SO$_4$</td>
<td>5.91</td>
</tr>
<tr>
<td>Distilled Water</td>
<td>1917.62</td>
</tr>
</tbody>
</table>
Table 3 - Composition of Maljamar Crude Oil

<table>
<thead>
<tr>
<th>Carbon</th>
<th>Molec. wt.</th>
<th>wt. %</th>
<th>moles</th>
<th>mole fr.</th>
<th>mole fr. * MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.04303</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>30.07012</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>44.09721</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>58.1243</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>72.15139</td>
<td>0.084639</td>
<td>0.001173</td>
<td>0.002551</td>
<td>0.184060</td>
</tr>
<tr>
<td>6</td>
<td>86.17848</td>
<td>1.699442</td>
<td>0.019720</td>
<td>0.042883</td>
<td>3.695663</td>
</tr>
<tr>
<td>7</td>
<td>100.2055</td>
<td>5.688423</td>
<td>0.056767</td>
<td>0.123444</td>
<td>12.17023</td>
</tr>
<tr>
<td>8</td>
<td>114.3262</td>
<td>6.045557</td>
<td>0.052923</td>
<td>0.115088</td>
<td>12.14686</td>
</tr>
<tr>
<td>9</td>
<td>128.4297</td>
<td>5.556552</td>
<td>0.043322</td>
<td>0.094210</td>
<td>12.08346</td>
</tr>
<tr>
<td>10</td>
<td>142.5368</td>
<td>4.862933</td>
<td>0.034176</td>
<td>0.074322</td>
<td>10.57509</td>
</tr>
<tr>
<td>11</td>
<td>156.6439</td>
<td>3.562913</td>
<td>0.022793</td>
<td>0.049567</td>
<td>7.748028</td>
</tr>
<tr>
<td>12</td>
<td>170.7510</td>
<td>4.173780</td>
<td>0.024502</td>
<td>0.053283</td>
<td>9.076439</td>
</tr>
<tr>
<td>13</td>
<td>184.8581</td>
<td>4.798474</td>
<td>0.026026</td>
<td>0.056598</td>
<td>10.43492</td>
</tr>
<tr>
<td>14</td>
<td>199.9652</td>
<td>3.021724</td>
<td>0.015230</td>
<td>0.033121</td>
<td>6.571311</td>
</tr>
<tr>
<td>15</td>
<td>215.0722</td>
<td>3.460480</td>
<td>0.011582</td>
<td>0.025188</td>
<td>5.350641</td>
</tr>
<tr>
<td>16</td>
<td>220.1793</td>
<td>2.963478</td>
<td>0.013086</td>
<td>0.028458</td>
<td>6.444478</td>
</tr>
<tr>
<td>17</td>
<td>240.2864</td>
<td>2.375220</td>
<td>0.009877</td>
<td>0.021479</td>
<td>5.165232</td>
</tr>
<tr>
<td>18</td>
<td>250.3935</td>
<td>2.006172</td>
<td>0.011811</td>
<td>0.025666</td>
<td>6.357322</td>
</tr>
<tr>
<td>19</td>
<td>268.5006</td>
<td>2.146785</td>
<td>0.007994</td>
<td>0.017385</td>
<td>4.668470</td>
</tr>
<tr>
<td>20</td>
<td>282.6077</td>
<td>2.097637</td>
<td>0.007423</td>
<td>0.016143</td>
<td>4.561590</td>
</tr>
<tr>
<td>21</td>
<td>296.7148</td>
<td>2.020759</td>
<td>0.006813</td>
<td>0.014816</td>
<td>4.394409</td>
</tr>
<tr>
<td>22</td>
<td>310.8219</td>
<td>2.026648</td>
<td>0.006524</td>
<td>0.014188</td>
<td>4.407216</td>
</tr>
<tr>
<td>23</td>
<td>324.9290</td>
<td>1.920722</td>
<td>0.005916</td>
<td>0.012866</td>
<td>4.176866</td>
</tr>
<tr>
<td>24</td>
<td>339.0361</td>
<td>1.850660</td>
<td>0.005464</td>
<td>0.011883</td>
<td>4.024507</td>
</tr>
<tr>
<td>25</td>
<td>353.1432</td>
<td>1.762409</td>
<td>0.005379</td>
<td>0.010783</td>
<td>3.950277</td>
</tr>
<tr>
<td>26</td>
<td>366.2502</td>
<td>1.752227</td>
<td>0.004999</td>
<td>0.010111</td>
<td>3.899612</td>
</tr>
<tr>
<td>27</td>
<td>380.3573</td>
<td>1.643476</td>
<td>0.003625</td>
<td>0.007910</td>
<td>2.704104</td>
</tr>
<tr>
<td>28</td>
<td>394.4644</td>
<td>1.591597</td>
<td>0.003460</td>
<td>0.008020</td>
<td>2.590000</td>
</tr>
<tr>
<td>29</td>
<td>408.5715</td>
<td>1.526532</td>
<td>0.003105</td>
<td>0.006732</td>
<td>2.752877</td>
</tr>
<tr>
<td>30</td>
<td>422.6786</td>
<td>1.473821</td>
<td>0.002818</td>
<td>0.006345</td>
<td>2.683108</td>
</tr>
<tr>
<td>31</td>
<td>436.7857</td>
<td>1.420372</td>
<td>0.002621</td>
<td>0.006124</td>
<td>2.675607</td>
</tr>
<tr>
<td>32</td>
<td>450.8928</td>
<td>1.371138</td>
<td>0.002439</td>
<td>0.005878</td>
<td>2.960307</td>
</tr>
<tr>
<td>33</td>
<td>464.9999</td>
<td>1.324097</td>
<td>0.002261</td>
<td>0.005678</td>
<td>2.640215</td>
</tr>
<tr>
<td>34</td>
<td>478.1070</td>
<td>1.279416</td>
<td>0.002087</td>
<td>0.005427</td>
<td>2.695276</td>
</tr>
<tr>
<td>35</td>
<td>492.2141</td>
<td>0.651464</td>
<td>0.001321</td>
<td>0.002873</td>
<td>1.416695</td>
</tr>
<tr>
<td>36</td>
<td>506.3211</td>
<td>1.931424</td>
<td>0.003809</td>
<td>0.008824</td>
<td>4.200139</td>
</tr>
<tr>
<td>C37+</td>
<td>561.0995</td>
<td>20.93135</td>
<td>0.031711</td>
<td>0.080834</td>
<td>45.51801</td>
</tr>
</tbody>
</table>

\[ \text{100.459847} = \text{MW} \]
Table 4 - Summary of the Experiments

<table>
<thead>
<tr>
<th>run #</th>
<th>cc/hr</th>
<th>G/L</th>
<th>I.S</th>
<th>I.M</th>
<th>s.c</th>
<th>P</th>
<th>ΔP_m</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>0.5</td>
<td>4/1</td>
<td>SS</td>
<td>SAG</td>
<td>2500</td>
<td>0.8877</td>
<td>0.0266</td>
</tr>
<tr>
<td>26</td>
<td>1.0</td>
<td>4/1</td>
<td>SS</td>
<td>SAG</td>
<td>2500</td>
<td>0.3275</td>
<td>0.0494</td>
</tr>
<tr>
<td>25</td>
<td>2.0</td>
<td>4/1</td>
<td>SS</td>
<td>SAG</td>
<td>2500</td>
<td>0.3262</td>
<td>0.0622</td>
</tr>
<tr>
<td>27</td>
<td>4.0</td>
<td>4/1</td>
<td>SS</td>
<td>SAG</td>
<td>2500</td>
<td>0.3170</td>
<td>0.1138</td>
</tr>
<tr>
<td>101</td>
<td>0.5</td>
<td>4/1</td>
<td>SS</td>
<td>PRF</td>
<td>2500</td>
<td>0.4729</td>
<td>0.0925</td>
</tr>
<tr>
<td>96</td>
<td>1.0</td>
<td>4/1</td>
<td>SS</td>
<td>PRF</td>
<td>2500</td>
<td>0.3610</td>
<td>0.3817</td>
</tr>
<tr>
<td>100</td>
<td>2.0</td>
<td>4/1</td>
<td>SS</td>
<td>PRF</td>
<td>2500</td>
<td>0.3039</td>
<td>0.7406</td>
</tr>
<tr>
<td>99</td>
<td>4.0</td>
<td>4/1</td>
<td>SS</td>
<td>PRF</td>
<td>2500</td>
<td>0.2151</td>
<td>0.0219</td>
</tr>
<tr>
<td>94</td>
<td>1.0</td>
<td>infinity</td>
<td>SS</td>
<td>P</td>
<td>2500</td>
<td>1.5024</td>
<td>0.0078</td>
</tr>
<tr>
<td>86</td>
<td>1.0</td>
<td>9/1</td>
<td>SS</td>
<td>SAG</td>
<td>2500</td>
<td>0.3387</td>
<td>0.0394</td>
</tr>
<tr>
<td>89</td>
<td>1.0</td>
<td>4/1</td>
<td>SS</td>
<td>SAG</td>
<td>2500</td>
<td>0.3600</td>
<td>0.0391</td>
</tr>
<tr>
<td>91</td>
<td>1.0</td>
<td>3/2</td>
<td>SS</td>
<td>SAG</td>
<td>2500</td>
<td>0.6427</td>
<td>0.0267</td>
</tr>
<tr>
<td>87</td>
<td>1.0</td>
<td>1/1</td>
<td>SS</td>
<td>SAG</td>
<td>2500</td>
<td>0.2784</td>
<td>0.0239</td>
</tr>
<tr>
<td>92</td>
<td>1.0</td>
<td>2/3</td>
<td>SS</td>
<td>SAG</td>
<td>2500</td>
<td>0.8192</td>
<td>0.0292</td>
</tr>
<tr>
<td>90</td>
<td>1.0</td>
<td>1/4</td>
<td>SS</td>
<td>SAG</td>
<td>2500</td>
<td>0.8099</td>
<td>0.0174</td>
</tr>
<tr>
<td>93</td>
<td>1.0</td>
<td>1/9</td>
<td>SS</td>
<td>SAG</td>
<td>2500</td>
<td>1.2700</td>
<td>0.0337</td>
</tr>
<tr>
<td>98</td>
<td>1.0</td>
<td>1/4</td>
<td>SS</td>
<td>PRF</td>
<td>2500</td>
<td>1.5024</td>
<td>0.0078</td>
</tr>
<tr>
<td>113</td>
<td>1.0</td>
<td>4/1</td>
<td>SS</td>
<td>SAG</td>
<td>2500</td>
<td>1.9179</td>
<td>0.0189</td>
</tr>
<tr>
<td>122</td>
<td>1.0</td>
<td>4/1</td>
<td>SS</td>
<td>SAG</td>
<td>300</td>
<td>0.8351</td>
<td>0.0423</td>
</tr>
<tr>
<td>117</td>
<td>1.0</td>
<td>4/1</td>
<td>SS</td>
<td>SAG</td>
<td>500</td>
<td>0.5782</td>
<td>0.0469</td>
</tr>
<tr>
<td>119</td>
<td>1.0</td>
<td>4/1</td>
<td>SS</td>
<td>SAG</td>
<td>1000</td>
<td>1.1461</td>
<td>0.0236</td>
</tr>
<tr>
<td>124</td>
<td>4.0</td>
<td>4/1</td>
<td>SS</td>
<td>SAG</td>
<td>200</td>
<td>1.4207</td>
<td>0.1013</td>
</tr>
<tr>
<td>128</td>
<td>4.0</td>
<td>4/1</td>
<td>SS</td>
<td>SAG</td>
<td>500</td>
<td>1.1305</td>
<td>0.1411</td>
</tr>
<tr>
<td>126</td>
<td>4.0</td>
<td>4/1</td>
<td>SS</td>
<td>SAG</td>
<td>1000</td>
<td>0.1339</td>
<td>0.1095</td>
</tr>
<tr>
<td>50</td>
<td>0.5</td>
<td>4/1</td>
<td>B</td>
<td>WAG</td>
<td>0</td>
<td>1.8889</td>
<td>0.0792</td>
</tr>
<tr>
<td>105</td>
<td>1.0</td>
<td>4/1</td>
<td>B</td>
<td>WAG</td>
<td>0</td>
<td>0.8888</td>
<td>0.0397</td>
</tr>
<tr>
<td>107</td>
<td>2.0</td>
<td>4/1</td>
<td>B</td>
<td>WAG</td>
<td>0</td>
<td>1.5395</td>
<td>0.0328</td>
</tr>
<tr>
<td>52</td>
<td>4.0</td>
<td>4/1</td>
<td>B</td>
<td>WAG</td>
<td>0</td>
<td>2.3760</td>
<td>0.1194</td>
</tr>
<tr>
<td>72</td>
<td>1.0</td>
<td>4/1</td>
<td>B</td>
<td>PRF</td>
<td>0</td>
<td>0.6071</td>
<td>0.1844</td>
</tr>
<tr>
<td>70</td>
<td>2.0</td>
<td>4/1</td>
<td>B</td>
<td>PRF</td>
<td>0</td>
<td>0.6477</td>
<td>0.1598</td>
</tr>
<tr>
<td>69</td>
<td>4.0</td>
<td>4/1</td>
<td>B</td>
<td>PRF</td>
<td>0</td>
<td>0.7929</td>
<td>0.0825</td>
</tr>
<tr>
<td>106</td>
<td>1.0</td>
<td>1/4</td>
<td>B</td>
<td>WAG</td>
<td>0</td>
<td>1.5192</td>
<td>0.0217</td>
</tr>
<tr>
<td>104</td>
<td>1.0</td>
<td>2/1</td>
<td>B</td>
<td>WAG</td>
<td>0</td>
<td>1.4985</td>
<td>0.0553</td>
</tr>
<tr>
<td>103</td>
<td>1.0</td>
<td>9/1</td>
<td>B</td>
<td>WAG</td>
<td>0</td>
<td>1.5699</td>
<td>0.0465</td>
</tr>
<tr>
<td>111</td>
<td>1.0</td>
<td>infinity</td>
<td>B</td>
<td>P</td>
<td>0</td>
<td>1.6253</td>
<td>0.0262</td>
</tr>
<tr>
<td>112</td>
<td>1.0</td>
<td>2/4</td>
<td>B</td>
<td>PRF</td>
<td>0</td>
<td>1.4290</td>
<td>0.0173</td>
</tr>
<tr>
<td>109</td>
<td>1.0</td>
<td>3/1</td>
<td>B</td>
<td>PRF</td>
<td>0</td>
<td>1.5130</td>
<td>0.0288</td>
</tr>
<tr>
<td>108</td>
<td>1.0</td>
<td>4/1</td>
<td>B</td>
<td>PRF</td>
<td>0</td>
<td>1.8326</td>
<td>0.0254</td>
</tr>
<tr>
<td>82</td>
<td>1.0</td>
<td>4/1</td>
<td>SS</td>
<td>WAG</td>
<td>2500</td>
<td>1.3487</td>
<td>0.0733</td>
</tr>
<tr>
<td>84</td>
<td>4.0</td>
<td>4/1</td>
<td>SS</td>
<td>WAG</td>
<td>2500</td>
<td>1.4940</td>
<td>0.1001</td>
</tr>
<tr>
<td>83</td>
<td>1.0</td>
<td>4/1</td>
<td>B</td>
<td>SAG</td>
<td>2500</td>
<td>0.6677</td>
<td>0.0394</td>
</tr>
<tr>
<td>85</td>
<td>4.0</td>
<td>4/1</td>
<td>B</td>
<td>SAG</td>
<td>2500</td>
<td>0.1712</td>
<td>0.1094</td>
</tr>
<tr>
<td>68</td>
<td>1.0</td>
<td>4/1</td>
<td>DW</td>
<td>WAG</td>
<td>0</td>
<td>1.3056</td>
<td>0.0899</td>
</tr>
<tr>
<td>67</td>
<td>4.0</td>
<td>4/1</td>
<td>DW</td>
<td>WAG</td>
<td>0</td>
<td>1.8001</td>
<td>0.0821</td>
</tr>
<tr>
<td>65</td>
<td>1.0</td>
<td>4/1</td>
<td>DW</td>
<td>DAG</td>
<td>0</td>
<td>0.7205</td>
<td>0.1273</td>
</tr>
<tr>
<td>66</td>
<td>2.0</td>
<td>4/1</td>
<td>DW</td>
<td>DAG</td>
<td>0</td>
<td>1.2201</td>
<td>0.1252</td>
</tr>
</tbody>
</table>

I.S: initial saturation  I.M: injection mode  G/L: gas-liquid ratio  
S.C: surfactant concentration  SS: surfactant solution  B: brine  
DW: distilled water  P: pure CO₂  
SAG: surfactant solution alternating with CO₂  PRF: pregenerated foam  
WAG: brine alternating with CO₂  DAG: distilled water alternating with CO₂
Appendix B: Micromodel Fabricating Procedure

Making a glass micromodel requires special procedure and experience. The following is a brief explanation of the procedure to make a glass etched micromodel based on the suggested procedure by Carr and Seright (1990).

Step 1: Preparing Pattern

The pattern may be a thin section from an actual porous media, or any other special design. Once the pattern is selected, a transparency is made of the pattern, with the void areas, pores and channels, black and white grains. This transparency is then reduced to the size of the micromodel which is to be fabricated.

Step 2: Preparing Glass Pieces

The glass is initially a piece of mirror (with a thickness of about 3 mm) cut to the desired dimension (about 1 cm larger than the pattern on each side). The mirror is coated with copper and a protective layer.

Step 3: Removing the Backing Layer

Removing the backing layer may be done using various chemical solutions. The formula of one solution that we have successfully tried is as follows:

Methylene chloride 85%
Submerge the mirror in the above mentioned solution. Depending on how many times the solution has been used, it will take about 15 seconds or more for the backing layer to peel off. Rinse the glass with tap water followed by rubbing the copper by a soft detergent to remove dirt on the copper. Rinse again with tap water. Tilt the glass back and forth while there is sufficient amount of acetone on the copper to cover it. Continue until a shiny copper surface is obtained. Wash the glass again with tap water, distilled water, and dry the glass with nitrogen. The whole step takes about three minutes. If the copper surface is oxidized or scratched, the finished micromodel may have a low quality.

**Step 4: Coating the Copper Surface**

Mix one part of Kodak thin film resist (KTFR) with two parts of Resist Developer (xylene) to prepare the coating solution. Pour sufficient coating solution on the copper while slowly tilting the mirror so that the whole copper surface is completely covered with the coating solution. Then drain the excess coating solution. This step should be performed in the hood and in relative darkness. Place the glass piece vertically in a dark area. After about twenty minutes, place the glass horizontally and leave it until it dries. Care should be taken to make sure that the coating (photo negative resist coat) has a uniform thickness over the entire surface of the copper.
Step 5: Exposing

After the photo negative resist coat has dried, the glass is placed on a black paper with the coated side facing upward. The transparency is placed on the glass such that the emulsion side of the transparency (the side on which the pattern may be removed by scratching) is in contact with the photo negative resist coat. A piece of glass (one or two mm thick) is then placed on the transparency to force uniform contact with the coating at every point. An ultra violet light source is placed above the glass and the whole system is covered under a black box; keeping the surroundings dark while exposing. The exact exposure time is a function of the ultraviolet source, the distance between the source and the glass, and the age of the photonegative resist. Using a twenty watt ultraviolet source and at a distance of about fifteen cm, an exposure time of ninety minutes is a good estimate. The right exposure time is determined after two or three glasses have been tested.

Step 6: Developing

The exposed glass is placed in an oven at a temperature of about 200° F for about 10 minutes. The glass is then cooled to room temperature in the dark. Next, hold the glass horizontally and pour sufficient xylene to cover the coating, while tilting it back and forth for about ninety seconds. During this period the whole surface should be kept wet with xylene. The excess xylene is drained and the surface is then washed with tap water and rinsed with distilled water. The pattern should appear on the copper. If the pattern does not appear, it has been overexposed. If the pattern or a part of it is washed
out, the pattern is underexposed. As mentioned, after two or three attempts the exact exposure time will be determined. The glass is again placed in the oven at the same temperature for about 10 minutes after which it is cooled to room temperature.

**Step 7: Etching with Nitric Acid**

The glass is then placed in a 50% nitric acid solution for a few seconds, or more depending on how many times the solution has been used. If the glass is left in nitric acid for a long time copper will be washed completely and makes it impossible for further steps to succeed. The glass is then washed with tap water and rinsed with distilled water. The copper is removed from the exposed area (pores and throats) at this step. Where the copper is not removed, use a needle or pour drops of nitric acid at some points to complete the pattern. The glass is placed again in the oven for another 10 minutes and then left to cool to room temperature.

**Step 8: Coating the Piece with Photo Negative Resist**

All parts on both sides of the glass (except the pattern area) and the edges of the glass are coated by photonegative resist so that the surface in these parts of the glass can be protected during etching with hydrofluoric acid. The glass is then placed horizontally until the coating dries.

**Step 9: Etching with Hydrofluoric Acid**

At this step, the glass in the pores and throats area will be etched by placing the
glass in a 48% hydrofluoric acid for about 6 minutes. The glass is then washed by tap water and cleaned with a brush in order to remove any loose glass deposits. The depth of the etched pore will be 2 to 4 thousandths of inch, depending on how many times the acid solution has already been used.

Step 10: Removing the Coating

The whole coating will be removed by a sharp knife. The glass is then left in 50% nitric acid solution until all the copper is removed and the glass is completely visible. The depth of the pores is then measured at several points to have an idea of the etched depth.

Step 11: Producing the Mirror Image Piece

If the micromodel is to be made of two etched glass pieces, the second piece is made using a transparency that is a mirror image of the first one. Otherwise, a smooth piece of glass is used as the second piece.

Step 12: Drilling the Inlet and Outlet Ports

The ports will be drilled in the upper piece using a diamond bit with the desired diameter. For the best quality, half of the depth is drilled from one side and the other half from the other side. This is a critical step because the glass can easily be broken during the drilling.
Step 13: Fusing

The two glass pieces are washed, cleaned thoroughly, and dried. They are then placed on each other with the etched sides facing each other and matching the pore system. A drop of water between the two pieces will help to hold the two pieces together while moving the two pieces to insure a match. When a match is achieved, two or three drops of glue will be poured on the corners of the two matched pieces to keep them in line while fusing. The matched pieces are then placed horizontally in an electric oven, temperature programmed, for fusing the glass.

Step 14: Measuring Pore Volume

When fusion is completed, the micromodel is thoroughly cleaned, dried, and weighed. The micromodel is then saturated with distilled water. Make sure air is completely removed from the micromodel. The external surface of the micromodel is then dried and the glass is weighed. This process is repeated several times to establish our precision. Having the density of the distilled water and the difference between the dried and saturated weights of the micromodel, the pore volume corresponding to the micromodel is calculated.

Step 15: Measuring Micromodel Average Porosity

The average porosity of the micromodel is calculated as the following:
\[
\phi = \frac{PV}{(D_U + D_L) \times (L) \times (W)} \times 100\%
\]

Where:

\( PV \) = micromodel pore volume

\( D_L \) = average etched depth of the lower piece

\( D_U \) = average etched depth of the upper piece

\( L \) = length of micromodel

\( W \) = width of micromodel

\( \phi \) = average porosity of micromodel

It should be noted that inlet and outlet channels also contribute to the measured pore volume, therefore giving a high value for the porosity.
This thesis is accepted on behalf of the faculty of the Institute by the following committee:

Adviser

Date